Draft 2 of Third World Ocean Assessment [text is unedited]

Section 1: Overall summary

Writing team (all members of the Group of Experts)

- Kwasi Appeaning Addo
- Maria João da Anunciação Franco Bebianno
- Ian Butler
- Donovan Campbell
- Mariamalia Rodriguez Chaves
- Felicia Chinwe Mogo
- Roberto De Pinho
- Mehdi Ghodrati Shojaei
- Rafael Gonzalez-Quiros
- Slimane Maliki
- Enrique Marschoff
- Carmen Mifsud
- Eric Okuku
- Renato Quinones
- Jörn Schmidt
- Vasily Smolyanitsky
- Joshua Tiwangye Tuhumwire
- Karenne Tun
- Katarina Viik
- Juying Wang
- Michida Yutaka
- Chang-Ik Zhang
- Tymon Zielinski

1. Introduction

The oocean plays a crucial role for life on Earth, ~~through sustaining~~ climate and ecosystems, and it supports world economies. Covering more than 70% of the Earth's surface, the ocean constitutes the largest and most interconnected ecosystem on Earth. ~~the oocean is the largest global ecosystem.~~ It sustains a diverse range of marine life ~~supports a vast range of species~~ and contributes to numerous, complex environmental processes.

~~The oocean plays a vital role in mitigating the effects of climate change consequences. It absorbs about 30% of the carbon dioxide, much of which has been produced mostly by human unsustainable activities, many of which are environmentally unsustainable. It absorbs about 30% of the carbon dioxide produced mostly by human unsustainable activities. The oceanIt also regulates temperature by distributing heat around the planet throughh ocean currents. The earth'splanetary climate would be much more extreme without the ocean's stabilizing role in the climate system.Due to the ocean's stabilizing role in the climate system, the planetary climate would be much more extreme.~~

~~[Alternative suggested paragraph; Rafa]~~

P~~It is p~~art of the climatic system of the planet, the ocean ~~and it~~ plays~~, and it will further play,~~ a fundamental role i~~o~~n the evolution of climate change. The ocean ~~It~~ has already absorbed more than 90% of the excess ~~of~~ heat and 30% of the C02 released to the atmosphere by the anthropogenic burning of fossil fuels.

Ocean currents, due to the high absorption capacity of the water and the enormous mass of the ocean, with an average depth of approximately 3600 m, contribute to redistribute heat and buffer temperatures at global to local scales. Modifications of global ocean current patterns are already conspicuous, and although the consequences for the evolution of climate change itself, no matter how, will be critical, are yet to be fully understood.

The majority ~~ocean is inhabited by the majority~~ of Earth's biodiversity is contained within the ocean. C~~and c~~oral reefs, for example, are among the most biologically diverse ecosystems on the planet, providing habitat for countless marine species~~and they provide habitat for many species~~. The o~~O~~cean is also home to not only fish, mammals, and numerous plants and algae but ~~also~~ microorganisms that are crucial in the global ~~nutrient cycles~~biogeochemical cycles. ~~These~~ The ocean ecosystems provide essential services, such as oxygen production, nutrient recycling, and support to food webs that sustain life on ~~in all regions of~~ our planet.

Many societies directly or indirectly depend on the ocean for their livelihood. Fisheries and aquaculture provide a significant portion of the world's protein supply, especially for coastal and island communities. The ocean also supports numerous industries like ~~e.g.~~ shipping, tourism, and renewable energy~~)~~, offering substantial contributions to the global economy.~~,~~ ~~thus contributing substantially to the global economy.~~

~~The ocean is a major player in the Earth's water cycle. Through evaporation, ocean contributes to the formation of clouds, which provide precipitation, hence moisture and freshwater supplies on land. This cycle is vital for securing water availability in ecosystems as well as for human needs.~~

~~The ocean is also directly connected with~~ Cultural, spiritual, and recreational values are strongly connected with the ocean. Coastal communities around the world have rich traditions and cultural identities tied to the ocean, whether through art, traditions, or heritage. Recreational use of the ocean supports mental well-being and contributes to local economies, underscoring the ocean's role in prosperity and human resilience.~~The ocean also attracts millions of people each year for numerous recreational activities, very important for mental well-being and economic prosperity of many humans.~~

The ocean is a key part of the planet's life support system. Improving the health of the ocean is essential not only for the sustainability of marine ecosystems but also for the well-being of all life on our planet. Advancing scientific understanding of the ocean across spatial and temporal scales is key for effective management of human activities and climate-related impacts.~~Therefore, all initiatives dedicated knowledgeto the enhancement in understanding how the ocean functions, regardless of the scale are crucial for the better understanding of all the complexity of environmental processes and mechanisms to better manage the climate change consequences.~~

Changes since WOA II

~~The World Ocean Assessment III (WOA III) follows on from previous reports, and thus references are made to the previous reports, especially to the findings of the WOA II, which was published in 2021. The chapter themes and structure are generally based on those of WOA II. Each chapter in WOA III provides specific information on the progress/changes which have been observed from 2018 until 2023. The novelty aspects of WOA III includes, the inclusion of a section on sustainability pathways, and s well as cross-cutting themes on gender, ITLK and governance, in every chapter where relevant.~~

The ~~World Ocean Assessment III (~~WOA III~~)~~ derives directly from the previous reports, ~~and thus references are made to the previous reports,~~ especially to the findings of the WOA II, which was published in 2021 with information up to 2018. ~~The chapter themes and structure are based on those of WOA II.~~ Each chapter provides specific information on the progress/changes which have been observed ~~since 2019~~between 2018 and 2023 except for those chapters that are newly introduced~~over the last 4 years~~. A key new feature of WOA III is that all relevant information in each chapter is described in relation to different ocean regions. The novelty aspects of WOA III includes, the inclusion of a section on sustainability

pathways, and cross-cutting themes on gender, ITLK and governance, in every chapter where relevant.~~What is especially new in WOA III is that, in every chapter where relevant, the information is described with respect to the different ocean regions.~~~~What is especially new in the WOA III is the fact that all information, in every chapter (wherever relevant) is described with respect to different ocean regions.~~

2. Stressors on the global ocean – drivers and pressures

The ocean is subject to both natural (e.g. tectonic, solar) and anthropogenic (e.g. greenhouse gas emissions, population growth) drivers, which lead to a variety of stressors and pressures (e.g. atmospheric CO_2 levels, habitat destruction and plastic pollution). Although progress is being made to manage drivers and mitigate pressures, many of these continue to negatively impact the world ocean, especially global biodiversity (see Social-ecological systems – Biodiversity and Habitats section below).

Drivers of change to the ocean (See also Section 4, Chapter 1)

~~affecting~~Drivers are widely recognised—across platforms such as Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Intergovernmental Panel on Climate Change (IPCC), the European Economic Area (EEA), and the Regional Seas Conventions—as natural or anthropogenic factors that influence ecosystem structure, function, or change.

The WOA III acknowledges the human drivers having the greatest influence on the marine environment and its sustainability are:

(a) Population growth and demographic changes,

Global human population increased from 7.7 billion to 8.2 billion between 2017 and late 2024, though the growth rate is slowly decreasing. Approximately 37% of the global population lives within 100 km of the coast and 11% live on land that is less than 10 m above sea level. The increasing population pressure on river catchments heightens demand for ~~as~~ food, space and resources, impacting the world ocean. Increasing populations also result in increased resource removal, such as fishing, which can be a major driver of habitat degradation.

(b) Economic activity

Economic growth, measured as gross domestic product per capita, is variable but has overall increased globally from 2.9% in 2019 to 3.3% in 2022-2024. Global energy consumption growth has accelerated from 1.5% per year around 2019, to 2.2% in 2023. The increased urbanization and industrialization, particularly in coastal regions, intensified demand for societal goods and benefits such as energy and other resources, increasing ocean pressure through extraction, production, consumption and waste generation.

(c) Technological advances

The growth of sustainable inclusive ocean economies, increasing urbanization and the industrialization on land and at sea has been accompanied by marine technological advances, offers both opportunities and potential increased impacts to the world ocean. For example, some fisheries technologies have both increased catches causing overfishing and helped to reduce by-catch.

(d) Changing governance structures and social, economic and geopolitical instability

Governance policies, politics, administration and legislation need to be vertically and horizontally integrated across the globe and across sectors. Each of the states' governance instruments requires an administrative body which results in overlapping statutory bodies. (see chapter 3). Governance structures are both improving rapidly with greater global collaboration, but also fracturing with global inconsistencies.

(e) Climate change, biodiversity loss and pollution

~~Climate influences~~Climate change is progressing rapidly, with widespread and cascading impacts across the global ocean. Climate both influences, and is influenced by oceanic conditions, which creates dynamic feedbacks within the Earth system. Although climate change represents a global exogenic pressure, its local manifestations require targeted responses at regional or national levels.

~~2.~~ Ocean stressors ~~stressors and change~~

~~The world ocean is subject to both natural (e.g. tectonic, solar) and anthropogenic (e.g. greenhouse gas emissions, population growth) drivers, which lead to a variety of pressures (e.g. atmospheric CO_2 CO2 levels, plastic pollution). Although steps in progress are being made to affect drivers and mitigate pressures, these are still altering the world ocean, in many cases in undesirable ways. For instance,~~ Although progress is being made to reduce greenhouse gas emissions, their~~but the~~ levels ~~of these gases~~ in the earth's atmosphere continues to rise, affecting the world ocean ~~in many~~ physically and chemically ~~ways~~. Since the WOA II~~#2~~, the world ocean continues to change quite rapidly, ~~and~~ in many ways ~~changing~~ faster than was previously understood. The tracking and understanding of the changes in physical and chemical properties of the ocean is critical to understanding the current state of the ocean and a key methodology for understanding the likely future. In the period covered by WOA III~~#3~~, technologies and collaboration for marine observation have continued to improve ~~since WOA II#2~~ and these technologies are revealing continued physical and chemical changes to the ocean globally.

Rapid, substantial climatic changes are taking place across the globe. ~~There have been and will continue to be~~ Ssignificant changes have occurred on coastal ocean dynamics which will impact regional communities into the future. ~~Nations will need to plan to adapt to them strategically to minimize damage to human communities and ecosystems they rely on.~~

The ocean continues to capture and store energy, leading to a sustained increase in ocean heat content~~leading to ongoing warming and continues to warm~~. ~~Sixteen percent~~ Notably, approximately 16% of the total increase in ocean heat content since 1955 has occurred since 2018~~Of theof ocean warming since 1955, 16% has occurred since 2018~~. The greatest relative warming has been observed in the Atlantic, and the southern parts of the Indian and the Pacific O~~o~~cean ~~and Southern oceans (+0.2ºC)~~.

Salinity varies across the globe depending on freshwater input and evaporation. Since 2018 salinity has decreased in the Pacific, North Atlantic and Southern oceans, but~~and~~ notably increased in mid-southern Atlantic and northern Indian oceans.

Sea level continues to rise at increasing rates from less than 2.0 mm yr^{-1} prior to 2015 to (~~greater than~~ 4.3~~2~~ mm yr^{-1} in 2023)~~)~~ through thermal expansion, melting ice with additional changes due to~~,~~ storm surges and tectonic/isostatic processes. Tropical seas are rising more rapidly than other areas as a result of thermal expansion.

Arctic sea ice extent continues to decrease, and the Southern Ocean is recently showing declines in sea ice extent, though it is variable across the region. The Arctic Ocean ~~could become open water~~ could become entirely ice-free in September ~~within the next 10-20 years~~The by mid- 21st century. ~~Arctic Ocean could be completely sea ice free in September within the next 10-20 years.~~

~~These s~~Sea ice changes are resulting in changes to ocean vertical stratification (e.g. temperature, salinity), mixing and circulation. These changes are most notable in the North Atlantic (i.e. Atlantic Meridional Overturning Circulation (AMOC)), related to changes in the Southern Atlantic and Indian oceans, and in the Arctic and Southern oceans (e.g. global overturning circulation).~~These sea ice changes are resulting in changes to ocean vertical stratification (e.g. temperature, salinity), mixing and circulation. These changes are most notable in the North Atlantic (i.e. Atlantic Meridional Overturning Circulation (AMOC)), related to changes in the Southern Atlantic and Indian oceans, and in the Arctic and Southern oceans (e.g. global overturning circulation).~~ The AMOC is still projected~~edicted~~ to weaken, but the ~~modelled~~ probability of ~~the~~ collapse ~~of AMOC~~ has decreased since WOA II~~#2~~.

Enhanced ocean chemistry monitoring reveals an ~~26% increase~~ la ~~very l~~ikely decrease in pH ~~acidity~~ranging from 0.06 to 0.10 units from 1985~~6~~ to 2022~~3~~ ~~(decrease of 0.1 pH units)~~ ~~since pre-industrial levels~~, with ongoing fluctuations and deeper penetration into the ocean (beyond 2000m). ~~Increased monitoring of ocean chemistry is revealing that ocean acidity has increased 26% since pre-industrial levels and is continually increasing (with high spatiotemporal variability), and spreading into greater ocean depths (2000m+).~~

Ocean carbon dioxide uptake is highly variable spatio-temporally but has tripled in the last 60 years (1960 – 2019) changing to ~~to 2019 to~~ 2.7 ± 0.3 p~~P~~etagrams of c~~C~~arbon per year as of 2019. Ocean uptake is expected to increase by 0.4 ± 0.1 p~~P~~etagrams of c~~C~~arbon per decade, though this will be attenuated as temperatures increase, which reduces CO_2 absorption. Total alkalinity (i.e. bicarbonate, carbonate), which buffers acidity in the ocean, has continued increasing in sub-tropical regions, but is highly variable across the globe.

Global ocean deoxygenation persists due to rising water temperature (reducing oxygen solubility) and intensified microbial activity caused by nutrient runoff from land. ~~Global deoxygenation of the ocean continues as a result of increasing water temperature (lower oxygen solubility) and increased microbial action from increased nutrification from terrestrial runoff.~~ The o~~O~~~~O~~cean hypoxic z~~o~~nes ~~one~~ continue~~s~~ to expand (4.5 million km^2 in last 50 years) and the ocean continues to loose around 1 Gigaton of oxygen per year decreasing by more than two per cent (4.8 ± 2.1 petamoles) since 1960.~~.~~

~~Since 2018, climate change has profoundly disrupted ocean nutrient cycles, affecting marine productivity, carbon sequestration, and greenhouse gas emissions. Climate change has significantly altered oceanic nutrient dynamics since 2018, impacting productivity, carbon sequestration, and greenhouse gas emissions.~~ Nitrogen availability and fixation are highly variable, with understanding of the processes still developing. Climate change, through temperature, stratification and circulation, – has also affected phosphorus dynamics, which itself interacts with nitrogen dynamics and fixation, with implications for marine productivity and ecosystems. ~~Ocean acidification is reducing silica availability, affecting diatom populations, while increased silica burial in sediments further limits its accessibility. Silica availability (e.g. diatoms) is being reduced by rising ocean acidification, with increased burial of silica in sediments. Silica is a key nutrient for growth in diatoms, which account for 40% of current marine primary production~~ Rising ocean acidification lowers the dissolution rate of biogenic silica and therefore increases the burial rate in sediments. This is expected to trigger diatoms decline, which require silicic acid to grow and currently account for near 40 percent of marine primary production.

~~**Drivers** (See also Section 4, Chapter 1)~~

~~Drivers are regarded widely (e.g. IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), IPCC (Intergovernmental Panel on Climate Change), EEA (European Economic Area?), Regional Seas Conventions, etc.) as any natural or human-induced factor directly or indirectly changing the ecosystem. The WOAIII acknowledges the human drivers having the greatest influence on the marine environment and its sustainability are:~~

~~(a) Population growth and demographic changes,~~

~~Global human population increased from 7.7 billion in 2019 and to 8.2 billion in late 2024, though the rate of increase is slowly decreasing. An estimated 37% of the global population lives within 100 km of the coast and 11% live on land that is less than 10 m above sea level. The pressure of the population on river catchments and demand for resources such as food, space puts pressure on the world ocean.~~

~~(b) Economic activity~~

~~Economic growth, measured as gross domestic product per capita, is variable but has overall increased globally from 2.9% in 2019 to 3.3% in 2022-2024. Global energy~~

~~consumption growth has accelerated from 1.5% per year around 2019, to 2.2% in 2023. The increased urbanization and industrialization, especially at the coast, has increased the demand for societal goods and benefits including energy and other resources which puts pressure on the world ocean through extraction, production, consumption and waste generation.~~

~~(c) Technological advances~~

~~The growth of sustainable inclusive ocean economies, increasing urbanization and the increasing industrialization on land and at sea has been accompanied by marine technological advances. These activities are both beneficial and adverse to the world ocean. For example, fisheries technologies have both increased catches and helped to reduce by-catch.~~

~~(d) Changing governance structures and geopolitical instability~~

~~Governance policies, politics, administration and legislation need to be vertically and horizontally integrated across the globe and across sectors. Each of the states' governance instruments requires an administrative body which results in overlapping statutory bodies. (see Governance chapter). Governance structures are both improving rapidly with greater global collaboration, but also fracturing with global inconsistencies.~~

~~(e) Climate change, biodiversity loss and pollution:~~

~~Climate change is occurring rapidly with a myriad of impacts across the world ocean. Climate both influences and is influenced by oceanic conditions. Climate change can be regarded as a global suite of exogenic unmanaged pressures in a marine area, but which may need to be managed locally.~~

Pressures (S4.C6)

The ocean has been subject to ~~several~~ many stressors generated by humans – such as pollution, invasions of non-indigenous species, erosion and sedimentation and marine infrastructure, as well as their cumulative effects. ~~,~~The combined influence of multiple stressors generates cumulative effects that can intensify and degrade ocean health, marine biodiversity, and pose risks to human well-being. As a result, progress toward achieving Sustainable Development Goal 14, Target 14.1, remains significantly off track.

Land-based as well as marine pollution sources continue to impact the ocean with chemicals and other materials (S4.C6 sub 5). There are many types of legacy (metals, persistent organic pollutants (POPs) and radioisotopes) and emerging contaminants (plastics, pharmaceutical compounds and personnel care products (PCPs) and per- and polyfluoroalkyl substances (PFASs)) that were introduced in the ocean. There is some evidence for a decline in emissions and precipitation of legacy contaminants such as mercury and some organic compounds in selected areas. However, persistent organic pollutants continue to impact polar regions and the deep sea as well as coastal marine ecosystems. Levels of pharmaceutical compounds in the ocean continue to increase, with new pharmaceutical compounds and personnel care products being detected particularly in coastal areas. The levels of antibiotics have increased and spread to other areas of the ocean. Toxicity studies show significant adverse effects of PPCPs on marine organisms including behavioural changes in various species such as fish, invertebrates, and algae. Therefore, action plans and priorities are needed to decrease the presence and potential impacts of PPCPs in the ocean.

Global plastic waste leaking into the ocean continues to rise, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering, and marine activities and with only limited knowledge about nanoplastics. These plastics, especially microplastics, impact all marine ecosystems and there is evidence of impact on over 4,000 species. Plastic pollution costs billions annually, so addressing this issue requires reducing production, advancing material science innovation, promoting recycling, and finding alternatives to single-use plastics to lessen the scale of the problem.

Improvements in wastewater treatment technologies are necessary to reduce levels of POPs, PPCPs, micro and nanoplastics in effluents, thereby alleviating the pressure on coastal marine environments.

The need for non-carbon electricity is increasing the demand for nuclear electricity, and consequently the related radioactive discharges.

~~that include several types of legacy (metals, organic compounds and radioisotopes) and emerging contaminants (plastics, pharmaceutical compounds and personnel care products (PPCPs) and per- and polyfluoroalkyl substances (PFASs)) that were introduced in the ocean from land-based or marine sources as well as the spread of non-Indigenous species (NIS) distributed around the world ocean. Both atmospheric deposition and riverine inputs are important pathways for these contaminants to reach the ocean. The impact of erosion and sedimentation and of marine infrastructures are other stressors that affect the ocean. These multiple stressors along with climate change induce cumulative effects that can be exacerbated and have a negative impact on the health of the ocean, its biodiversity and human health and therefore Target 14.1 of SDG14 is far from being achieved.~~

Non-~~I~~Indigenous Species

Non-i~~i~~Indigenous species (NIS) continue to spread with significant negative impacts on native species and habitats with global ecological, socio-economic, cultural and human health impacts. ~~These effects are exacerbated by climate change facilitating the spread and impacts of NIS and compromising the achievement of up to 11 of the 17 UN SDGs (Sustainable Development Goals) and other global conservation efforts.~~ Climate change exacerbates these effects by facilitating the spread and impact of NIS and undermines progress towards up to 11 of the 17 United Nations Sustainable Development Goals (SDGs), as well as other global biodiversity and conservation commitments.

Therefore, it is essential to prevent the introduction of NIS species either intentionally or unintentionally, although few mandatory global or regional regulations or policies are in place to do this. Systematic monitoring programs and data sharing at multiple and spatial scales are needed to allow the possibility of putting in place management effects and solutions.

Erosion and sedimentation

~~Human interventions increased pressures on the coastal zone that is also very susceptible to climate change. Trends and patterns of change of erosion and sedimentation were detected due to the increase availability of global and regional satellite data obtained since the mid-2010s.~~ Anthropogenic pressures are increasing and highly concentrated in coastal zones, which are inherently vulnerable to the impacts of climate change. Since the mid-2010s, the increased availability of satellite data has enabled the detection of changing patterns and trends in coastal erosion and sedimentation. Although there are still uncertainties and limitations of using of this technology, evidence exists that coastal erosion intensified in the Arctic due to permafrost thaw and increase in wave action attributed to sea-ice loss and longer ice-free seasons. Consequently, considerable amounts of nutrients have been released into the Arctic Ocean with emerging implications for carbon sequestration and marine ecosystems. Increasing the exposure of people, property and economic activities to coastal flooding and erosion across all latitudes was observed because of climate change.

Nature-based approaches, including the re-naturalisation of flood plains and intertidal areas, are being increasingly implemented on catchments and coasts in the Northern Hemisphere. These approaches aim to enhance resilience in the longer term.

Marine Infrastructures

Marine infrastructures development beyond coastal areas has intensified and ~~exert~~ is exerting new pressures on the ocean's ecosystems. This development puts increased pressure on~~, reduce~~ biodiversity, generating ~~e~~ noise and vibrations ~~another pressure~~ that affect marine life behaviour ~~and physiology, and intensifies the introduction of invasive species~~. Offshore wind farms continue to expand further offshore putting additional human pressure on understudied marine environments. ~~Offshore wind farms continue to expand~~

~~further offshore.~~ There is also an increasing rate in creation of oil and gas infrastructures, particularly in deeper waters, while at the same time some decommission of these infrastructures is taking place. In addition, changes and developments in submarine cables and pipelines continue to be developed forming a critical part of global communications infrastructures.

~~**Liquid Pollution from land-based sources**~~

~~Land-based as well as marine pollution sources continue to impact the ocean with invisible and visible chemicals and other materials although there is some evidence for a decline in emissions and precipitation of legacy contaminants such as mercury and some organic compounds in selected areas. However, persistent organic pollutants continue to impact polar regions and the deep sea as well as coastal marine ecosystems. Levels of pharmaceutical compounds in the ocean continue to increase, with new pharmaceutical compounds and personnel care products (PPCPs) being detected particularly in coastal areas. The levels of antibiotics have increased and spread to other areas of the ocean. Toxicity studies show significant adverse effects of PPCPs on marine organisms including behavioural changes in various species such as fish, invertebrates, and algae. Therefore, action plans and priorities are needed to decrease the presence and potential impacts of PPCPs in the ocean.~~

~~Global plastic waste emissions continue to rise, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering, and marine activities and with only limited knowledge about nanoplastics. These plastics, especially microplastics, impact all marine ecosystems and over 4,000 species have been affected. Plastic pollution costs billions annually, so addressing this issue requires reducing production, advancing material science innovation, promoting recycling, and finding alternatives to single-use plastics to lessen the scale of the problem.~~

~~Improvements in wastewater treatment technologies are necessary to reduce levels of POPs, PPCPs, micro and nanoplastics in effluents, thereby alleviating the pressure on coastal marine environments.~~

~~The need for non-carbon electricity is increasing the demand for nuclear electricity, and consequently the related radioactive discharges.~~

Cumulative effects **(S4.C6 Cumulative effects)**

Since WOA II there has been continued recognition and research of cumulative effects. Chemical contaminants can interact in multiple ways, and 7% of pesticides have been estimated to act in synergy. There is a need to jointly develop global platform(s) that map human pressures and natural assets, alongside a knowledge base to predict the potential effects of different combinations of human pressures on these assets. Therefore, c~~C~~umulative e~~E~~ffects a~~A~~ssessment can guide further development of assessment approaches for decision makers including scenario analyses of anthropogenic activities and the associated stressors to prevent unnecessary ecosystems damage.

Ocean Hazards of Natural Origin (S5B.C4)

Several ocean-related processes are sources of hazards for coastal societies and cause perturbations on marine and coastal ecosystems. Ocean Hazards of Natural Origin (OHNO) can be classified in three categories: a) Geophysical/Geological; b) Ocean Weather, Hydrology and Climate, c) Ecological and Biological. Chapter S5B.C4 focuses on the first two, since they affect ecological and biological hazards, which are in turn covered in other chapters of WOA III. S5B.4C stablishes a framework that connects climate and weather pressures, OHNOs, the types of impacts and disasters they cause and the mitigation, management and adaptation measures that can be implemented.

Among geophysical hazards, earthquakes, tsunamis and volcanic eruptions, are the most impactful OHNO in deaths and economic losses. Tectonic subsidence in coastal regions causes the lowering of the land with respect to sea level. This geological process operates at scales larger than decadal, although it makes areas more sensible to other OHNO, such as

fooding, storm surges or Sea Level Rise that are increasing or projected to increase with climate change, acting at different time scales. In the case of coastal erosion, climate change will cause the retreat of sandy coastlines in all continents. One-third of the global densely populated Low Elevation Coastal Zone (LECZ) is projected to experience shoreline retreat of more than 100m by 2050, and to rise between 52 percent to 63 percent by the end of the century, with a potential for a wide range of impacts, including important economic loss.

Ocean Weather, Hydrology and Climate hazards include cyclones, meteotsunamis, waves, Sea Level Rise, coastal flooding, marine heat waves, glacial melting, heavy rainfall and river flooding, draughts, saltwater intrusion, acidification and deoxygenation. These OHNO are projected to increase with climate change. Those being, or being related with, meteorological processes, such as cyclones, meteotsunamis or coastal flooding, act the time scales of events. Climate-related OHNOs act mainly at the scale of decades or over, whereas others such as droughts and saline intrusions act across all scales, as they are both related with meteorological and climatic processes.

The complex interactions between the nature of these OHNOs, the time scales at which they operate, and the modulation that weather conditions and climate change exert on many of them, cause different impacts and disasters including: loss of lives and land; infrastructures and property damage; tourism, food system and livelihood disruption; coastal flooding and erosion, habitat and biodiversity loss; cultural heritage loss; navigating and shipping challenges; and water quality issues, including saline intrusion. Accordingly, different actions can be implemented to mitigate the impacts, manage the consequences and stablish measures for adaptation. The approach identifies a first level of risk reduction actions that include: monitoring, forecasting and early-warning systems; warning, dissemination and communication; preparedness and response; sectoral medium to long term planning (zoning, infrastructure); Nature-Based Solutions; Digital Twins; Managed Retreat; infrastructure upgrading, climate proofing and building codes. However, these risk-reduction measures need to be implemented together with and imbibed in, high overarching governance, institutional or social transformations, including Marine and Maritime Spatial Planning; governance frameworks; Disaster Recovery Planning; Equitable Coastal Resilience; government investments, financing and insurance; capacity-building or Corporate Social Responsibility (CSR).

Furthermore, these overarching transformations have to be aligned with evolving international climate policy frameworks on ocean resilience, National Adaptation Plans (NAPs), Nationally Determined Contributions (NDCs) and international coordination of early warning systems (e.g. Tsunamis).

3. Social-ecological systems

One Health

The concept of One Health involves undertaking an integrated, unified approach to balancing the health of the physical and chemical marine environment, the inhabiting organisms and people interacting with both. It is recognized by the World Health Organization (WHO) as being particularly relevant for food and water safety, nutrition, the control of zoonoses, pollution management, and combatting antimicrobial resistance. The concept is based on several fundamental principles including equity, inclusivity, equal access, parity, socio-ecological equilibrium, stewardship, and trans disciplinarity.

Under this definition of “One Health”, all the chapters of Sections 4 and 5 in this WOA could have been included, as any taxonomical group, marine habitat, or ocean economy sector are interacting with each other and with societies, and must be balanced under an integrated, unified approach. However, ~~U~~under Section 5B (One Health), aspects with a higher social

component (e.g. human health, wellbeing, equity, gender and Indigenous P~~p~~eoples' knowledge) or with social ~~direct~~ high impact (e.g. the role of ecosystems in the carbon cycle, ocean hazards and COVID 19) have been grouped.

The role of marine ecosystems on the carbon cycle (S5B.C1)

The ocean contributes to around half of the Earth's annual primary production, supporting 80% of global animal biomass. Understanding and protecting the role of marine ecosystems in driving the carbon cycle is intrinsically linked to the health [S5B.C2] and well-being of billions of people [S5B.C3], due to the role of marine ecosystems in the regulation and potential mitigation of climate change and other related ecosystem services such as food provision.

The biological pump (Fig.5B.C1.1) is the process by which plankton and ~~micro~~nekton ~~organisms~~ drive carbon in the ~~open~~ ocean towards the deep sea where it is remineralised by organisms. When carbon reaches depths below 500 to 1000 m, it becomes sequestered for hundreds to thousands of years. ~~Despite only around 2% of carbon fixed at the surface reaches these depths, the large area comprised by the open ocean assures it will play a significant role on the evolution of climate change in the next decades to hundreds of years.~~ Although only about 2% of carbon fixed at the ocean surface reaches the deep sea, the large spatial extent of the open ocean ensures that it will continue to play a significant role in modulating climate change over decadal to centennial timescales.

However, the biological pump consists of a complex array of processes with high uncertainties on their relative contribution and differences across geographical areas. Examples of these include: the role of sinking material vs. migrating organisms; the composition of plankton communities; the dynamics of carbon within sediments; the amount of carbon exported from shelf areas towards the open ocean, and; factors related with climate change (e.g. ocean stratification deoxygenation or ocean acidification). Reducing these uncertainties is critical to understand the role of the ocean as one of the major contributors to carbon sequestration.

Blue Carbon Ecosystems

The term Blue Carbon (BC) was first used for three vegetated coastal ecosystems, ~~salt marshes~~saltmarshes, seagrass meadows and mangroves, which capture and store more carbon per unit area than terrestrial forests.

~~The term Blue Carbon~~BC ~~-~~has broadened beyond these original Coastal Blue Carbon Ecosystems (CBCEs)~~'s~~ to include other habitats. Unvegetated, seafloor sediments on the continental shelf make up around 9% of the total marine area but hold the biggest carbon store in shelf systems, and over 80% of organic carbon is buried in these subtidal sediments.

~~The protection and restoration of Coastal Blue Carbon Ecosystems (CBCEs) are seen as a Nature-based Solution (NbS) for marine climate change mitigation, and may contribute to Nationally Determined Contributions (NDC's) under the Paris Agreement.~~ The protection and restoration of CBCEs are increasingly recognised as a Nature-based Solution (NbS) for marine climate change mitigation and may contribute to the achievement of Nationally Determined Contributions (NDCs) under the Paris Agreement. Several countries have initiated strategies to enhance the carbon sink capacity of coastal ecosystems through targeted conservation, restoration, and management interventions.

~~Recent estimates suggest, however, that with full restoration of CBCEs, the total contribution to climate mitigation is around 2% globally.~~ Recent estimates indicate that, with full restoration, CBCEs would contribute approximately 2% to global climate change mitigation potential.

In temperate regions, the small geographical area of these ecosystems means it is unlikely to play a significant role in meeting ~~climate~~ mitigation targets. For small island nations, which have larger geographical extent of BC habitats, the contribution ~~to their NDC's~~ may be significantly higher. Further, the huge global variability of carbon stocks in the same habitat

makes it difficult to accurately assess carbon sequestration, and studies are often under-represented in the global south. Access to international financing and capacity building, including scientific cooperation, training and transfer of marine technology, are particularly critical for the assessment and management of blue carbon and to acomplish NDC's in the global south, and therefore for achieving global targets.

~~The term Blue Carbon has broadened beyond the original CBCE's to include other habitats. Unvegetated, seafloor sediments on the continental shelf make up around 9% of the total marine area but hold the biggest carbon store in shelf systems, and over 80% of organic carbon is buried in these subtidal sediments.~~

Macroalgae~~,~~ have been recently suggested as a CBCE. Although most of algal production is remineralised annually, a fraction is potentially exported towards the open ocean or a small fraction buried in the sediments.

Whilst it may seem counterintuitive, calcification by marine~~calcifying~~ organisms, ~~(e.g.~~such as corals corals and bivalves,~~)~~ provokes a net emission of ~~emit~~ CO_2 ~~because calcium carbonate removal reduces the capacity to buffer acidification (i.e alkalinity) more than the amount of carbon that is removed because more alkalinity is removed than carbon, , because more alkalinity is removed than carbon,~~ and many calcifiers additionally produce CO_2 through respiration. Recently, coralline algal beds found in sediments have also been suggested to be ~~Blue Carbon~~Blue Carbon habitats, because the carbon captured and stored through photosynthesis may exceed the ~~carbon~~ CO2 released by calcification.

~~**Human wellbeing (S5B.C3)**~~

~~**Ocean ecosystems extensively contribute to human well-being, ranging from economic value to non-market benefits, such as spiritual, cultural, recreational services. Non-market valuation of marine ecosystems, despite its challenges, remains crucial to understanding and quantifying the non-monetary value of the oceans, which can enable policy decisions that support both human well-being and environmental health. Subjective well-being is further linked to the therapeutic and restorative qualities of marine environments, reinforcing the significance of accessible blue spaces for mental and physical health. Furthermore, ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge, intergenerational heritage and social cohesion, being particularly critical in the case of Indigenous Peoplescommunities.**~~

~~**Several case studies in S5B.C3 illustrate how different communities interact with and depend on ocean resources, often employing innovative strategies to balance conservation with socio-economic needs. However, growing environmental challenges—such as climate change, pollution, and resource depletion—pose severe risks to these benefits, underscoring the necessity for robust policy frameworks and community-driven conservation. The integration of cultural, economic, and ecological perspectives into ocean management policy ensures that the ocean continues to support human well-being, cultural heritage, and sustainable development for future generations.**~~

~~**[Alternative writing of the summary of S5B.C2 and S5B.C3 into a single section**~~

Ocean and Human Health (S5B.C2) and Human wellbeing (S5B.C3)

The health of the ocean and human populations is deeply interconnected within a complex global network, making a healthy ocean essential for supporting human health and well-being. These interactions provide numerous health benefits, derived from a higher sport activity in coastal areas, the consumption of seafood, and the development of marine-derived pharmaceutical compounds.

In addition, ~~Additionally,~~ biotechnology, economic benefits, and opportunities for cultural, spiritual, and artistic expression contribute to the well-being of coastal communities. Ocean ecosystems extensively contribute to human well-being, ranging from economic value to non-market benefits, such as spiritual, cultural, recreational services.

Non-market valuation of marine ecosystems, despite its challenges, remains crucial to understanding and quantifying the non-monetary value of the ocean, which can enable policy decisions that support both human well-being and environmental health. Subjective well-being is further linked to the therapeutic and restorative qualities of marine environments, reinforcing the significance of accessible blue spaces for mental and physical health.

Furthermore, ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge, intergenerational heritage and social cohesion, being particularly critical in the case of Indigenous Peoples. Several case studies in S5B.C3 illustrate how different communities interact with and depend on ocean resources, often employing innovative strategies to balance conservation with socio-economic needs.

The health and well-being benefits derived from ocean ecosystems are at risk due to

~~However, However, growing environmental challenges—such as climate change, pollution, and resource depletion—pose severe risks to health and wellbeing benefits.~~ escalating environmental challenges such as climate change, pollution, and resource depletion. Human health is increasingly challenged by harmful algal blooms (HABs), pathogenic bacteria and viruses, antimicrobial resistance (AMR), and toxic chemicals, including persistent organic pollutants (POPs), heavy metals (mercury, cadmium, and lead), hydrocarbons, pesticides, and emerging contaminants such as pharmaceutical residues, personal care products, nano-/microparticles (especially plastics increasingly detected in marine species), and per- and polyfluoroalkyl substances (PFAS), also known as "forever chemicals." Additionally, environmental radiation can further threaten marine ecosystems (S4.C6). Contaminated seafood presents serious food safety concerns and may lead to endocrine disruption, neurotoxicity, renal dysfunction, osteoporosis, and various types of cancer in humans.

The integration of cultural, economic, and ecological perspectives into ocean management policy ensures that the ocean continues to support human health benefits and well-being, cultural heritage, and sustainable development for future generations.

~~**Ocean Hazards of Natural Origin (S5B.C4)**~~

~~Several ocean-related processes are sources of hazards for coastal societies and cause perturbations on marine and coastal ecosystems. Ocean Hazards of Natural Origin (OHNO) can be classified in three categories: a) Geophysical/Geological; b) Ocean Weather, Hydrology and Climate, c) Ecological and Biological. Chapter S5B.C4 focuses on the first two, since they affect ecological and biological hazards, which are in turn covered in other chapters of WOA III. S5B.4C stablishes a framework that connects climate and weather pressures, OHNOs, the types of impacts and disasters they cause and the mitigation, management and adaptation measures that can be implemented.~~

~~Among geophysical hazards, earthwquakes, tsunamis and volcanic eruptions, are the most impactful OHNO in deaths and economic losses. Tectonic subsidence in coastal regions causes the lowering of the land with respect to sea level. This geological process operates at scales largerd than decadal, although it makes areas more sensible to other OHNO, such as~~

foolding, storm surges or SSea LLevel RRise that are increasing or projected to increase with climate change, acting at different time scales. In the case of coastal erosion, climate change will cause the retreat of sandy coastlines in all continents. One-third of the global, densely-populated, Low Elevation Coastal Zone (LECZ) is projected to experience shoreline retreat of more than 100m by 2050, and to rise between 52 52 percent to 63 63 percent by the end of the century, with a potential for a wide range of impacts, including important economic loss.

Ocean Weather, Hydrology and Climate hazards include cyclones, meteotsunamis, waves, Sea Level Rise, coastal flooding, marine heat waves, glacial melting, heavy rainfall and river flooding, draughts, saltwater intrusion, acidification and deoxygenation. These OHNO are projected to increase with climate change. Those being, or being related with, meteorological processes, such as cyclones, meteotsunamis or coastal flooding, act the time scales of events. Climate-related OHNOs act mainly at the scale of decades or over, whereas others such as droughts and saline intrusions act across all scales, as they are both related with meteorological and climatic processes.

OHNOs include: Tsunamis, earthquakes, volcanic eruptions, tectonic subsidence, coastal erosion, tropical and extra-tropical cyclones, meteotsunamies, sea level rise, waves, storm surge and coastal flooding, marine heatwaves, glacial melt, rain fall and river flooding, droughts, salt water intrusion, ocean acidification and ocean oxygenation. The complex interactions between Tthe nature of these OHNO, the time scales at which they operate, and the modulation that weather conditions and climate change exert on many of them, cause different impacts and disasters including: Loss of lives and land; infrastructures and property damage; tourism, food system and livelihood disruption; coastal flooding and erosion, habitat and biodiversity loss; cultural heritage loss; navigating and shipping challenges; and water quality issues, including saline intrusion. Depending on the nature of the OHNO, the impacts and disasters that they cause and the scales of operationAccordingly, different actions can be implemented to mitigate the impacts, manage the consequences and stablish measures for adaptation. The approach identifies a first level of risk reduction actions that include: Monitoring, foerecasting and early-warning systems; Warning, dissemination and communication; Preparedness and response; Sectoral medium to long term planning (zoning, infrastructure); Nature-Based Solutions; Digital Twins; Managed Retreat; Infrastructure Upgrading, Climate proofing and BluildingBuilding codes. However, these riskh -reduction measures need to be implemented together with and imbibed in, high overarching governance, institutional or social transformations, including:including Marine and Maritime Spatial Planning; Governance frameworks; Disaster Recovery Planning; Equitable Coastal Resilience; Government Investments, Financing and Insurance; Capacity Building or Corporate Social Responsibility.

Furthermore, these overarching transformations have to be aligned with evolving international climate policy frameworks on ocean resilience (UNFCCC, 2023, 2024a, b), National Adaptation Plans (NAPs) by the Nationally Determined Contributions (NDCs) and international coordination of early warning systems (e.g. Tsunamis).

Pandemics including COVID-19 Impacts (S5B.C7)

Many direct and indirect effects of the COVID-19 pandemic remain uncertain, underscoring the need for further research to prepare for future global health crises. However, the COVID-19 pandemic had severe impacts on the health and safety of seafood workers and coastal communities. Seafood workers faced hight risks of contracting the virus due to their working conditions. High infection risks, declining seafood demand, and global tourism losses disrupted several business activities such as fisheries, port operations, and supply chains. The COVID-19 pandemic also affected marine ecosystems. Increased plastic waste, particularly from discarded face masks, threatened several marine species (S4.C6. Poll). Reduced shipping, recreation, and fishing led to behavioural changes and increased biodiversity, though marine mammals and birds were also affected. Lower underwater noise altered species communication, while disruption of scientific research and fisheries

monitoring ~~fueled~~fuelled illegal fishing in certain regions. As a result of COVID-~~-~~19 pandemic, many new policies were created to deal with health and safety issues related to ocean related employment (e.g. workplace safety).

Biodiversity and h~~H~~abitats ~~and biodiversity~~

Marine Biodiversity (S4.C4)

~~Marine biodiversity encompasses the diversity of life forms within oceanic ecosystems, from microscopic plankton to large marine mammals. It serves as the basis for a healthy oceans, supporting ecosystem functions such as primary productivity, carbon cycling, and climate regulation.~~ Marine biodiversity encompasses the variety of life forms within ocean ecosystems, ranging from microbes to large marine mammals. It underpins ocean health by supporting primary productivity, facilitating carbon cycling, and contributing to climate regulation.

The vast network of marine life interacts in complex ways to guarantee resilience and stability of ecosystems. Marine biodiversity has undergone significant changes since WOA II, influenced by several elements affecting species composition, population dynamics, and ecosystem stability. Plankton is the base fuelling the pelagic food web and for most of the shelf and deep-sea benthic habitats. It plays a fundamental role in biogeochemical cycles (S5B.C1) and for higher trophic levels, including those sustaining fisheries. ~~Plankton encompasses an extremely diverse group, which exhaustive analysis is beyond the scope of the WOA.~~

The most dramatic changes since WOA II were observed in the Arctic Ocean, with increasing phytoplankton biomass associated to warming and sea-ice coverage, changes in abundance, composition, phenology and distribution. Globally, phytoplankton blooms have increasingly exhibited unpredictability, disrupting carbon cycling and the accessibility of food availability for higher trophic levels. Zooplankton populations, especially krill, have demonstrated regional declines (S4. C4a). ~~The impacts of climate change on plankton in other regions is not as clear, most likely a result of the paucity of long-term observation time-series, particularly in coastal areas and in the Southern Hemisphere.~~ The impacts of climate change on plankton in many regions remain unclear, largely due to the limited availability of long-term observational time series—particularly across the Southern Hemisphere.

Some studies show conspicuous responses in abundance and composition associated to climate related extreme events. ~~(e.g. marine heat waves).~~

Cephalopods demonstrate resilience due to their short life cycles and high reproductive rates, with some populations thriving as a result of increasing temperatures. Nevertheless, distribution patterns have changed, and certain exploited species consistently face pressures from fisheries (S4. C4b).

Marine benthic invertebrates, particularly corals, are experiencing increased stress due to the rising frequency of widespread bleaching events caused by elevated sea temperatures. The lack of knowledge about deep-sea species, together with their vulnerability to some destructive activities such as trawling, persists despite the positive effects observed from conservation efforts and marine protected areas ~~(MPAs)~~ since WOA II (S4. C4c).

Fish populations consistently face challenges due to overfishing and habitat degradation, despite a heightened emphasis on sustainable fisheries and bycatch reduction compared to WOA II. While many reef fish continue to decline, some species like tuna show signs of recovery because of improved fishing rules (S4. C4d).

Marine mammals persistently face risks from entanglement to vessel collisions, and plastic pollution. While some ~~whale~~ species (e.g. Mediterranean seals and dolphins) show slight recovery, others like the North Atlantic right whale remain critically endangered since WOA II. Moreover, increased underwater noise pollution (e.g. armed conflict, shipping, offshore infrastructure) is disrupting marine mammal migration and communication (S4.~~-~~C4e).

Marine reptiles, particularly sea turtles, struggle with habitat loss, plastic pollution, and climate change. Conservation efforts have led to nesting success~~;~~ since WOA II, however

general trends are alarming, especially as increasing sand temperatures are skewering hatchling sex ratios towards females (S4. C4f)

Seabirds are similarly affected by climate change, as changes in prey availability influence their reproductive success. Following WOA II2, the frequency of plastic ingestion and bycatch-related mortality has risen;, although mortality of some bird species is being reduced as a result of modified fishing techniques (S4. C4g).

Marine vegetation, including seagrass and mangrove ecosystems, is essential for carbon sequestration and coastal protection, and serves as key habitat supporting marine biodiversity.. Still, pollution and coastal development are causing their global drop to continue. Following WOA II2, their climate-mitigating properties have become more well-known, which has spurred restoration projects (S4. C4h). Algae like kelp forests, have diminished due to rising water temperatures and changing herbivore populations since WOA II. Some regions have shown resilience due to conservation efforts; however, invasive macroalgae increasingly threaten native biodiversity (S4. C4i).

Overall, the key findings underscore persistent challenges confronting marine biodiversity, including climate change, habitat loss, pollution, particularly plastics, and overexploitation. Conservation efforts, strengthened regulations, and global cooperation are crucial for mitigating these impacts and preserving the resilience of marine ecosystems.

Habitats (S4.C5)

Marine habitats encompass diverse ecosystems, ranging from shallow coastal zones to deep-sea environments, and are all vital for maintaining biodiversity, providing ecosystem services, and supporting human livelihoods. These habitats are highly dynamic, with species and flows of nutrients linking different regions of the ocean. However, they are increasingly impacted by pollution, habitat loss, climate change, and human activities. Sea-level rise, ocean acidification, increased extreme events, and habitat fragmentation have all contributed to changes in a variety of marine habitats since WOA II. Conservation efforts have grown, with a focus on nature-based solutions, ecosystem restoration, and sustainable management techniques. Below is a summary of key habitats and the changes they have undergone since WOA II.

The intertidal zone has historically and continues to experience significant transformations and habitat loss caused by sea level rise and coastal squeeze, with biodiversity also at risk from extreme events and rising temperatures.. Eutrophication, and pollution included micro-plastic accumulation increased, affecting species and ecosystem services (S4.C6 Poll). Attempts to incorporate intertidal ecosystems into programs aimed at mitigating climate change have increased despite some challenges since WOA II. The importance of marine vegetated habitats in sequestering carbon is recognized by blue carbon initiatives. To increase resilience, conservation strategies now incorporate green-grey infrastructure, ecosystem co-design, and nature-based solutions (S4.C5A, S5A. C9).

Biogenic reefs and sandy, muddy, and rocky shores face intense pressures from climate change and human activity, with rising sea level, coastal hardening, and pollution impacting biodiversity and ecosystem functions that threaten biodiversity and disrupt ecosystem functions. Coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by century's end, compromising resilience to sea-level rise. Emergent threats like plastic pollution (S4.C6 Sub 5Poll) and artificial light at night further strain these environments requiring target research and mitigation strategies. Safeguarding coastal habitats requires robust governance that integrates diverse knowledge systems (e.g. including traditional, Indigenous Peoples' and local knowledges) and encourages participatory decision-making. Greater research is needed in tropical and subtropical regions, where data gaps persist, while addressing disparities in coastal management between high- and middle-income countries (S4.C5B).

New findings, include the Antecedent Karst Theory and insights into atoll hydrogeology, challenging previous models of atoll formation. Carbonate sand production and storm-driven sediment transport may help sustain atoll islands despite rising sea levels. Atolls face

different threats, with ocean acidification and warming seas weakening reefs and increasing coral bleaching. While some remote reefs recover within years, densely populated atolls, like the Maldives, take over a decade to regenerate (S4.C5C).

Coral reefs are declining rapidly ~~threatening biodiversity and ecosystem stability~~due to a range of stressors. Increasing disturbances ~~like~~ such as marine heatwaves and storms ~~leave~~leave little time for recovery, pushing reefs toward collapse. Since 2018, multiple global bleaching events have caused widespread coral mortality, with projections suggesting 90% of reefs could disappear if warming exceeds 1.5°C. Even historically resilient areas like the South Atlantic are experiencing severe losses, while rising hypoxia and ocean acidification add further stress. The Northeast Atlantic and Mediterranean are warming at triple the global rate, and the Caribbean has lost 80% of coral cover since the 1970s. The Indian Ocean, Red Sea, and Persian Gulf ~~— once seen as refuges —~~ are now experiencing rapid declines. On remote protected atoll reefs of the Chagos Archipelago recovery to net accretion, albeit with reduced biodiversity, has been achieved within 2–6 years following past El Niño Southern Oscillation (ENSO) episodes ~~(e.g. Lange et al., 2023)~~. This compares with a period of 14 to 16 years on some densely populated atolls in the Indian Ocean ~~(Montefalcone et al., 2018)~~, underlining the need for a wholistic approach to supporting coral reef recovery (S4.C5D).

Although, c~~C~~old-water corals and sponges (CWCS) face increasing threats, ~~leading to habitat degradation and biodiversity loss. N~~new discoveries, such as extensive reefs on the Blake Plateau, highlight their role in carbon sequestration and ecosystem dynamics. Ocean acidification continues to weaken coral structures, while habitat suitability models predict severe declines under high-emission scenarios. Advances in CWCS ecology, ~~including nutrient cycling and resilience mechanisms,~~ improve our understanding of these fragile ecosystem, but long-term monitoring and policy integration remain limited. Expanding protection and global research efforts are urgent priorities (S4.C5E).

Estuaries and deltas face increasing pressure, changing the dynamics of sediments and the stability of ecosystems. Since WOA II, land-use changes, and dam construction have drastically changed sediment fluxes, leading to coastal retreat and subsidence in many areas (S4.C5F).

Seagrass meadows are essential for carbon sequestration, habitat biodiversity and coastal protection. They are declining worldwide, with an ~~estimated annual rates of 7% in certain regions and an~~ overall decline of around 29% since the late 19th century. Since WOA II, marine heatwaves, storms, and sea-level rise have intensified these declines, especially in East and Southeast Asia, ~~China,~~ and certain regions of the North Atlantic. A large area (~~92,000~~ covering between 66,000 and 92,000 km²) of seagrass beds were discovered in the Bahamas ~~(Gallagher and others 2022)~~. Major gaps remain, including outdated global, inadequate mapping in deep or turbid waters, insufficient comprehension of climate resilience and carbon sequestration rates, and an absence of conservation policies (S4.C5G).

Mangroves offer important ecosystem services such as coastal protection, biodiversity and carbon sequestration, with an estimated economic value of $65 billion annually. ~~Since WOA II, a~~Annual mangrove loss ~~has slowed to 102.4 km² (2010-2020)~~ A net mangrove loss has declined to 102.4 km2 between 2010-2020 compared to previous decade, primarily due to conservation efforts. However, losses persist due to aquaculture, urbanization and sea-level rise. Notable restoration projects include China's goal to restore 18800 ha by 2025, Indonesia's goal to restore 600,000 ha by 2024 and Iran's initiative to plant~~ing of 10 million 1,000 ha~~ of mangrove ~~seedlings~~forests. ~~A global campaign launched in 2022 (supported by 50 governments) aims to protect 15 million hectares of mangroves worldwide~~ (S4.C5H).

Coastal development, pollution, sea level rise, and invasive species are causing salt marshes to be in global decline. Since WOA II, losses have continued ~~at an estimated rate of 0.28% yearly;~~steadily, with some areas ~~have seen~~experiencing mangrove encroachment driven ~~s~~on by climate change. While oil and chemical pollutants have dropped, plastic accumulation now causes great worry (S4.C5I, S4.C6 Sub 5)~~Poll)~~.

Continental slopes and submarine canyons are increasingly affected by direct anthropogenic impacts, and by climate change. Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, placement of seafloor infrastructures, noise generation, and tourism appear as the most impacting human activities. Despite substantial advances in slope and canyon knowledge, conservation, and management, many of the gaps identified in WOA II remain. Most continental slope and submarine canyon habitats remain unexplored, and long-term data is limited, making it difficult to assess changes over the past 5-10 years (S4.C5J).

Significant changes have taken place in high-latitude sea ice since WOA II. Arctic Sea ice is still declining, with an ice-free Arctic September probable within the forthcoming decades. The Antarctic Sea ice has transitioned from a gradual increase (1979-2015) to a rapid decline after 2016, possibly indicating a regime shift. ~~Since the 1990s, loss of continental ice from the Greenland and Antarctic ice sheets and shelfs has quickened; this contributed 21.0 mm to global sea-level rise~~ Loss of continental ice has accelerated from Greenland since the early 1990's and from Antarctic ice sheets since the late 1990s, contributing 21.0 mm to global sea-level rise for~~rom~~ 1992-2020. ~~.~~ Important gaps ~~still exist about~~remain in several areas including the recent sharp declines in Antarctic Sea ice, ice thickness~~,~~ ~~and~~ snow cover quantification~~,~~ ~~subglacial processes regulating ice-sheet discharge,~~ and future ice loss and sea-level rise projections enhancement (S4.C5K).

Seamounts and pinnacles are submerged mountains that support distinctive deep-sea biodiversity, encompassing corals, sponges, and economically valuable fish species. Deep-sea fisheries are increasingly exploiting these ecosystems, resulting in habitat degradation. Since WOA II, conservation initiatives have intensified, resulting in enhanced protection of seamounts via marine protected areas and heightened recognition of their ecological significance. Nonetheless, enforcement and sustainable fisheries management continue to pose significant challenges (S4.C5L).

Abyssal plains, extensive deep-sea areas, are among most understudied marine habitats. These regions host unique species adapted to extreme conditions and contribute to global carbon cycling. An increasing potential threat from deep-sea mining for rare minerals raise concerns about the resulting potential for habitat destruction and biodiversity loss. Following WOA II, research on these ecosystems has increased as has development of a deep-sea mining code (S4.C5M).

The pelagic domain plays a crucial role in global climate regulation, carbon cycling, and biodiversity. Since WOA II, advancements in observational technologies~~,~~and environmental DNA (eDNA) techniques have enabl~~ed~~inged extensive data collection and supported multidisciplinary studies ~~that enhance biodiversity understanding across ecosystems~~. ~~The Coupled Model Intercomparison Project (MIP6) highlights more frequent extreme events~~ The latest Coupled Model Intercomparison Project (CMIP6) Earth System Models have projected greater warming, acidification, deoxygenation, and nitrate reductions in the ocean, while new ecological insights, such as trophic amplification, show declining biomass in higher trophic levels. Fisheries data indicate mixed trends, with growing interest in mesopelagic fisheries and persistent threats from overfishing and pollution. Key knowledge gaps include the role of species movements and ecological interactions among organisms across trophic levels, the impacts of extreme events, ~~deep-sea mining risks,~~ quantitative estimates of fish and plankton biomass, and digitizing and mobilizing existing data (S4.C5N).

Recent advances in deep-sea research highlight significant progress in hadal trench exploration, facilitated by new technologies, while progress on exploration of ridge systems remains limited. Since WOA II, significant findings on mid-ocean ridges have highlighted key areas of biodiversity and the impacts of human activities. The Mid-Atlantic Ridge ~~has shown~~ exhibits high biodiversity, supporting ~~diverse~~ a wide variety of demersal fish and benthic invertebrates. In the Arctic Mid-Ocean Ridge (AMOR) faces notable~~,~~ impacts from fishing, mineral extraction, and bioprospecting ~~are notable, though further research is needed on soft sedimentary slopes and other regional features.~~ Habitat suitability modelling (HSM) is increasingly used to predict the distribution of faunal communities for management of data-

poor areas. Despite ongoing progress, several gaps ~~remain~~pesists including deep-sea sampling ~~the deep-sea~~, the management of ridges, plateaus and trenches ~~in areas~~ located beyond national jurisdiction~~, capacity development and knowledge transfer~~ (S4.C5O).

Hydrothermal vents and cold seeps host high microbial and animal biomass supported by chemosynthesis and contribute to broader productivity and fisheries in surrounding systems. Technological advances have enabled discovery of thousands of sites in the past, as well as development of deep oil, gas and gas hydrate activities (seeps), and new mining exploration contracts (vents) issued in the Atlantic and Indian oceans ~~and to develop deep oil, gas and gas hydrate activities (cold seeps), and new mining exploration contracts (vents) issued in the Atlantic and Indian o~~Oceans. Additional pressures include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. Conservation actions to date include scientific and industry codes of conduct, spatial protection (VMEs(Vulnerable Marine Ecosystems), MPAs (Marine Protected Areas)), EBSAs (Ecologically or Biologically Significant Areas) and IUCN (International Union for the Conservation of Nature) red list designati~~te~~ons. Key gaps include understanding symbioses and other mutualistic interactions among species, genetic resource potential at vents and cold seeps, vent-seep-organic fall connectivity and the role of inactive and ecotone/transition vent and cold seep (S4.C5P).

The Sargasso Sea supports a unique surface ecosystem based upon floating aggregations of two species of Sargassum (*S. natans* and *S. fluitans*). The Sargasso Sea is an iconic high seas ecosystem internationally recognized as a fundamentally important part of the global ocean. Since WOA II, significant environmental changes have been observed in the Sargasso Sea, driven by climate change, oceanographic shifts, and human activities. Fishing effort remains low in the Sargasso Sea, but research shows most fishing activity requires heavy subsidies to reach the area. Ship traffic has increased on the Sargasso Sea over time and *de facto* shipping routes have been established by shipping companies. However, significant knowledge gaps remain, concerning bycatch, illegal, unreported, and unregulated (IUU) fishing, the movements of highly migratory species, plastic pollution, and the impacts of deep-sea mining~~Gaps in knowledge for the area include bycatch, IUU (Illegal, Unreported and Unregulated fishing), movements of highly migratory species, plastics, impacts from deep sea mining, and deep-sea ecology~~ (S4.C5Q).

Fjords are ecologically carbon organic-rich regions. Global warming is already affecting the northern and southern hemisphere fjords, and freshwater fluxes are likely to increase/decrease. The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors/processes in fjords habitats. A critical knowledge gap exists for fjords habitats, as only a small percentage of the world's fjords have been studied. In addition, little is known about the resilience of ~~F~~fjord ~~S~~systems to changes in hydrologic~~)~~ and oceanography conditions (S4.C5R).

Marine food systems

Food systems must ensure global food security and nutrition for a population expected to reach nearly 10 billion by 2050. The ocean covers more than 70~~4~~% of the earth but provides only 4-8% of human food ~~(Costa-Pierce et al.,~~and others ~~2022)~~. In addition, food systems provide livelihoods for those along the food supply chain. Food systems are not only highly dependent on the environment but also exert significant pressure on it. Sustainable wild fish and mariculture production is the foundation for sustainable seafood trade.

Marine resources are unevenly distributed around the world, and human population centers are often geographically distant from areas of high abundance. The uneven distribution of marine resources has driven trade from local to global scales for millennia, but the proportion of marine production that is exported has increased in recent decades.

Seafood trade (S5A.C1f) can have positive or negative impacts on local environments, economies, and communities, and the impacts depend on the institutional and governance

context. Direct employment in fishing processing and related value chain activities is close to half a billion people. Climate change is also reshaping the global distribution of seafood. Although landings of wild marine fish levelled off in the mid-1990s, total aquatic food exports nearly doubled between 1996 and 2020, with aquaculture accounting for most of the increase. During this period, interregional trade remained dominant for many regions, but Asia became an increasingly important destination. Accordingly, there have been shifts in the top importers and exporters of marine products. Trade regulations, certifications and traceability tools are emerging to support sustainable seafood trade, but unknowns remain regarding aspects of their impact and effectiveness.

Due to the high perishability of fish and fishery products, and their importance in food, nutrition security and global trade, effective processing techniques are essential to extend shelf life, increase revenues, and enhance nutritional value (S5A.C1e). In 2022, of the 165 million tons of fish destined for human consumption, about 43 percent was live, fresh or chilled. This was followed by frozen (35 percent), prepared and preserved (12 percent) and cured (10 percent). Moreover, freezing is the main method of preserving seafood, accounting for 62 percent of the 93 million tonnes of processed aquatic animal production for human consumption. This represents about 89% for direct human consumption, with the remaining 11% for non-food purposes such as fishmeal for aquaculture and biofuel.

Since WOA II, significant progress was made in prioritizing seafood and aquatic food systems within the UN Decade of Science for Sustainable Development and the UN SDGs. Technological advances in seafood processing have great potential to promote sustainable growth and food security and to contribute to the conservation of marine ecosystems. As global demand for seafood increases, integrated policy frameworks and value chain improvements must be aligned to foster a more inclusive and resilient industry. Advanced processing techniques, particularly in the areas of traceability and rules of origin, will play a key role in ensuring compliance and meeting the diverse needs of stakeholders. By addressing some of the social and economic issues in coastal communities, the seafood processing industry can play a central role in promoting gender inclusion, fair wages, and decent working conditions for all.

Due to uncertainties and lack of global disaggregated data on small, medium and large-scale aquaculture, it is difficult to segregate the contributions and impacts of each sub-sector (S5A.C1c, S5A.C1d). In WOA III, medium and large-scale aquaculture refers to commercial orientated production for domestic or export markets, conducted by companies ranging from medium-scale enterprises through to large-scale multi-national companies. Between 2018 and 2022, marine aquaculture production increased from 55.7 million tonnes to 60.2 million tonnes, and the overall value increased from $76 billion USD to $89.2 billion USD.

Over the last two decades, aquaculture production increased at a rapid pace, and the sector has become more integrated into the global food system. However, there are still bottlenecks and challenges that need to be addressed if the sector is to significantly increase production and further contribute to sustainability goals. There have been many improvements in farming methods in medium and large-scale aquaculture as well as major developments throughout aquaculture value chains, with aquaculture products now amongst the most globalised food items. Digitalisation and emerging technologies (e.g. block chain) are playing an increasingly important role in medium and large-scale aquaculture production. Increased attention has also been paid to the farming of low-trophic marine species, including large-scale molluscs and algae farming. However, issues of social acceptability remain, highlighting the need for more meaningful engagement with local communities in the planning and management of aquaculture in the future.

Over the past decade, significant efforts have been made to reduce the dependence on antibiotics in aquaculture, particularly due to the potential for antimicrobial resistance (AMR) and its impact on human health. For feed aquaculture (e.g., fish and shrimp), concerns remain about the use of fishmeal and fish oil, overexploitation of wild stocks, and feed-food competition.

Climate change also poses challenges for medium and large-scale aquaculture production and the supply chain. Climate-related events affecting marine aquaculture include marine heat waves, harmful algal blooms, hypoxia/deoxygenation,- storms, and typhoons. There is a need to focus more efforts on adapting aquaculture production to and mitigating climate change.

The assessment of small-scale aquaculture (SSA) in WOA III (S5A1.d) focused on SSA practiced in two environments: (i) nearshore marine aquaculture (NSMA) and (ii) coastal marine aquaculture (CMA). The latter is typically practiced in constructed ponds onshore or in intertidal zones. SSA plays a significant role in global food security, livelihoods, nutrition, and health.

On a global scale, most of the world's small-scale production of seaweed, sea cucumbers and sea molluscs are from NSMA, while crustacean production, primarily takes place in onshore coastal brackish water ponds and tanks. In this case, CMA is dominated by brackish water shrimp and a few species of fish, crayfish and crabs. Some species and well-managed practices in SSA have little or no negative impacts on the ocean health (e.g. seaweeds and molluscs).

However, given the potential negative impacts of aggregation of small-scale aquaculture operations, spatial planning and consideration of carrying capacity limits should be promoted at national and regional levels. Over the past several decades, NSMA and CMA have experienced major disease outbreaks. Best management practices, including biosecurity measures, should be implemented to protect the activity and make SSA more sustainable with the least negative impact on the health of the oceans. NSMA and CMA cannot be sustainable without addressing the impacts of climate change and of stressors from land-based sources. In addition, the communities involved in NSMA and CMA are relatively poor and have limited resources, which limits their resilience to climate change in many countries. There appears to be a serious lack of specific national legislation to regulate the sustainability of small-scale inshore and coastal aquaculture.

Fisheries are categorized based on the scale and scope of their operations, which significantly influence their environmental impact, economic contribution, and social dynamics. Small-scale fisheries (SSF) are of high social, economic, cultural and environmental importance and play a critical role in fostering food and nutrition security for millions of people. Small-scale and subsistence fisheries contribute significantly to national and global economies and are of great social and cultural importance. However, SSF are under increasing pressure from declining fish stocks and competition from industrial fisheries.

The cumulative effects of a wide range of environmental stressors and climate drivers pose significant threats to the viability and resilience of SSF and subsistence fisheries worldwide. The viability of SSF is increasingly threatened in many regions. Creating sustainable pathways for small-scale and subsistence fisheries must involve a commitment to principles

of equity and justice, human rights and security, and emphasize the knowledge and capacity of small-scale fishers.

Large-scale fisheries (LSF) and medium-scale fisheries (MSF) differ in scale and scope of operations, each with its own set of practices, impacts, and sustainability measures. LSF and MSF differ in their operational approaches, with each playing a unique role in the global fishing industry (S5A.C1a). While MSF plays a vital role in supporting local economies and livelihoods, LSF operations often have broader environmental and economic impacts that demand careful management and regulation. WOA III report recognizes certain limitations, such as the complexities of defining these two fisheries sectors across diverse contexts and the challenges of balancing economic growth with environmental and social sustainability. In their own ways, LSF and MSF contribute to complex challenges in the marine environment, underscoring the need for tailored, sustainable management approaches. WOA III emphasizes the importance of ecosystem-based management, transparency, traceability, and stakeholder collaboration to mitigate the negative impacts of MSF and LSF.

Overfishing is among the most pressing concerns in the sustainable use of the ocean resources and according to the Food and Agriculture Organization (FAO)., The fraction of global fishery stocks within biologically sustainable levels decreased to 62.3 percent in 2021~~approximately 33% of global fish stocks are overexploited~~, down from 64.6% in 2019, while many others are reaching their full exploitation or are in decline. It is estimated that between 8 and 14 million metric tonnes of unreported catches, globally traded illicitly yearly, representing gross revenues of US$9 to US$17 billion per year associated with these catches. In addition to the damage to fish populations and ecosystems caused by IUU, the estimated annual economic impact loss due to the diversion of fish from the legitimate trade system is estimated to be between US$26 to US$50 billion. Effective governance structures are essential to ensure that the LSF and MSF sectors contribute positively to sustainable development.

Marine recreational fishing (MRF) is defined as fishing of marine animals (mainly fish) that do not constitute the individual's primary resource to meet basic nutritional needs and are not generally sold or otherwise traded on export, domestic or black markets (S5A.C2). It plays an important role in many coastal ecosystems worldwide, particularly in developed countries. MRF contributes billions of dollars annually, especially in developed countries, supporting local communities through job creation and encouraging marine stewardship. It is estimated that 121 million people worldwide participate in MRF. While the total estimated global marine recreational harvest is about 1% of total commercial landings, recreational removals are generally concentrated in a narrow band of coastal areas, and impacts are most intense in localized areas.

The lack of formal recognition of the MRF sector is a fundamental problem in fisheries management, contributing to overfishing, conflicts with commercial and subsistence fishers, and reduced societal benefits from recreational fisheries. Despite its importance, only about two-thirds of countries mention recreational fisheries in primary fisheries legislation. Recreational fisheries could put pressure on stocks already being depleted by commercial fisheries. Addressing data gaps, stakeholder collaboration, socio-economic integration, and compliance through education and normative approaches are essential for effective management and societal benefits of MRF.

Sustainable resource use, goals and pathways

The sustainable use of natural resources is a key to global environmental, economic, and social stability and the ocean plays an essential role in the process through regulating the climate, maintaining biodiversity and providing resources vital for humans, such as food,

minerals and energy (e.g.~~,~~ fisheries, oil, gas, and offshore wind). The ocean is under stress due to overexploitation, pollution, and the effects of climate change~~ (IPCC, 2023)~~. Sustainable resource use refers to managing ocean resources in a manner that satisfies present needs without compromising the ability of future generations to meet their own needs~~ (Duarte, 2014, Wang and otherset al., 2024)~~.

However, we still live in the world of increasing competition for all resources~~, both living and non-living ones~~. I~~i~~n the case of biological resources for example~~ living resources~~, the shift is clearly from capture fisheries to coastal and offshore aquaculture (see relevant chapters and marine food systems). The demand for ~~non-living resources~~minerals, energy, and space-based resources has several dimensions as described in more detail below.

The observed trends in ocean renewable and non-renewable technology developments include offshore wind farms, tidal, and wave energy systems (S5A.C3a, S5A.C3b). While renewable energy developments center on efficiency and cost reduction, non-renewable energy exploration efforts keep enhancing, despite concerns over environmental adverse impact, however, more sustainable approaches are visible.

Emerging trends such as increased global interest in offshore renewable energy, the potential use of geoengineering solutions, and growing awareness of the importance of ocean conservation present both opportunities and challenges ~~(https://www.unepfi.org/publications/harmful-marine-extractives-offshore-oil-gas/)~~. As the world trends should aim at shifting towards a more sustainable future, it is essential to balance the benefits of ocean resource use with the necessity to protect marine ecosystems and secure social equity~~ (IPCC, 2023)~~.

The development of offshore wind energy has become one of the main solutions in the field of renewable energy sector, since offshore wind farms provide clean energy while minimizing the environmental impact in comparison to fossil fuels. On the contrary, extraction of offshore oil and gas resources poses threats to marine environments, including habitat destruction and potential oil spills~~ (https://www.unepfi.org/publications/harmful-marine-extractives-offshore-oil-gas/)~~.

Sustainable ocean resource management also involves other types of pollution, particularly plastic waste, which has become a significant issue for marine ecosystems. The challenge lies in minimizing pollution while balancing economic growth, which usually causes environmental degradation.

The role of ocean geoengineering solutions, i.e. deliberate modification of the planet's environment, remains a contentious issue, with limited data and research on the impacts of this technology on the oceans and broader environment (S5A.C10). H~~h~~owever, it is among p~~roposedotential~~ solutions to the global climate crisis. Marine g~~G~~eoengineering techniques involve the altering or utilization ~~manipulation~~ of ocean systems as a proposed tool for climate change mitigation. Examples include but are not limited to~~, through e.g.~~ ocean fertilization (aiming at increasing carbon absorption by stimulating phytoplankton growth) or ocean alkalinity enhancement (neutralization of ocean acidity).

While geoengineering is still an active area of research, some studies warn of its potential to ~~These solutions may~~ disrupt marine ecosystems, harm biodiversity, and pose unknown consequences on global weather patterns). Furthermore, there are ethical and governance challenges related to the geoengineering solutions, since they may affect vulnerable communities, including coastal populations and therefore, there is a strong need for

recognition of the ecological, social and economic impacts of such technologies and the development of international frameworks to govern them ~~(https://www.ciel.org/govern-geoengineering/)~~.

Accounting for ~~close to~~ 8~~0~~% of all world trade, shipping plays a vital role in global trade, and it is a basis of today's commerce, enabling the movement of goods and connecting businesses with customers worldwide (S5A.C6) ~~(https://sin.clarksons.net/)~~. However, shipping produced 2.3% of global TTW emissions in 2024 ~~(https://sin.clarksons.net/)~~ ~~these activities contribute about 3% of total CO_2 emissions,~~ and the estimates show that this number can rise by a half by 2050. In times of climate and environmental unprecedented changes green and sustainable shipping are becoming of critical importance. Examples of such approaches include cleaner fuels, technologies to reduce carbon emissions, and optimizing shipping routes to reduce environmental impact.

Roughly 90% of commercial vessels use bunker fuel, a highly polluting energy source ~~((https://sin.clarksons.net/)~~. This situation limits efforts to significantly cut emissions in the near future and a significant number of newly planned ships, more than 70%, will continue to be fuelled by traditional fuels ~~((https://sin.clarksons.net/).~~

Therefore, environmental regulations, driven by concerns about pollution and climate change are becoming increasingly rigorous. Ocean water desalination and salt production show increasing reliance on renewable energy, applied to support desalination plants. Technologies based on reverse osmosis and electrodialysis are improving efficiency. Globally, salt production methods are fast evolving toward sustainable practices.

Like in many other ocean development activities, ocean genetic resources and biotechnology continuous to show rapid growth since WOA II, with advances in marine genomics, which lead to discoveries in sustainable bioproducts, pharmaceuticals, and biofuels (S5A.C5). Developments in novel search for compounds and enzymes are observed globally, however, on the positive side, innovations in marine biotechnology tend to conform to sustainability practices, hence help to reduce ecological impact of ocean exploitation.

Global sea level rise and increasing strong storm frequency pose a significant threat to coasts across the world, requiring dedicated mitigation plans and actions. Progressing flooding and erosion have adverse impact on planned developments, making it difficult to foster sustainable communities. Additionally, the pressure on ecosystems, such as e.g. mangroves, coral reefs, and wetlands, is very strong and leads to disruption of these habitats, and biodiversity loss. Regulatory solutions, along with conflicts between economic development and environmental conservation, lead to tensions between stakeholders. The high cost of ongoing and upgrading maintenance of coastal infrastructures, combined with unpredictable climate change consequences, makes coastal areas most vulnerable areas on Earth.

The observed rapid growth of coastal tourism, despite many positive aspects for humans, can be connected with the threat of habitat destruction, pollution, and overexploitation of marine resources, such as coral reefs and fish stocks (S5A.C4). Unsustainable tourism, including cruise ships and recreational boating, contribute to marine pollution, including plastic waste, noise and hazard of oil spills, which harm marine life. Overcrowding of popular destinations leads to the degradation of local ecosystems and adversely affects the well-being of coastal communities ~~(Papathanassis, 2023)~~. The emerging sustainable tourism practices, such as responsible waste management, eco-friendly infrastructures, and community-based conservation, are crucial to mitigate these impacts and secure sustainability.

Socio-economic inequalities are reported in many coastal regions, where ocean dependent communities, particularly women and Indigenous Ppeoples, often face limited access to markets, capital, and technology (S5B.C5). Therefore, policies planned for creating an inclusive ocean economy must emphasize social equity, access to resources, and the participation of marginalized groups in decision-making processes (Li and otherset al., 2024).

Ocean industries such as fishing, tourism, and renewable energy contribute significantly to economic growth, but they also create challenges in terms of wealth distribution and access to resources. Therefore, inclusive economy concept is crucial for securing benefits of ocean resources and their fair distribution across society, including marginalized groups (https://www.unwomen.org).

The UN Sustainable Development Goals put strong focus on the importance of gender equality in every aspect of sustainable development, including the governance of ocean resources (https://www.unwomen.org). Integrating gender perspectives into ocean policies secures that the needs, perspectives, and rights of women are recognized, ensuring inclusive and effective management of marine resources (S5B.C6) (Global Sustainable Development Report 2023).

Gender-oriented policies and programs that provide women with equal access to resources, decision-making power, and economic opportunities are crucial for promoting both gender equality and the sustainability of ocean resources ((https://openknowledge.fao.org; Crosman and otherset al., 2022).

There is progress towards ocean related SDGs (Global Sustainable Development Report 2023), but the targets that were set to be achieved 2025 have not been achieved and those with a target in 2030 are unlikely to be achieved. Some of the major reasons for this involves: increasing economic pressures; lack of governance, unwillingness to use nature-based solutions, and the changing geopolitical landscape.

Mangrove forests, salt-marshes and seagrass beds are increasingly recognized for their role as blue carbon ecosystemssinks, with initiatives aiming to (re-)establish and protect these habitats for their ecological and economic value.- Seagrasses contribute to several Sustainable Development Goals (SDGs), including carbon sequestration and disaster resilience (SDG 13), protection of coastal communities (SDG 11), and food and economic security (SDG 10), while promoting sustainable use (SDG 12), marine conservation (SDG 14), and partnerships (SDG 17) (United Nations, 2015). Their value was highlighted in UNEP's 2020 report Out of the Blue: The Value of Seagrasses to the Environment and People (UNEP, 2020). Seagrass conservation efforts, including the 2030 Seagrass Breakthrough, align with global climate commitments (https://unfccc.int/decisions, 2024UNFCCC COP28, 2023) and all ten targets listed within SDG 14. However, unintended consequences of development initiatives remain a concern.

There are ongoing Blue Carbon projects in different regions of the world. Mangroves are of particular concern with regard to carbon sequestration and for achieving SDG targets. Some examples include: restoration and conservation action such as planting of 1,000,000 mangrove seedlings encompassing 10,,000 hectares of mangrove forest habitat in the Persian Gulf;, China's plan to improve coastal ecosystem carbon sink capacity and restore 18,800 ha of mangrove by 2025; while the National Mangrove Rehabilitation Program of

Indonesia aimeds to restore 600,000 ha of degraded mangroves by 2024 and contribute to SDG targets.

Marine spatial planning, governance and management processes

Introduction

Marine spatial planning, governance, and other management processes are crucial for the sustainable use and protection of the global ocean. These processes aim to balance ecological, economic, and social interests while addressing the growing pressures on marine ecosystems (S3).

Ocean governance Marine planning, governance and management processes

Introduction

Ocean governance, Mmarine spatial planning, governance, and other management processes are crucial for the conservation and sustainable use and protection of the global ocean. These processes aim to balance ecological, economic, and social interests while addressing the growing pressures on marine ecosystems.

This is the first time that a dedicated ocean governance section is included in a WOA report, as previous WOA reports addressed ocean governance within specific chapters.

Marine spatial planning helps allocate and manage ocean resources more effectively, reducing conflicts between different users and ensuring sustainable exploitation. By providing a framework for sustainable ocean economy initiatives, marine spatial planning supports responsible economic growth in coastal and ocean areas. Marine spatial planning aligns with global initiatives like the UN Sustainable Development Goals (SDGs), supporting the achievement of targets related to ocean health and sustainable use.

Ocean governance frameworks facilitate collaboration between States on shared marine resources and transboundary issues. By providing a structured approach to ocean management, these governance frameworks are essential for addressing the complex challenges facing our global ocean and ensuring its long-term health and productivity.

Other ocean management processes (e.g. environmental protection) can promote ecosystem-based approaches to conserve marine biodiversity and protect vulnerable habitats.

This is the first comprehensive ocean governance section in a WOA report, as previous WOA reports addressed ocean governance within specific chapters.

Marine spatial planning

Marine spatial planning processes are advancing internationally, with various degrees of maturity. Marine spatial planning may interact with existing terrestrial planning, especially in physically overlapped areas. Examples of recent marine spatial planning and protected areas are described in Section 3.

Ocean Governance

Ocean governance is underpinned by a highly complex and dynamic interplay of States, multilevel intergovernmental institutions and regimes where concepts, principles and means of implementation are developed and used.

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) sets out the key legal framework within which all activities in the ocean and seas must be carried out. Other global treaties have been progressively agreed in the last 70 years, including two in the last

five years that are yet to come into force (BBNJ Agreement, 2023; Fisheries Subsidies Agreement, 2022). They are devoted to different aspects of the marine environment, including biodiversity protection, pollution from sectoral activities and other threats to the marine environment.

In addition, a large number of non-binding instruments, customary law and associated intergovernmental policy processes focus on the marine environment. These processes can facilitate cooperation, action and coordination between States (e.g. UN mechanisms such as UN-OCEANS) or the development of a common scientific understanding (e.g. IPCC, IPBES, WOA and UN Decade of Ocean Science). International courts and tribunals within specific proceedings provide interpretation on these legal instruments. Many of the governance instruments that are developed globally further develop UNCLOS concepts (e.g. ecosystem approach, precautionary principle/approach, best available science).

Yet, the fragmentation of ocean governance at global and regional levels has continued to draw significant attention over the past five years. Most of the new binding and non-binding instruments in recent years were developed to strengthen the existing governance framework and address gaps in ocean governance, including mechanisms for cross-sectoral interplay (e.g. Convention on Biological Diversity, Kunming-Montreal Global Biodiversity Framework (CBD GBF), 2022; Fisheries Subsidies Agreement, 2022; BBNJ Agreement, 2023; International Maritime Organisation (IMO) Greenhouse Gas (GHG) Emissions Strategy, 2023)

Other significant elements within the global ocean governance are the concepts, principles and means of implementation that have developed over time in different institutions of the ocean governance regime and have progressively penetrated such regime. For example, governance concepts emerging from national experiences and non-state actors' proposals and practices, such as the sustainable blue economy and marine spatial planning, have gained increased significance in State-led governance developments.

The ocean governance overview provided in section 3 of the present WOA report highlights the central role of both natural and social sciences, including the knowledge systems of Indigenous Peoples and local communities, and the importance of their integration in all stages of the policy cycle at all geographic scales.

~~The past five years have seen increasing references to human dimensions, including human rights and use of social sciences. Some governance concepts developed through non-state actors (e.g. NGOs) have become a part of State-centred governance development, such as sustainable inclusive ocean economies and marine spatial planning (e.g. Ocean Economy).~~

~~Since WOA II, there has been a focus on marine plastic pollution, biodiversity, environmental assessment status and monitoring, supported by the development of indicators.~~

~~**Global governance**~~

~~The 1982 United Nations Convention on the Law of the Sea (UNCLOS) establishes thea key legal framework for the global ocean governance. sets out the key legal framework within which all activities in the oceans and seas must be carried out. Customary law, oOther establishes a key legal framework for the global ocean governance. Other global treaties, and a large number of non-binding instruments, customary law and associated intergovernmental policy processes focus on the marine environment (see Section 3 – Global Overview of Ocean Governance). These processes can facilitate cooperation, action and coordination between States (e.g. UN mechanisms such as UN-OCEANS) or the development of a common scientific understanding (e.g. IPCC, IPBES, WOA and UN Decade of Ocean Science). International courts and tribunals within specific proceedings provide guidance interpretation on these legal instruments. Many of the governance instruments that are developed globally further develop UNCLOS concepts (e.g. ecosystem approach, precautionary principle/approach, best available science).~~

Most recently, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) was adopted in June 2023. It is the first international legally binding instrument for the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction. It includes modern environmental standards to be applied in areas beyond national jurisdiction (ABNJ), such as: environmental impact assessments (including cumulative impacts), and area-based management tools, including marine protected areas. It also sets provisions for the access to marine genetic resources and the sharing of its benefits and the strengthening of capacities and marine technology transfer to support further protection measures. The entry into force and robust implementation of the BBNJ Agreement, as well as effective implementation of ocean governance at the regional and national levels (see Section 3.3) are crucial for meeting SDG 14.

Other multilateral governance agreements to protect biodiversity are further addressed in Section 3: A global overview of ocean governance.

A key issue that has been central to dynamic policy developments in the last five years is the need to overcome institutional and topic fragmentation in ocean governance. Most of the new binding and non-binding instruments in recent years were developed to strengthen the existing governance framework and address gaps in ocean governance (e.g. CBDConvention on Biological Diversity, GBFKunming-Montreal Global Biodiversity Framework, (CBD GBF), 2022; Fisheries Subsidies Agreement, 2022; BBNJ Agreement, 2023; International Maritime Organisation (IMO) Greenhouse Gas (GHG) Emissions Strategy, 2023). These can be complex processes and many instruments are in ongoing negotiation and development (e.g. plastic treaty, exploitation regulations for seabed mining in ABNJ and IMO regulations to address GHG emissions from shipping). New governance is developing, in conjunction with international courts/tribunals, for legal order and human rights issues.

Regional governance

There are 20 sea region areas with various mechanisms to coordinate States' protection of the marine environment. Six of these areas are directly administered by the United Nations Environment Programme (UNEP) and consist of regional, intergovernmental bodies and institutions which administer the marine environment, and activities and research in those areas. The arrangements among the sea regions, States, regional bodies, institutions and scope are highly variable, but with pollution, fisheries and biodiversity historically key target areas.

Cross-cutting issues in governance

Globally there is a rapid increase in the number of regional or other entities involved with the development of governance initiatives, leading to fragmentation and gaps in the marine governance (e.g. marine plastics, climate change and ocean acidification). Political instruments such as SDG 14, the 2022 Kunming-Montreal Global Biodiversity Framework, provide targets and tools to drive and assess progress in overcoming adverse effects from fragmentation in the context of the protection of the marine environment. Procedural interactions between sub-regimes and systemic integration approaches provide ways through this (e.g. Memorandums of Understanding (MOUs) among and between global and regional levels). Parallel narratives are also supporting coordinated governance, for example sustainable and inclusive ocean pathways (i.e. blue economy), ocean health, blue justice, maritime and food security.

Development of governance

Governance is now commonly developed and modified using a multi-year integrated management cycle approach – key issues are identified in the marine environment, consulting and collaborating takes place to generate a methodology to address the issue, then putting in place monitoring, compliance and enforcement. These management cycles repetitively examine governance to ensure that fundamental principles remain as part of the

governance, principles initially framed in UNCLOS but which have been enhanced or clarified through subsequent instruments (e.g. Rio Declaration 1992, the 1995 UN Fish Stocks Agreement, FAO Ccode of Cconduct for Responsible Ffisheries 1995, the BBNJ Agreement). Some of these principles are environmental focussed and include, for example: ecosystem approaches, precautionary principle/principlesapproach, due diligence, best available science, environmental impact assessments and cumulative impacts. Area based management tools, including and marine protected areas are a more recent governance conceptss which are increasingly adopted.

The principle of equity has evolved separately, and focuses on capacity building and technology transfer and fair and equitable sharing of benefit, which recently is increasingly applied to Indigenous Ppeoples and local and traditional communities.

Finally, the governance management cycles require appropriate and meaningful reporting, monitoring and compliance to be effective. Monitoring and reporting assist with the development of baselines to understand change and to support compensation, restoration and rehabilitation. Compliance is equally important but challenging to implement – though there have been successes (e.g. World Customs Organisation to Facilitate Global Trade).

Recent developments in governance

Over the last five years, substantive areas of concern in the work of relevant intergovernmental institutions have extended beyond traditional marine environmental pressures (e.g. pollution and fisheries), to more recent priorities (e.g. climate change mitigation and adaptation, marine plastics, monitoring and ocean observation) and non-traditional areas such as maritime security, migration by sea, human-rights based approach and food security.

Overarching objectives such as a sustainable and inclusive ocean economies (e.g. blue economy), blue health, and blue justice are playing central roles in ocean governance developments. Remote monitoring technologies are assisting with more rapid governance and management.

The past five years have seen increasing references to human dimensions, including human rights and use of social sciences.

New international agreements and frameworks have been developed or are in negotiation (e.g. the Kunming-Montreal Global Biodiversity Framework, WTO Agreement on Fisheries Subsidies, the international legally binding instrument on plastic pollution, including in the marine environment). Tas well as there have been calls for better data collection and monitoring of marine ecosystems, including improved integration of Indigenous Peoples' knowledge and local perspectives.

Marine spatial planning

Marine spatial planning processes are advancing internationally, with various degrees of maturity. Marine spatial planning is increasingly expected to may interact with existing terrestrial planning, especially in physically overlapped areas. Marine spatial planning, including a diverse array of marine protected areas, are being developed and have been approved across the globe. International stakeholders are working to establish the first "blue corridors" or Large Scale Marine Protected Areas to protect and ensure the long-term health of biodiversity. Marine planning is increasingly expected to interact with existing terrestrial planning, especially in physically overlapped areas. Examples of recent marine spatial planning and protected areas are described in Section 3.

4. Marine observations and ocean knowledge

The collection of new information and retention/application of global ocean knowledge are important parts of managing our ocean. Diverse scientific technologies and methodologies are developing rapidly in marine observation, data collection and modelling, which is greatly

improving our knowledge and scientific understanding of our ocean. Knowledge systems are the practices, values, methodology and culture surrounding the collection of information and how it is used. The majority of WOA III~~#3~~ focusses on ~~traditional~~ classical scientific knowledge, but there is increased acknowledgment of the relevance to global ocean understanding via alternative or complementary Indigenous Peoples', traditional and local knowledges. WOA III~~#3~~ has begun the process of better acknowledging and including these~~is~~ complementary knowledges (S.5b Ch8).

Marine observations, technological developments advancing our scientific understanding of the ocean~~s~~

Technology is developing rapidly in ocean observation and data collection in diverse areas. Drones, autonomous vessels, remote sensing, aerial surveillance, airborne LiDAR (Light Detection and Ranging technology), and satellites are all enhancing real-time data collection on physical/chemical conditions, sea level, ocean circulation, pollution (including noise), biochemistry and biology, as well as improving high resolution sea-floor mapping. Research vessels are increasingly serving as motherships for unmanned, remotely operated or autonomous vessels, including aerial or underwater drones which enables the collection of large amounts of video, image, physical and chemical data.~~information.~~ Deep ocean areas are more readily accessible. Independently operating vehicles, through for example the Argo program, are now operational throughout the world ocean collecting biogeochemical information throughout the water column. Through such programs, scientists are better understanding conditions - including difficult to capture extreme events - across the globe simultaneously. New things are being discovered completely, such as deep-sea biological communities (Western Antarctic Peninsula), and new physicochemical processes, for instance geo-chemically generated oxygen.

Through technological development in remotely operated technologies, coupled with advanced data gathering (e.g. video monitoring), deep-sea submersible technology (e.g. Chinese submersible "Striver"), seabed scanning and analysis (Artificial Intelligence (AI) modelling) techniques, coupled with machine learning and AI, scientists have increased knowledge about remote locations, including those historically more inaccessible areas (e.g. deep ocean, seamounts, fjords). Globally, all major hadal trenches have been surveyed with new technologies revealing a rich diversity of habitats. The understanding of Abyssal taxa have extended into hadal depths and new trench-endemic species and ecological relationships revealed with a rich hadal microbial flora, including viruses, bacteria and fungi that contribute to biochemical processes. We are now aware of over 10,000 submarine canyons and thousands of new seamounts, with more yet to be mapped in underexplored oceanic regions. Recent discoveries of new deep-sea species (e.g., sponges, gastropods, octocorals and corals) include, for example, 111 unique taxa off the Western Antarctic Peninsula.

These remote technologies also enable better monitoring of our environments. They are enabling the development of key metrics (e.g. habitat condition, population trends) for monitoring and decision to support biodiversity treaties (e.g. BBNJ). Satellite imagery, video systems, drones applying aerial photogrammetry and Geographic Information Systems (GIS) are increasingly used for monitoring coastal changes, erosion, sedimentation and coastal health (e.g. Red tide algal bloom monitoring) and marine plant distribution (e.g. mangrove forests), as well as the restoration of these areas (e.g. Mangrove regeneration projects around the globe). Population assessments are improving as a result of remote technologies (e.g. marine mammals, seabirds). These technologies are also assisting with ship monitoring and weather observations.

Data collection, analysis and modelling

New developments in data processing, machine learning and artificial intelligence are being applied in many areas, greatly enhancing data analysis, model production and predictive capacity, as well enhanced integration of data networks. These are greatly improving the availability of spatiotemporal data to be fed into biological, physical and chemical models which are then combined into more cumulative large oceanographic and ecosystem models. These large-scale environmental models are improving our understanding of biological (productivity, communities, food webs) and physical (e.g. integrated coastal and hydrodynamic modelling of estuaries and deltas with catchments) (e.g. Delft3D, MIKE21 and SWAN models) aspects of our ocean. New models are being developed and/or updated for ocean behaviour and ecosystems. (e.g. work by Fisheries & Marine Ecosystem Marine Intercomparison Project (FishMIP)). Ecosystem service models are improving for coastal mangrove areas, including carbon storage potential

Habitat suitability modelling (HSM) is increasingly used to predict the distribution of faunal communities for the management of data-poor areas (e.g. deep-sea corals near New Zealand). Modelling and spatial planning software also aid the design of offshore protected or managed areas (e.g. South Pacific Regional Fisheries Management Organisation (SPRFMO)) vulnerable marine ecosystems). Work is being carried out to develop “digital ocean twins” to assist in modelling of ocean habitats.

Global treaties and non-binding instruments help facilitate new collaborations, shared databases and information sources among regions, which provide information and maps for marine observations and offshore structures (e.g. European Marine Observation and Data Network (EMODnet); Bureau of Ocean Energy Management (BOEM); Mid-Atlantic Ocean Data Portal (MARCO); Open Infrastructure Map, and; European Maritime Affairs). Efforts continue to achieve FAIR (Findable, Accessible, interoperable, reusable) data standards.

Climate change

Scientific knowledge is rapidly expanding on natural and anthropogenic contributions to climate change and the impacts to the world ocean. There is rapid development of monitoring, reporting and verification of CO_2 emissions, including associated modelling which support ~~the IPCC reporting,~~ resource managers and policymakers across the globe. Scientists ~~also~~ have also increased understanding of marine plant role in carbon sequestration. Significant advances are being made via remote techniques to understand ice related processes in polar areas and their influence on global circulation and climate change.

Genetic/molecular technologies

There has been rapid development of genetic technologies (e.g. sequencing methods, eDNA (environmental DNA), isotope analysis) leading to a relatively rapid increase in understanding of biological communities, trophic systems and ecosystems (e.g. range, numbers of species, population size) and of the food web (e.g. seabird and plankton diet) for all marine taxonomic groups. Libraries and taxonomic reference collections of genetic information are developing quickly, now with more information about microbiomes, plants and animals from remote areas (e.g. cold water corals). Functional trait analysis, along with eDNA, is offering new perspectives for ecosystem modelling.

Socio-economic knowledge

Globally, there is an increase in socio-economic and socio-ecological research and improved methodologies to support better outcomes for marine planning and resource use aimed at improving human well-being and equity. Indigenous Peoples', traditional and local knowledges are~~is~~ increasingly used to complement scientific understanding. Research continues in non-market goods and services, such as clean air, biodiversity, and recreational ~~spaces,which~~spaces, which contribute non-trivially to human well-being. The ability to value the environment in terms of economic (e.g. value of environment goods and services such as contingent valuation and travel cost methodologies) as well as developing non-economic valuation methodologies for restoration and preservation of marine environment is increasing.

The understanding of equity is improving steadily and efforts are being made globally to support participatory ocean governance requires that all rights holders and stakeholders are recognized, that all affected actors are included, and that diverse knowledge systems and perspectives are represented in decision-making are an important part of good policy making.

Engineering and marine structures

Marine related engineering technology is rapidly developing in a wide variety of fields – from deep-sea mining/drilling to coastal infrastructure and renewable energy platforms and aquaculture. Drilling, wind turbines, mining and trawling are all being developed further from the coast and in/at greater depths. Recent technological developments are also occurring for controlling sea level rise, with increasing estuarine barriers and hard defences, alongside the nature-based solutions and habitat creation (S5A. C9. New offshore renewable energy technologies are developing rapidly – floating wind turbines, tidal and wave energy generation, as well as more novel approaches such as salinity gradients and ocean thermal energy conversion. Grid integration (and offshore micro-grids) and energy storage is also improving rapidly. AI is being used to optimise predictive modelling for energy production. There is growing understanding of noise, electromagnetic fields and their effects on the environment. Ocean carbon capture and storage technologies are also being developed and trialled, as are hydrogen storage technologies for energy created by renewable sources.

Fish and fisheries

Improvements are being made in tagging, video monitoring, and fish genetics ~~of fishes~~. Advanced technologies, such as remote cameras, satellites, computer vision, and aerial and underwater drones, enable in-situ monitoring of fishing activities, species populations, and habitats. These innovations allow for the assessment of fishing pressure and fish behaviour patterns, which can be integrated into monitoring programs. Genetic sequencing, in-situ sequencing platform, synthetic biology, metagenomics and eDNA/metabarcoding have increased for fishing/fisheries information since the last WOA, with substantial reductions in cost. Ecosystem-b~~B~~ased f~~F~~isheries m~~M~~anagement is being developed, along with improved modelling and understanding of spatial and temporal trends in fish biomass. Fish data are increasing in shared global databases. There is better understanding of fish communication and the potential impacts of noise on fish communities. Fisheries extraction technological improvements are also improving, reducing bycatch.

Gaps

Although developing rapidly, there are still large gaps in our understanding of the ocean. Large tracts of the ocean remain unknown. Currently only 28% of the ocean seabed is mapped in high resolution, ~~with some areas with~~while other areas have very little information at all (e.g. Arctic and Southern oceans)~~high seas areas)~~. Monitoring of deepwater areas (e.g. continental slopes, submarine canyons, abyssal plains, hydrothermal vents, seeps) is still

weak in many areas and limited to exclusive economic zones for countries. Many regions lack capacity (e.g. skills, experts, vessels) for deepwater research and this prevents setting baselines and ongoing monitoring. High resolution coverage is still lacking for remote monitoring coastal vegetation (e.g. mangroves, seagrasses) and there is a lack of funding for monitoring programs of coastal areas (e.g. mangroves) in many parts of the world ocean. Fjord systems remain largely unknown.

Scientists still have a weak understanding of species movements and interactions at different trophic level in pelagic environment, which prevents effective management and conservation. Remote, deep-sea and inaccessible microbial and invertebrate communities (e.g. hydrothermal vents) and marine plants lack documentation, monitoring and genetic information. Major ~~capacity~~ gaps still exist in less developed countries in a variety of research areas (e.g. coral reefs) for restoration and monitoring technologies (e.g. eDNA, 3D photogrammetry).

We still have limited understanding of climate driven changes to the ocean~~s~~ and what will change in the future. Scientists still struggle to understand cumulative impacts of extreme or global events at various spatiotemporal scales, including how they interact with global climate systems (e.g. Pacific Decadal Oscillation, ~~ENSO~~ENSO, Atlantic Multidecadal Oscillation) and anthropogenic effects. There is still very little understanding of the impacts of rapidly changing areas, like the polar areas, and their role as a heat sink and for freshwater input for driving global circulation.

There is a lack of observations and understanding of coastal carbon cycles and sequestration, which make it difficult to understand past, current and predict future carbon sequestration (e.g. in marine plants). There is a gap in the understanding coastal shelf sediments, carbon accumulation/release rates and how anthropogenic activities affect the storage or release of CO_2~~CO2~~. The carbon cycle in coastal wetlands and their CO_2~~CO2~~ storage is not fully understood with regard to greenhouse gas emissions. There is a lack of information about bacterio-plankton and heterotrophic eukaryotes and their roles in decomposition and carbon cycling.

In general, approaches to ocean governance, from local to international, continue to under-represent certain groups (e.g., Indigenous Peoples and small-scale fisheries).

Scientific understanding is still developing regarding the effects of noise, wind farms, offshore farming, seabed mining and nano-plastics on biological communities.

Scientists still struggle to engage with policymakers and to have scientific knowledge/data used for policy development. Continually increasing competition for limited funding is occurring generally across ocean research areas. The availability and exchange of scientific information/data is still hampered by issues related to language, gender, socio-economics and education.

Data gaps

There is still ~~remains~~ a need to generate long-term historical datasets ~~for~~of the open ocean, but especially deep sea and coastal areas for plankton to understand variability and extreme events. There was substantial loss of data during the COVID 19 pandemic, including the generation of gaps in what were long term historical datasets.

Existing models and databases are still lacking for coastal zone understanding and prediction. There is insufficient data for modelling erosion and sedimentation along many regional coastlines, especially in Small Island Developing States, Caribbean and South Atlantic areas. Although the trajectory of sea ice in the Arctic region ishas a trajectory towards considerably reduced cover, pPolar ice models (especially in the Antarctic) still unable to predict future annual changes to ice and the resulting impact to the globe. There remains a disconnect between anthropogenic stressors and spatiotemporal ecosystem responses and a clear need to develop global platforms to map human pressures and natural assets and modelling to predict anthropogenic pressures.

Data sharing is improving, but information tends to remain in silos (e.g. pelagic systems, seagrasses) (e.g. 81% of zooplankton monitoring data are at most only partially accessible). It is difficult to standardise global approaches to data management and data accessibility.

Scientists still struggle to engage with policymakers and to have scientific knowledge used for policy development. Funding for science is decreasing across the globe. The exchange of scientific information is still hampered by issues related to language, gender, socio-economics and education.

Indigenous Peoples', traditional and local knowledges

Indigenous Peoples', traditional owner and local community knowledges (ITLK) collectively refers to knowledge systems developed by Indigenous Peoples, traditional communities and local communities through extended close interaction with their surrounding environment or long-standing continuous culture (See Section 5B Chapter 8 for in-depth description). Indigenous Peoples', traditional and local knowledges areis increasingly being acknowledged as an alternativea source of information complimentary to non-Indigenous or classical scientific information.

The uptake of ITLK is experiencing both successes and challenges. There is growing recognition that ITLK knowledge can provide insights for sustainable resource management and biodiversity conservation. This has led to the incorporation of ITLK into global processes and assessments such as the Global Assessment Report on Biodiversity and Ecosystem Services, Intergovernmental Panel on Climate Change and contributions to the Convention on Biological Diversity. One of the challenges to non-Indigenous knowledge, classical scientific method and governance systems is that they often treat the ocean as being separate from the land-based communities. There is also an assumption that these other knowledgesITLK need to be integrated with or validated by non-Indigenous knowledge or classical scientific methodologies.

ITLK and the World Ocean Assessment

The World Ocean Assessment/ Regular process has also recognized the need to meaningfully integrate weave ITLK throughout the assessment in order to capture a more holistic understanding of the state of the marine environment and inform sustainable ocean governance. The Regular ProcessWOA is looking to increase ITLK content throughout the WOA. Regional workshops were carried out by in Brazil, Jamaica, Seychelles, Portugal, and the United States by the United Nations Division of Ocean Affairs and Law of the Sea (UNDOALOS) and to understand keyincluded consideration of regional global ITLK issues.

Key findings included:

Workshops identified that • ITLK plays a vital role in supporting ocean governance, maintaining cultural heritage and fostering community resilience

- ~~ITLK .~~ It provides valuable, culturally authoritative, and context-specific insights for managing coastal and marine resources.
- ~~-~~ITLK groups can provide relevant information to the management of coastal resources and resource use pattern and that the impact on these communities can't be understood without Indigenous Peoples', traditional or local perspectives.
- ~~-~~The loss of a biological species is not only a significant ecological loss but also leads to the loss of cultural identity.
- ~~-~~The cultural assets of most Indigenous Peoples', traditional and local communities are linked to the natural environment and significant changes in these environments can undermine the cultural security of these communities.
- ~~-~~Future projections and outlooks are different across societal and cultural groups and may vary greatly between Indigenous and non-Indigenous ~~communities~~Peoples. Certain social classes and groups will be impacted differently than others.

Future WOAs will build on these findings to further ~~look to better~~ ~~integrate~~ weave ITLK throughout its content. ~~The ongoing WOA process and future assessments will aim to better integrate~~ include ~~Indigenous, traditional and local knowledges alongside scientific knowledge. This follows the global trend to better recognize and engage with ITLK to support better environmental and social management outcomes. There are many sections in the WOA which could better integrate~~ include ~~ITLK (e.g. Ocean Governance, Biodiversity, Socio-ecological systems, sustainable and inclusive ocean economy and One Health).~~

~~References~~

~~Costa-Pierce BA, Thorarensen HT and Strand A. 2022. Editorial: Ocean/aquatic food systems: Interactions with ecosystems, fisheries, aquaculture, and people. Front. Sustain. Food Syst. 6:1021801. doi: 10.3389/fsufs.2022.1021801~~

~~Duarte, C. M. (2014). *Global change and the future ocean: a grand challenge for marine sciences*. Frontiers in Marine Science, Volume 1 – 2014. https://doi.org/10.3389/fmars.2014.00063.~~

~~https://www.unesco.org/en/decades/ocean-decade.~~

~~Wang, S. et al. (2024). *Mineral resource extraction and resource sustainability: Policy initiatives for agriculture, economy, energy, and the environment*. Resources Policy, Elsevier, vol. 89(C). DOI: 10.1016/j.resourpol.2024.104657.~~

~~FAO, https://doi.org/10.4060/cd0683en.~~

~~Gaillet, G. Asselin, A-C., Weirmeille, A. (2022). *Sustainable fisheries: Towards operationalization of decision making accounting for biodiversity.* Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2022.132103.~~

~~Gallagher, A.J., Brownscombe, J.W., Alsudairy, N.A. et al. Tiger sharks support the characterization of the world's largest seagrass ecosystem. Nat Commun 13, 6328 (2022). https://doi.org/10.1038/s41467-022-33926-1~~

~~IPCC 2023; https://www.ipcc.ch/report/sixth-assessment-report-cycle/.~~

~~https://www.unepfi.org/publications/harmful-marine-extractives-offshore-oil-gas/.~~

~~Pathiranage, H. S. K. (2024). *Navigating the trade-offs between economic growth and environmental sustainability: A global analysis of long-term trends and strategic policies*. Sustainable Environment, 10(1), 2419161. https://doi.org/10.1080/27658511.2024.2419161~~

~~Van der Zwaag, D., Mahamah A. (2024). *Ocean Development & International Law Volume 55, 2024 - Issue 4: Enduring and Emerging Issues of the Law of the Sea: A Special Issue in Honor of Professor Ted L. McDorman*.~~

https://www.imo.org/en/MediaCentre/PressBriefings/pages/Marine-geoengineering.aspx

https://www.ciel.org/govern-geoengineering/

https://www.emsa.europa.eu/we-do/sustainability/environment/sustainable-shipping.html

https://globalmaritimeforum.org/

https://greenshippingchallenge.org

Knutson, T. R., Camargo, S. Chan, J. R., et al. (2019). *Tropical cyclones and climate change*. Bulletin of the American Meteorological Society, August 2019101(3), DOI:10.1175/BAMS-D-18-0194.1.

Pang, T. et al. (2023). *Coastal erosion and climate change: A review on coastal-change process and modelling*. Ambio. https://doi.org/10.1007/s13280-023-01901-9.

Tregarot, E. et al. (2023). *Effects of climate change on marine coastal ecosystems – A review to guide research and management*. Biological Conservation. https://doi.org/10.1016/j.biocon.2023.110394.

Singhvi, A., Luijendijk, A., van Oudenhoven, A. (2022). *The grey – green spectrum: A review of coastal protection interventions*. Journal of Environmental Management, Volume 311, 1 June 2022, 114824. https://doi.org/10.1016/j.jenvman.2022.114824.

https://sin.clarksons.net/

Papathanassis, A. (2023). *A decade of 'blue tourism' sustainability research: Exploring the impact of cruise tourism on coastal areas*. Cambridge Prisms: Coastal Futures 1: 1–11.

UNWTO (2021). *Tourism and the ocean: Toward sustainable tourism development in coastal areas*. United Nations World Tourism Organization.

Li, Y., et al. (2024). *Imbalance of coastal sustainability research hinders equality*. Sustainable Horizons. Volume 11, September 2024, 100107. https://doi.org/10.1016/j.horiz.2024.100107.

https://www.unwomen.org/sites/default/files/Headquarters/Attachments/Sections/Library/Publications/2020/Womens-economic-empowerment-in-fisheries-in-the-blue-economy-of-the-Indian-Ocean-Rim-en.pdf

https://openknowledge.fao.org/server/api/core/bitstreams/fafdf1a2-711c-40a3-86ca-60892002b0d3/content.

Crosman, K., et al. (2022). *Social equity is key to sustainable ocean governance*. Ocean Sustainability 1(1):4, DOI:10.1038/s44183-022-00001-7.

United Nations, 2015.

UNEP, 2020.

https://unfccc.int/decisions, 2024UNFCCC COP28, 2023.

Section 2: Approach to the assessment

1. Key Points

- The third World Ocean Assessment aims to provide the best available, scientifically informed review of the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis, through the development of regular targeted outputs that respond to policy needs, and by building capacity to support decision making at all levels;
- Its development relies on the efforts of scientists and experts from around the globe, under the guidance of the United Nations Members States and the support of the United Nations Secretariat;
- ~~The collaborative process includes regional workshops in support of the scoping and drafting of the Assessment and multiple rounds of reviewing, by peers, UN system organisations and United Nations Member states~~The collaborative process involves regional workshops for scoping and drafting, followed by multiple rounds of review by peers, UN system organizations, and UN Member States.;
- ~~The UN General Assembly, in its resolution 79/144, reaffirmed the importance of ensuring that assessments, such as those prepared under the Intergovernmental Panel on Climate Change, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and the Regular Process, support one another and also recalled the importance of compatibility and synergies between such assessments and assessments at the regional level;~~ UN General Assembly resolution 79/144 reaffirmed the need for synergy among assessments from bodies and processes such as the IPCC, the IPBES, and the Regular Process, ensuring compatibility between global and regional evaluations;
- Some definitions and vocabulary were highlighted that required careful consideration during the development of this Assessment.

2. Introduction/background

The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (Regular Process) ~~is a multilevel initiative which was created following the 2002 World Summit on Sustainable Development.~~ is a multilevel initiative established after the 2002 World Summit on Sustainable Development.

The overall objective of the Regular Process, and set by the Working Group on the proposed framework of the Regular Process (A/64/347, annex), is as follows:

The regular process under the United Nations would be recognized as the global mechanism for reviewing the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis by providing regular assessments at the global and supraregional levels and an integrated view of environmental, economic and social aspects. Such assessments would support informed decision-making and thus contribute to managing in a sustainable manner human activities that affect the oceans and seas, in accordance with international law, including the United Nations Convention on the Law of the Sea and other applicable international instruments and initiatives.

In its resolution 64/71, the General Assembly endorsed the recommendations adopted by the Ad Hoc Working Group of the Whole at its first meeting, including that, in the first cycle, the scope of the

Regular Process would focus on establishing a baseline and that, in subsequent cycles, the scope would extend to evaluating trends (A/64/347, para. 19). In its resolution 75/239, the General Assembly also endorsed the recommendations adopted by the Ad Hoc Working Group of the Whole at its thirteenth meeting, including that, for the second cycle of the Regular Process the scope would extend to evaluating trends and identifying gaps (A/75/362, annex, para. 2).

The third cycle of the Regular Process (2021-2025) focuses on three key outcomes: (1) assessments of the marine environment's condition, including socioeconomic aspects; (2) support for and collaboration with other ocean-related intergovernmental processes, such as producing a series of concise documents highlighting specific policy-relevant information from the second World Ocean Assessment (WOA II); (3) capacity-building, including a program designed to enhance the capacity of States in strengthening the ocean science-policy interface at national, regional, and global levels.

Building on the previous efforts, the program of work for the period 2021-2025 for the third cycle of the Regular Process as it relates to the development of the third World Ocean Assessment (WOA III), focused on two specific major components: on a sustainable and inclusive economy and of One Health, in addition to evaluating trends after WOAII, as directed by a scoping exercise.
Development of the World Ocean Assessment relies on the efforts of scientists and experts from around the Globe, under the Guidance of the United Nations Members States and the support of the United Nations Secretariat.

To organize tasks associated with writing and review processes, various actors and parties connected to the Regular Process assumed different roles and performed tasks as contributors, institutional reviewers or as other key participants in the Regular Process.

The Regular Process is overseen and guided by the Ad Hoc Working Group of the Whole on the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects of the UN General Assembly, which includes representatives of all Member States of the United Nations. This group has two Co-Chairs (one from a developing country and one from a developed country), which are appointed by the President of the General Assembly.

Between sessions of the Ad Hoc Working Group of the Whole, a Bureau of the Ad Hoc Working Group of the Whole (“the Bureau”) ensures the implementation of the decisions of the Ad Hoc Working Group of the Whole. The Bureau consists of the Co-Chairs of the Ad Hoc Working Group of the Whole, plus representatives from fifteen Member States – three appointed by each of the five regional groups in the General Assembly.

A Group of Experts has been established with the general task of carrying out assessments under the Regular Process. It consists of up to 25 experts, representing five regional groups. They structure outputs for the World Ocean Assessments and ensure that they are delivered on time following the available guidance and the highest standards.

A Pool of Experts to assist the Group of Experts is constituted under the Mechanism for the establishment of the Pool of Experts for the third cycle of the Regular Process, developed by the Bureau in accordance with resolution 75/239. Without detracting from the other principles which the General Assembly has endorsed, the allocation of tasks to members of the Pool of Experts must reflect the principle of adherence to equitable geographical representation in all activities of the Regular Process and have due regard to a desirable balance between genders.

Members of the writing teams of each of the various outputs were drawn from the Pool of Experts and were responsible for writing the draft of the outputs under the Guidance of the Group of Experts. The

members of the writing teams were selected based on relevant expertise, with a view towards regional representation and gender balance within the overall writing team.

In its decision on 30 December 2022, the UN General Assembly noted the endorsement by the Ad Hoc Working Group of the Whole of the Guidelines for the Writing and Review Process of the next Assessment(s) of the Third Cycle, developed by the Group of Experts in accordance with the programme of work for the third cycle,[1] in which the vision and mission for the third cycle are specified as follows:

Vision: For the World Ocean Assessment (WOA) to become the key instrument to build environmental, economic and social resilience by informing decision-makers of the challenges and opportunities for achieving a healthy ocean environment that supports sustainable development.

Mission: To provide the best available, scientifically informed review of the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis, through the development of regular targeted outputs that respond to policy needs, and by building capacity to support decision making at all levels.[2]

The Vision and Mission statements above indicate that the main intended audience of the present Assessment are people in all sectors who will be making decisions that will affect the marine environment. They cover a broad range of individuals and backgrounds, including, but not limited to, policy-makers and legislators, scientists, business leaders and the general public.

The development of WOA III can be organized into the three major steps of (i) Scoping, (ii) Development of the outline, and (iii) Drafting and reviewing. Each of these major steps is described in this Section. Interwoven within these steps, discussion were centred on the frameworks and methodologies to be adopted, strategies to updating WOA II, the expertise needed to produce this Assessment and delivery methods.

3. Scoping the assessment

A first round of five regional workshops was held between July 2022 and December 2022, with a view to inform the scoping of the Assessment and the development of an annotated outline for the Assessment, collecting regional-level data, raising awareness on the Regular Process and generating interest from the scientific community in contributing to the drafting of the Assessment. It should be noted that at this stage of development, it was under discussion if the output would be produced as single document or if it would be split into multiple assessments.

During the five workshops of the first round, participants were asked to consider various elements of the structure, format and content of what would form the assessment of the third cycle. These five regional workshops were held in:

- Tanzania, 25-27 July 2022, with a focus on the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea and Gulf of Aden and the ROPME/RECOFI area
- Jamaica, 12-14 September 2022, with a focus on the North Pacific and the Wider Caribbean area. It was convened by the International Seabed Authority;
- Argentina, 28-30 September, with a focus on the South Atlantic (between the African and American coasts) and the Wider Caribbean area;

[1] See A/RES/77/248, para. 347.
[2] See A/77/596, annex I.

- Kingdom of the Netherlands, 28-30 November, with a focus on the North Atlantic, the Baltic Sea, the Mediterranean Sea and the Black Sea region;
- Indonesia, 13-15 December, with a focus on the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea and Gulf of Aden and the ROPME/RECOFI area and the North and South Pacific.

Resounding feedback from the workshops was that previous formats of the World Ocean Assessment were challenging in terms of accessibility, searchability and therefore utility. These challenges resulted in many participants noting that they had not frequently used the World Ocean Assessments. Workshop participants recommended that the Group of Experts explore mechanisms to improve the ability of stakeholders to access the assessment, find information within it and then utilise that information. Further, it was identified that a greater emphasis should be placed on the social components of the assessments.

The workshops also identified that it would be of greater use to present information on pressures on the ocean and the human activities and responses to mitigate and manage those pressures in an integrated manner, rather than providing them as separate chapters. Further, it was identified that the social components of the assessment were underdeveloped and there should be greater emphasis placed on these elements. Likewise, while the previous assessment adopted, in different degrees, modified versions of the drivers-pressures-state-impacts-response frame-work (DPSIR). In WOA II, it influenced the overall design of the outline, while in WOA III, this framework was used, when relevant, within individual chapters of the assessment, thereby providing direct linkages between pressures, impacts and responses.

4. Outline of the assessment

Taking into account the extensive input from workshop participants, the Group of Experts undertook a series of in-depth brainstorming sessions to identify the key elements from the workshops that would form part of the basis for the scope of this assessment.

In addressing the identified demands, particularly to give more prominence to the socioeconomic aspects of the Assessment, its main elements were organized around the changes since WOA II (Section 4) and Socio-ecological systems (Section 5). The latter provides an integrated view of the social and ecological systems (coupled human-environment systems) of the ocean and the interactions between them. It is further organized into a sustainable and inclusive ocean economy sub-section (Section 5A) and a One Health sub-section (Section 5B).

The period considered for the changes since WOA II was 2018-2023. Changes over longer time periods have been included where gaps were identified in the content of previous assessments.

During the brainstorming sessions, another aspect that became salient was the demand to feature potential responses to perceived challenges. As a result, Sustainability Pathways were incorporated into the outline of the Assessment. They comprise forward-looking feasible pathways, identifying the scientific data, tools and knowledge that could be utilized at local, regional and global scales to ensure that human activities are sustainable and inclusive, while providing examples of where policy has been effective, including management approaches. The intention was not to prescribe specific uses of these data, tools and knowledge for specific sectors or situations, but rather identify evidence-informed plausible scenarios of the future that incorporate the use of the data and knowledge currently available within the context of achieving the Sustainable Development Goals.

In addressing these demands, and in line with the vision of informing decision-makers of the challenges and opportunities for achieving a healthy ocean environment that supports sustainable development, each chapter under the inclusive ocean economy sub-section (5A) include content relating to (i) Pressures, (ii) Sustainability pathways, (iii) Social economic components (Benefits and disbenefits,

Equity, Gender, Indigenous Peoples', Traditional ~~Owner~~ and Local Community Knowledges (ITLK)) and sector relevant governance.

Section 5B is organized within the framework of "One Health", an integrated and unifying approach which sustainably balances and optimises the health of people, animals and ecosystems. It recognises that the health of humans, domestic and wild animals, plants and ecosystems are intrinsically linked while also being interdependent (OHHLEP, 2022). Section 5B encompasses three main components: (i) The physical and chemical marine environment, (ii) The organisms that live in the marine environment, and (iii) People. The One Health approach is recognised by the World Health Organization as being particularly relevant to food and water safety, nutrition, zoonosis control, pollution management and antimicrobial resistance.

Other new elements introduced in the outline of WOA III that should be noted include: a new sub-chapter on Fjord systems (Section 4- Sub-Chapter 5R), a new section providing a global overview of ocean governance (Section 3) and a new chapter on ocean hazards of natural origin (Section 5B – Chapter 4). Sub-chapter 5N: Pelagic domain of Section 4 is an extension of Chapter 7N of WOA II on the Open Ocean and covers epipelagic, mesopelagic, and bathypelagic zones.

To address issues of utility, accessibility and searchability , it was decided to produce most of the assessment in web-based format that allows for digital linking between chapters and to core and external resources, including literature, graphics and supplemental material. This Assessment is available in the six official languages of the United Nations.

5. Drafting and reviewing the assessment

To further develop the new and refocused elements for scope of the Assessment, a second round of five workshops was held between May and November 2023. These workshops focused on the development of sustainability pathways for the chapters under section 5A (a sustainable and inclusive ocean economy) and the cross-cutting themes of equity, gender and Indigenous Peoples', Traditional and Local Community Knowledges for contributing to the chapters in section 5B (One Health) and supporting the development of the social components addressed in each chapter of section 5A (a sustainable and inclusive ocean economy). Regional workshops have played a critical role in the development of the World Ocean Assessment by ensuring that the voices, knowledge, and priorities of regional stakeholders are meaningfully integrated into the global assessment process. These workshops are designed as inclusive, highly participatory events that bring together representatives from governments, academia, civil society, and Indigenous Peoples and Local Communities to co-create content that reflects regional realities and national specificities. By fostering open dialogue and knowledge exchange across diverse disciplinary, cultural, and institutional perspectives, the workshops help ensure that the WOA is grounded in both scientific evidence and lived experience.

Importantly, these regional engagements not only serve to inform the assessment but also function as platforms for capacity sharing and mutual learning, disseminating the work of the Regular Process, identifying and recruiting expertise for the Writing Teams, and strengthening regional ownership and relevance of the final outputs. The success of these workshops, and the Ocean Future Scenarios and Pathways Workshop described below, relied heavily on the time, commitment, and collaborative spirit of participants. Their contributions are essential to shaping an assessment that is globally coherent yet regionally nuanced, policy-relevant, and actionable.

These workshops were held in:

- Santos, Brazil, from 10 to 17 May 2023, for the South Atlantic (between the African and American coasts) and the Wider Caribbean regions;
- Kingston, Jamaica, from 12 to 16 June 2023, for the North and South Pacific regions and the Wider Caribbean area. It was convened by the International Seabed Authority;

- Mahe, Seychelles, from 30 July to 4 August 2023, for the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea and Gulf of Aden and the
- ROPME/RECOFI regions;
- Lisbon, Portugal, from 25 to 27 September 2023, for the region of the North Atlantic, the Baltic Sea, the Mediterranean Sea, and the Black Sea;
- New York, United States, from 27 to 29 November 2023, for the region of the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea, the Gulf of Aden, and the ROPME/RECOFI area.

An Ocean Future Scenarios and Pathways Workshop in support of WOAIII took place in Berlin on 14 and 15 December 2023. It was organised by the German Marine Research Consortium (KDM), together with the Leibniz Centre for Tropical Marine Research (ZMT) and with the support of the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The aim of this workshop was to create a technically sound vision of sustainable oceans in 2050 and to highlight the most important characteristic aspects. To make this possible, an interdisciplinary team worked for two days in three separate groups to sketch out what sustainable oceans could look like in 2050.

The outputs from these workshops were compiled and provided to the relevant writing teams for specific consideration and incorporation into the chapters and sub-chapters of section 5 of the assessment. Writing teams took varying approaches to how they considered and incorporated these outputs.

~~The outputs gathered from this workshop later informed the writing teams in the development of their chapters.~~

As the second round of workshops were happening, writing teams were being assembled, starting by the selection of their Coordinating Authors. The Group of Experts, once identified each Coordinating Authors, worked with them for identifying the members of each writing team, striving to fill existing gaps. Pursuant to the Guidelines for the Nomination and Appointment of Experts to the Pool of Experts, Writing Teams and Peer Reviewers to Support the Works of the Third Cycle of the Regular Process,[3] due regard was given to reflect the principle of equitable regional representation and of gender balance of the required expertise in all activities of the Regular Process. Further to the steps and procedures outlined in the Mechanism for the establishment of the Pool of Experts for the third cycle of the Regular Process,[4] additional guidance was provided to guide recommendations of experts to the Pool of Experts for the third cycle, affording due consideration to the following:

a. Regional balance;
b. Gender balance;
c. Early career professionals;
d. Traditional knowledge holders; and
e. Non-academic stakeholders.

A Coordinating Authors Meeting was assembled in Lisbon, Portugal, in February 2024 to facilitate the effective planning and coordination of the development of WOA III.

~~An in-person meeting of ITLK experts was held in Paris in August 2024. This meeting facilitated direct interaction with ITLK experts to solicit feedback on the draft of the ITLK chapter of WOA III. The gathering ensured the presence of multi-disciplinary experts to advance chapter components and allowed relevant ITLK experts to provide direct guidance to the chapter, facilitating its development~~

[3] See A/77/596.
[4] See A/76/391, annex I.

~~and finalisation.~~ An in-person meeting of ITLK experts, including Indigenous Peoples' knowledge holders and scientists from diverse disciplinary and cultural backgrounds took place in Paris in August 2024, allowing direct interaction for feedback on the ITLK chapter draft of WOA III. Multi-disciplinary experts contributed to refining the chapter and providing guidance for its development.

~~After the development of chapter drafts by the Writing Teams, they underwent reviews by the Group of Experts, a concurrent peer review and a preliminary review by UN system organisations, and two rounds of reviews by United Nations Member States and UN system organisations.~~ Once the Writing Teams completed the chapter drafts, they underwent reviews by the Group of Experts, a peer review, and preliminary evaluations by UN system organizations, followed by two review rounds by UN Member States and UN system organizations.

~~Regarding the use of Artificial Intelligence (AI) in the development of chapters and other elements of WOA III, writing teams were limited to using generative AI only to improve the readability and language of the text. In these cases, it should only be done with human oversight and control, and all work should be reviewed and edited carefully, understanding that all writing team members are responsible and accountable for the contents and integrity of the work presented.~~ Artificial Intelligence (AI) in WOA III chapter development was limited to enhancing readability and language. Its use required human oversight, with all work reviewed carefully, ensuring writing teams remained accountable for content integrity. ~~The writing teams were further directed to disclose any use of AI and AI-assisted technologies and to include a citation to the AI system used to generate the text. AI output was not acceptable as a replacement for key writing tasks such as producing scientific insights, drawing scientific conclusions or providing recommendations. These procedures were rooted in the Principles for the Ethical Use of Artificial Intelligence in the United Nations System (CEB/2022/2/Add.1).~~ Writing teams were required to disclose any use of AI and cite the AI system utilized when generating text. AI-generated content could not replace critical tasks such as deriving scientific insights, conclusions, or recommendations, in line with Principles for the Ethical Use of Artificial Intelligence in the United Nations System (CEB/2022/2/Add.1).

6. Definitions and vocabulary

Some definitions and vocabulary were highlighted that required careful consideration during the development of this Assessment, some of which influenced the organization and coordination of subjects between chapters. These salient cases are presented here.

Large Scale Fishing (LSF), Medium Scale Fishing (MSF), and Small Scale Fishing (SSF) are defined and primarily addressed in Sub-chapter 1a: Medium and large-scale fishing and Sub-chapter 1b: Small-scale fishing including subsistence fishing of Section 5A. ~~The scale and scope of operation between Large Scale Fishing (LSF) and Medium Scale Fishing (MSF) (and also Small Scale Fishing –SSF-) are distinct, each with its own set of practices, impacts, and sustainability measures. Fisheries are categorized based on the scale and scope of their operations (FAO,2023). LSF and MSF differ in their operational approaches, with each playing a unique role in the global fishing industry.~~ They operate distinctly, each with unique practices, impacts, and sustainability measures. Fisheries are classified by operational scale (FAO, 2023), with LSF and MSF fulfilling different roles in the global fishing industry. LSF is characterized by their use of large, high-capacity boats, often exceeding 130 meters in length with a hold capacity of more than 2,000 tonnes (FAO, 1985). MSF often occurs regionally with moderate-sized vessels FAO (1985). They serve as a bridge between artisanal (or SSF) and MSF, adapting various fishing methods and technologies (Halimatussadiah and others, 2023). ~~See S5A.C1a and S5A.C1b.~~

The FAO defines SSF as place-based and for primarily family consumption (low production), characterized by limited capital or resource inputs, but labour intensive, and based on trips that are spatially and temporally limited (i.e., close to shore, completed within a day) (FAO, 2018). However, individual nation states have adopted a wide range of definitions linked to gear type (i.e., type and size of nets), length of boat and means of power, vessel ownership, trip duration, and area of fishing activity (i.e., inshore, nearshore, etc.) (Pita and others 2020; Smith and Basurto, 2019). See S5A.C1a and S5A.C1b.

Small, medium, and large-scale aquaculture are defined and primarily addressed in Sub-chapter 1c: Medium and large-scale aquaculture and Subchapter 1d: Small-scale Aquaculture. ~~There are no formal definitions that separate small, medium and large-scale aquaculture, and scale can refer to a range of production, technological economic, social and environmental~~ There are no formal, globally accepted definitions distinguishing small, medium, and large-scale aquaculture, and scales can refer to different ranges in production, technology, economy, social factors, and environmental considerations and contexts (Krause et al., 2020). In WOAIII, medium and large-scale aquaculture refers to commercial orientated production for domestic or export markets, conducted by companies ranging from medium-scale enterprises with employees at several farm sites through to large-scale multi-national companies with thousands of employees.

Since there is no single, globally accepted definition of small-scale aquaculture currently available, in Subchapter S5A.C1d, “small-scale” is referred to as single or clustered (community-based) farming units operated by individual farmers, their families, and/or groups of farmers, using minimum technology, inputs, services, and resources. See S5A.C1c and S5A.C1d.

The term 'blue carbon' refers to the capture and long-term storage of carbon in certain marine habitats and its potential for climate change mitigation. The term was first applied to three coastal vegetated habitats - mangroves, seagrass meadows and salt marshes - that store high stocks of carbon buried in their sediments by unit of area. Later, it was applied to other habitats, such as marine sediments, which store significant amounts of carbon due to their geographical extent despite low accumulation rates compared to coastal zones. More recently, other habitats such as kelp forests, although with high rates of organic matter remineralisation, have been suggested as blue carbon.

In this Assessment, the term " Sustainable and inclusive ocean economy" is preferred over "Blue Economy¨, which it replaces. The replacement circumvents the ambiguity deriving from the of multiple definitions that are adopted for "Blue Economy". The concept of a “sustainable and inclusive ocean economy” recognizes that economic growth and environmental stewardship must go hand in hand with social and individual well-being. It encompasses how we use marine resources and the systems in place to govern them.

Nature-based solutions (NBS) is defined in UNEA Resolution 5.2 "UNEP/EA.5/Res.5" as "Actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems that simultaneously address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits.

The level of confidence assigned to a finding are expressed using four main qualifiers that synthesize the writing teams' judgments about the validity of findings as determined through evaluation of evidence and agreement. These consist of the following:

a. **Inconclusive**: representative of a suggestion or speculation with no or limited evidence. It is expected that this term will be used infrequently, but it provides writing teams with the opportunity to emphasize issues that are not established in science, but that are important to policymakers or might have been highlighted by a different audience.

b. **Unresolved**: representative of multiple independent studies that exist, but where conclusions do not agree.

c. **Established but incomplete**: representative of general agreement, although in a situation where a limited number of studies currently exist, and where no comprehensive synthesis has been conducted, or the studies that do exist imprecisely address the question.

d. **Well established**: where a comprehensive meta-analysis or other syntheses/multiple independent studies that agree exist. This represents multiple, consistent independent lines of high-quality evidence. Key findings may be further emphasised where there is high confidence using "very well established" where there is a comprehensive evidence base and very high agreement, and "virtually certain" where the evidence consists of very robust data covering multiple temporal and spatial scales and almost no disagreement.

7. Acknowledgement

This Assessment has benefited from resources from the regular budget of the United Nations and would not have been possible otherwise. Likewise, it relies on the scientific output of the global scientific community, the result of the efforts of countless researchers and the investment of governments and society in general from around the globe.

The Regular Process is grateful to Argentina, Brazil, France, Germany, Indonesia, Jamaica, the Netherlands, Portugal, Seychelles, the United Republic of Tanzania, and the United States of America for their support for the present Assessment. Support was also provided by the International Seabed Authority, Intergovernmental Oceanographic Commission, and United Nations Environment Programme. The Regular Process is also grateful to Ireland, New Zealand, the Philippines, and the Republic of Korea for their voluntary contributions to the trust fund for the Regular Process during the third cycle.

Neither the members of the Group of Experts nor the Pool of Experts have received any remuneration for their work.

References

Food and Agriculture Organization (FAO). Definition and classification of fishery vessel types. Fisheries Technical Paper, 1985.

FAO. The State of World Fisheries and Aquaculture: Meeting the sustainable development goals. 2018.

Food and Agriculture Organization (FAO). Illuminating Hidden Harvests: The contributions of small-scale fisheries to sustainable development – Executive summary, 2023.

Halimatussadiah, Alin, and others. Co-management of large-scale and medium-scale fisheries: An assessment of the fishery tax system in Indonesia. Marine Policy, vol. 148, art. 105458, 2023.

Krause, Gesche and others. Visualizing the social in aquaculture: How social dimension components illustrate the effects of aquaculture across geographic scales. Marine Policy, vol. 118, art. 103985, 2020.

One Health High-Level Expert Panel (OHHLEP), Adisasmito WB, Almuhairi S, Behravesh CB, Bilivogui P, Bukachi SA, et al. (2022) One Health: A new definition for a sustainable and healthy future. PLoS Pathog 18(6): e1010537. https://doi.org/10.1371/journal.ppat.1010537

Pita, Cristina, and others. Small-Scale Fisheries in Europe: Challenges and Opportunities. In J. J. Pascual-Fernández, C. Pita, & M. Bavinck (Eds.), Small-Scale Fisheries in Europe: Status, Resilience and Governance (pp. 581–600). Springer International Publishing. 2020.

Smith, Hillary, and Xavier Basurto. Defining Small-Scale Fisheries and Examining the Role of Science in Shaping Perceptions of Who and What Counts: A Systematic Review. Frontiers in Marine Science, 6. 2019.

United Nations System Chief Executives Board for Coordination. “Principles on the Ethical Use of Artificial Intelligence in the United Nations System.” UNSCEB, n.d., https://unsceb.org/principles-ethical-use-artificial-intelligence-united-nations-system. Accessed 25 Feb. 2025.

Section 3 - Global Overview of Ocean Governance

Members of the Group of experts responsible for the section: Mariamalia Rodríguez Chaves and Enrique Marschoff.

Coordinating-authors: ~~Carina Costa de Oliveira and~~ Youna LBL Lyons and Carina Costa de Oliveira

Writing team[5]: Michelle Scobie, Paul Foley, Rakhyun E. Kim, Sarra Sefrioui, Senia Febrica, Vonintsoa Rafaly, Youngdawng Moh.

[5] The writing team is grateful for the comments and additions from a large number of collaborators chosen for their varied geographic origin and expertise in different topics covered: Ana-Flávia Barros-Platiau, Andrei Polejack, Angelique Pouponneau, Christian Bueger, David Alasdair Campbell Freestone, Denis Bailly, Elisa Morgera, Karen Scott, Maria Teresa Infante, Nengye Liu, Philile Mbatha, Quentin Hanich, Robert Blasiak, Robin Mahon, Thandiwe Gxaba, Violeta Radovich, Anais Remont.

Key Findings

- Ocean governance is shaped by a ~~underpinned by a highly~~ complex and dynamic interplay of multilevel intergovernmental institutions, instruments and regimes where concepts, principles and means of implementations are developed ~~and used~~;
- The application of~~use and implementation of global~~ ocean governance concepts ~~and principles~~ across ~~different~~ global and regional institutions strengthens ~~shows~~ legal connectivity~~, that supports and~~ enhanc~~inges overall~~ coherence and synergies in ~~ocean~~ governance;
- The fragmentation of ocean governance ~~fragmentation of ocean governance~~ at global and regional levels has continued to draw ~~garner~~ significant attention over the past five years~~, addressed through~~ thereby promoting the development of different~~the use of a diversity of~~ mechanisms including cross-sectoral interplay~~institutional mechanisms (e.g. in sectoral sub-regimes)~~, systemic responses such as in the BBNJ Agreement and judicial proceedings;
- In t~~T~~he past five years ~~have seen a significant accentuation of references to~~ human dimensions, including human rights and ~~use of~~ social sciences, have gained increased prominence in ocean governance discussions;
- Governance concepts ~~that have arisen and developed through~~ emerging from national experiences and non-state actors' proposals and practices, such as the blue economy and marine spatial planning, have gained increased significance ~~e~~ i~~mposed themselves as~~ in ~~central to~~ State-led~~centred~~ governance developments~~development s, such as the blue economy and marine spatial planning~~.
-

Introduction

This is the first dedicated section on ~~comprehensive~~ ocean governance ~~section~~ in a WOA report, as previous ~~WOA~~ reports addressed ~~ocean governance~~ it within specific chapters, such as~~e.g. for~~ fisheries. Earlier analyses of global ocean governance ~~of course~~ exist and were consulted (e.g. IUCN, 1995; Mangalagiu and others, 2019). This section provides first a brief overview of the institutional and legal architecture of ocean governance at global and regional levels (Part 1) that other substantive updates included in WOA reports relate to, with a particular focus on developments in the last five years. Thi~~s~~e approach recognises ~~taken acknowledges~~ the central role played by States in shaping ~~the making of institutional and substantive concepts of~~ ocean governance concepts, principles and means of implementation ~~but it also encompasses and acknowledges~~ while also incorporating the ~~the participation and~~ influence of non-state actors for a ~~broader and~~ more inclusive framework ~~ocean governance framing~~ (e.g. Campbell and others. 2016 and Niner and others. 2024). The analysis first examined fifty-seven global~~multilateral~~ treaties agreed between 1946 and 2024, that are applicable to marine~~the~~ protection and

preservation ~~of marine environment at the global level were first examined~~. In addition to these treaties and their associated institutions many non-binding intergovernmental processes have been central to the development of other ~~complementary~~ elements and concepts of ocean governance at global and regional levels, within and outside the United Nations' system that are included in the overview. Public-private and non-state processes can also be essential development nodes to form a polycentric (Mahon and Fanning, 2019; Naidoo and others, 2021) governance system (most recently Ostrom, 2010; WOA III S5A.C8, 8.5.3 and S5A.C1c~~-~~) and shape new governance narratives. These are included in the second part of this section on the most prominent and fast developing principles, concepts and means of implementation that underpin these global and regional polycentric (Mahon and Fanning, 2019; Naidoo and others, 2021) ocean governance developments and provides means to overcome the institutional and sectoral fragmentation. See also WOA III S4.C1 (2.4). To suit the non-exhaustive ~~and~~ global and regional approach of the WOA, graphs and figures were used to introduce the complexity of this matter including connections at different scales.

1. Developments and updates in global and regional institutional and legal mechanisms

The geographic scope and mandate of these mechanisms can be global (1.1) or regional (1.2) and vary greatly in substantive scope. Interplays have been developed between these institutions and instruments to overcome adverse effects from fragmentation of the resulting governance complex (1.3).

1.1 Global

~~Generally recognised a~~As the constitution for the ocean (Mann Borgese, 1975; Koh, 1983), the 1982 United Nations Convention on the Law of the Sea (UNCLOS) (UNCLOS, 1982) plays a structuring role in the global ocean governance framework (Boyle, 2005; SDG14(c)) and applies to all types of pollution of the marine environment and all activities at sea (UNCLOS, Art.194; ITLOS, 2024). Other 57 global treaties (Table 3.1.1) have been progressively agreed in the last 70 years (Graph 3.1.1(a)), including two in the last five years that are yet to come into force (BBNJ Agreement, 2023; Fisheries Subsidies Agreement, 2022). They are devoted to different aspects of the marine environment, including biodiversity protection, pollution from sectoral activities and other threats to the marine environment. These treaties are further complemented by numerous binding and non-binding instruments adopted by the many international frameworks whose mandate include the protection of the marine environment and its sustainable use (Figure 3.1.1.). Whereas some of those are restricted to the ocean realm, others also

apply to the terrestrial environment (Table 3.1.1). Adoption of treaties by States, which has been steady overall with occasional peaks that can be linked to the global or regional environmental political agenda at different times, has continued over the last five years (Graph 3.1.1(c)). However, some treaties are less widely adopted, potentially creating free-riders' situations (e.g. Barkin and Rashchupkina, 2017).

The implementation of international treaties and their further developments for policy-making purposes are shaped and prioritised by a great diversity of non-binding intergovernmental processes as well as arrangements with non-state actors. These processes can facilitate cooperation and coordination between states, UN Agencies and other international relevant bodies (e.g. Interpol, UN mechanisms such as UN-OCEAN amongst UN agencies) or the development of a common scientific understanding (e.g. IPCC, IPBES, WOA and UN Decade of Ocean Science). They can also identify and operationalise actions to address a given issue or even contribute to driving them at regional and national scales (e.g. GBF, 2023; UNGA, 2019-2024; ILC on sea-level rise -ILC, 2024). These are further supported by international courts and tribunals that e.g. provide guidance in the interpretation of relevant legal instruments, independently and as a whole (Tanaka 2023) and are instrumental or incremental in progressing the implementation of UNCLOS (Scott, 2023). Non-governmental processes and hybrid processes that involve States and non-state actors can also impact on the law-making or on the normative implementation ~~be very influential~~ (Mazzega and others, 2021; UNDESA, 2021)).

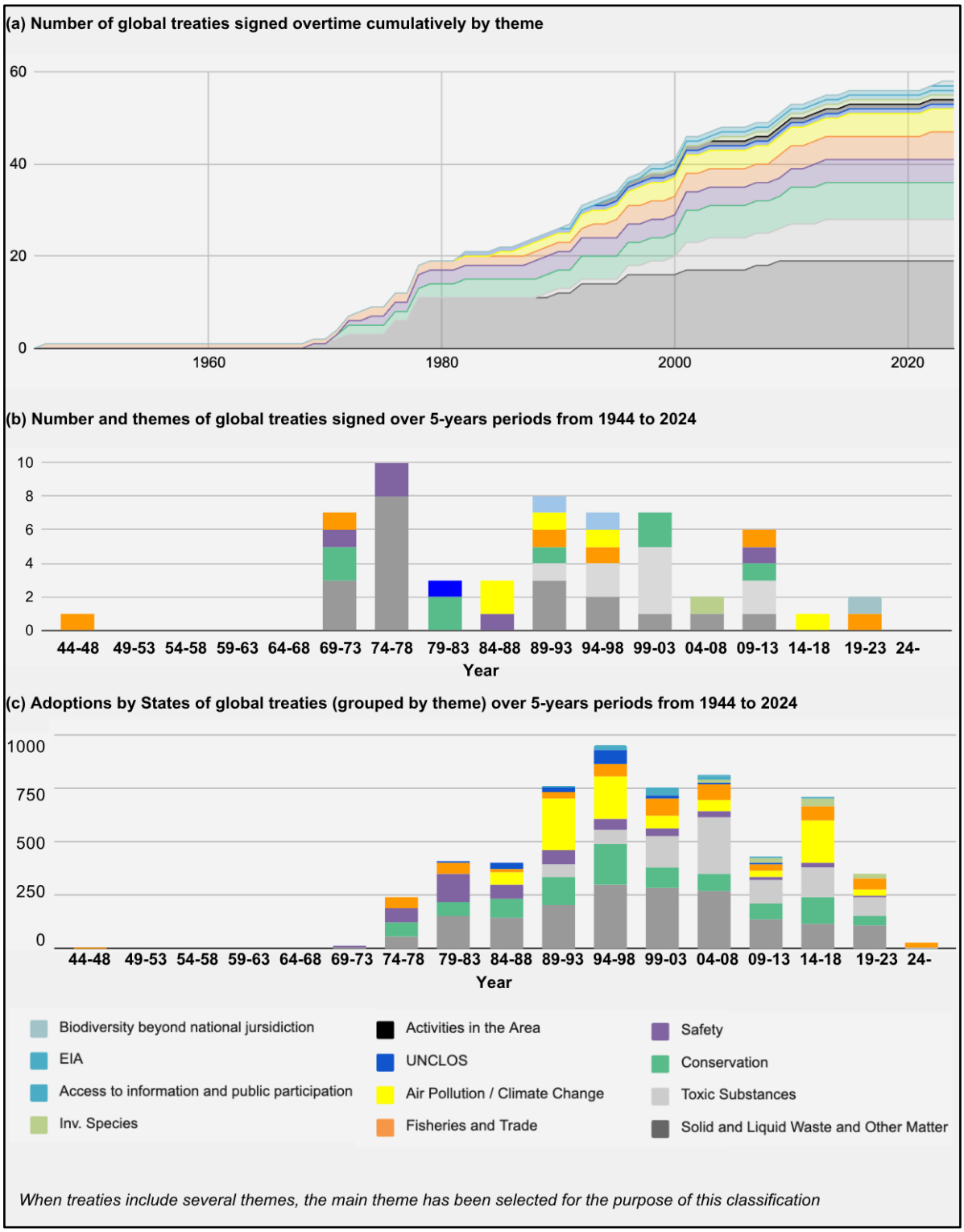
Table 3.1.1. Global treaties on the protection of the marine environment

DOI: 10.5281/zenodo.16420950

GLOBAL TREATIES ON THE PROTECTION OF THE MARINE ENVIRONMENT

Includes all global treaties adopted since the Whaling Convention that relate to, or are directly relevant to the protection of the marine environment. It provides the date of signature of the treaty, its name, whether it applies primarily to the ocean environment (Y) or also applied to the terrestrial environment (N) and whether it has come into force (IF) or not (NYIF), has ceased (C) or is defunct (D)

Date	Treaty	Ocean sp.	Status
1946	International Convention for the Regulation of Whaling	Y	IF
1969	International Convention on Civil Liability for Oil Pollution Damage (CLC)	Y	IF
1971	Convention on Wetlands of International Importance (Ramsar Convention)	N	IF
1972	Convention Concerning the World Cultural and Natural Heritage (World Heritage Convention)	N	IF
1971	International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND 1971)	Y	C
1972	Convention on the International Regulation for Preventing Collision at Sea (COLREGS) (as amended in 1981, 1987, 1989, 1993, 2001, 2007)	Y	IF
1972	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)	Y	IF
1973	Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) / 1979 Bonn Amendment / 1983 Gaborone Amendment	N	IF
1974	International Convention for the Safety of Life at Sea (SOLAS)	Y	IF
1976	Convention on the Limitation of Liability for Maritime Claims (LLMC)	Y	IF
1976	Protocol relating to the 1969 International Convention on Civil Liability for Oil Pollution Damage (CLC PROT)	Y	D
1976	Protocol relating to the 1971 International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (PROT FUND 1971)	Y	C
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) and Annex I	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes II	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes III	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes IV	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes V	Y	IF
1978	Protocol relating to the 1974 International Convention for the Safety of Life at Sea (SOLAS)	Y	IF
1979	Convention on the Conservation of Migratory Species of Wild Animals (CMS)	N	IF
1982	Paris Protocol relating to the 1971 Convention on Wetlands of International Importance (Ramsar Convention Prot)	N	IF
1982	UN Convention on the Law of the Sea (UNCLOS)	Y	IF
1985	Vienna Convention for the Protection of the Ozone Layer	N	IF
1987	Montreal Protocol on Substances that Deplete the Ozone Layer	N	IF
1988	Protocol relating to the 1974 International Convention for the Safety of Life at Sea (SOLAS PROT)	Y	IF
1989	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal / 1995 Amendment	N	IF
1990	International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC)	Y	IF
1991	Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention)	N	IF
1992	Convention on Biological Diversity (CBD)	N	IF
1992	Protocol relating to the 1969 International Convention on Civil Liability for Oil Pollution Damage (CLC PROT)	Y	IF
1992	1992 Protocol to Amend the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1971 (IOPC-FUND)	Y	IF
1992	UN Framework Convention on Climate Change (UNFCCC)	N	IF
1994	Agreement Relating to the Implementation of Part XI of the UNCLOS	Y	IF
1995	UN Agreement for the Implementation of the Provisions of the UNCLOS Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA)	Y	IF
1996	Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS)	Y	NYIF
1996	Protocol relating to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Prot)	Y	IF
1996	Protocol relating to the 1976 Convention on the Limitation of Liability for Maritime Claims (LLMC PROT)	Y	IF
1997	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annex VI	Y	IF
1998	Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade	N	IF
1998	UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention) and its 2009 Kiev Protocol	N	IF
2000	Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS 2000)	Y	IF
2001	Agreement on the Conservation of Albatrosses and Petrels	Y	IF
2001	Convention on the Protection of the Underwater Cultural Heritage	Y	IF
2001	International Convention on Civil Liability for Bunker Oil Pollution Damage (Bunkers Convention)	Y	IF
2001	International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS)	Y	IF
2001	Stockholm Convention on Persistent Organic Pollutants (POPs)	N	IF
2003	Kyev Protocol on Pollutant Release and Transfer Registers	N	IF
2004	International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM)	Y	IF
2007	Nairobi International Convention on the Removal of Wrecks (Nairobi WRC)	Y	IF
2009	FAO Agreement on Port State Measures to Prevent, Deter and Eliminate IUU Fishing (PSMA)	Y	IF
2009	Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (SRC)	Y	IF
2010	Nagoya Protocol (Access and Benefit Sharing)	N	IF
2010	Protocol to the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS PROT)	Y	NYIF
2012	Cape Town Agreement on Fishing Vessel Safety	Y	NYIF
2013	Minamata Convention on Mercury	N	IF
2015	Paris Agreement	N	IF
2022	Agreement on Fisheries Subsidies	Y	NYIF
2023	Agreement under the UNCLOS on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction	Y	NYIF



Graph 3.1.1 - Global treaties on the protection of the marine environment: signature and adoption by theme over time

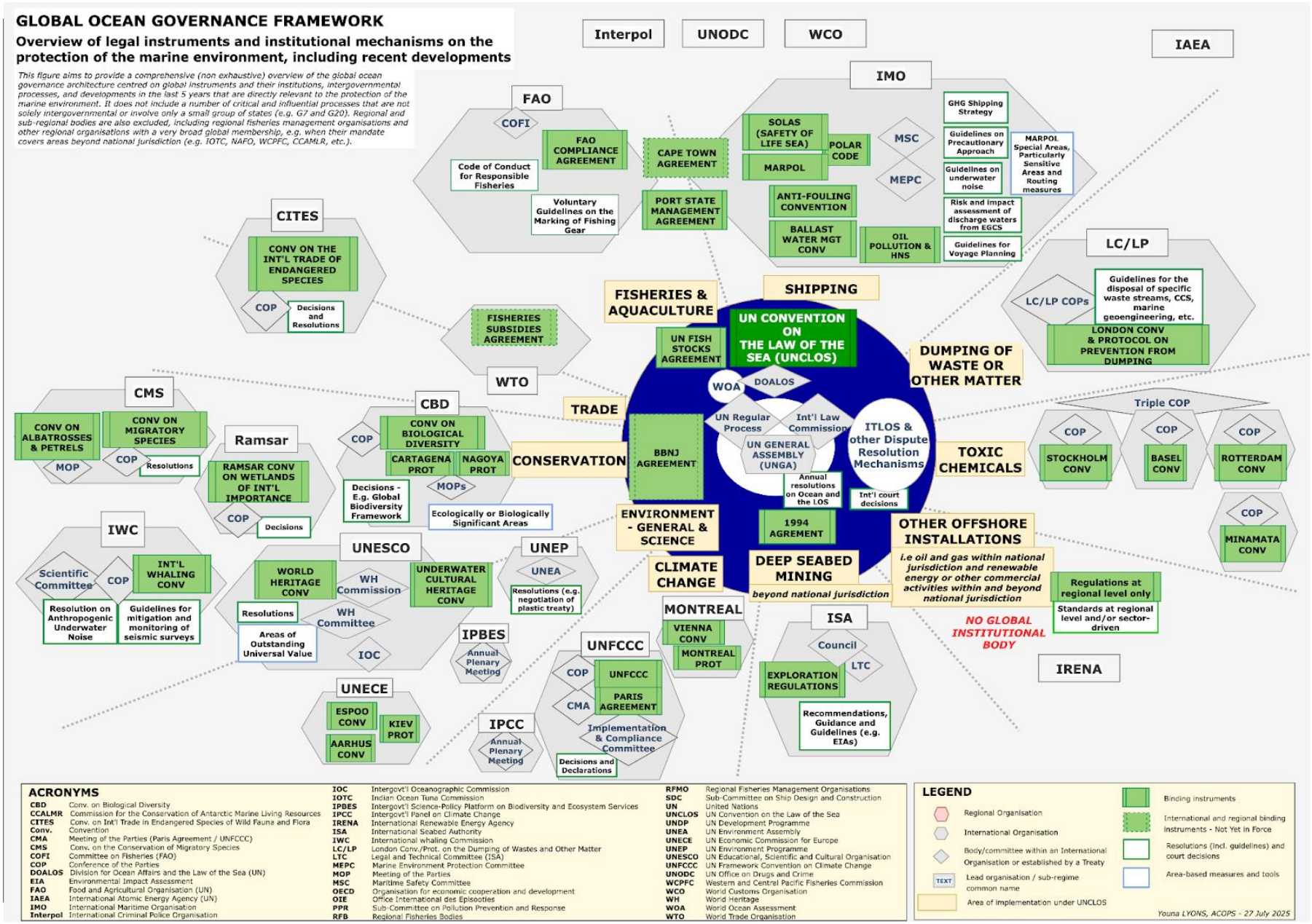
DOI 10.5281/zenodo.16447195

Cross-cutting challenges have been central to dynamic policy developments in the last five years and a recurring reminder of the need for better means to overcome institutional and topic fragmentation in ocean governance developments. Most of the new binding and non-binding instruments were developed to strengthen the existing governance framework and address gaps in ocean governance accordingly (e.g. CBD GBF, 2022; Fisheries Subsidies Agreement, 2022; BBNJ Agreement, 2023; IMO GHG Strategy, 2023) (Tanaka, 2023b; Kim, 2024). Many negotiations of new instruments in the last five years are still ongoing~~works in progress~~ (e.g. international legally binding instrument on plastic pollution, including in the marine environment (Brander and others, 2024), exploitation regulations in the Area ~~for seabed mining in ABNJ~~ (Campanella, 2024; Blanchard, 2023) and amendments to IMO regulations to better address GHG emissions from shipping (Garcia, 2021; Chircop and others, 2020; WOA III S5A.C6). ~~However, some critical marine ecosystems, habitats and species remain inadequately integrated (e.g. macroalgae, see WOA III S4.C4i) and vast areas of the ocean undersampled.~~ Many issues that are the subject of increasing attention in ocean policy-making have also been brought to international courts and tribunals, including in relation to overall coherence of the international legal order and human rights issues (ITLOS, 2024; ICJ, 2023; ICHR, 2017;Nyman 2020; WOA III S4.C6.sub5).

1.2 Regional

Multi-purpose organisations and arrangements focused on the protection of the marine environment form essential components of regional governance frameworks that complement the global governance level (Mahon and Fanning, 2019). These include twenty regional sea areas with mechanisms (Figure 3.1.2) devoted to states' coordination and the protection of the marine environment in their ~~adjacent~~ EEZ, and in some cases some ABNJ (e.g. OSPAR, Noumea Convention, CCAMLR). Six of these regional sea area mechanisms were established by and are still directly administered by UNEP (Oral, 2015; UNEP, 2024). These regional sea areas are characterised by an interplay of several regional intergovernmental bodies, institutions and arrangements charged with different aspects of the coordination and/or management of the marine environment, activities and research in those regional sea areas (Naidoo and others, 2021; Vince and others, 2017; Scheiber and Paik, 2013; Abdenur, 2014). Foundational instruments often integrate definitions from UNCLOS to which they also specifically refer (e.g. pollution and dumping in Noumea Convention and OSPAR Convention). Historical mechanisms have also often been strengthened, including through the modernisation and update of older instruments (e.g. 1986 South Atlantic UNGA Resolution A/RES/41/11 on fostering scientific research and environmental protection; Hatje and others, 2021). They continue to evolve through the adoption of new binding and non-binding instruments (e.g. South Atlantic and Benguela Convention) or completed through crossover with other global and regional programmes (e.g. IMO Glofouling in the South Pacific). Other arrangements have

been agreed in addition between sub-regional groupings of states sharing common ocean-related issues (e.g. through economic integration arrangements such as APEC) particularly on marine scientific research cooperation (e.g. All-Atlantic Ocean Research and Innovation Alliance; Polejack and others, 2021) or to enhance cooperation with a view to protecting a particular area (e.g. Sargasso Sea Commission WOA III S4.C5q)


GLOBAL OCEAN GOVERNANCE FRAMEWORK
Overview of legal instruments and institutional mechanisms on the protection of the marine environment, including recent developments
This figure aims to provide a comprehensive (non exhaustive) overview of the global ocean governance architecture centred on global instruments and their institutions, intergovernmental processes, and developments in the last 5 years that are directly relevant to the protection of the marine environment. It does not include a number of critical and influential processes that are not solely intergovernmental or involve only a small group of states (e.g. G7 and G20). Regional and sub-regional bodies are also excluded, including regional fisheries management organisations and other regional organisations with a very broad global membership, e.g. when their mandate covers areas beyond national jurisdiction (e.g. IOTC, NAFO, WCPFC, CCAMLR, etc.).
Interpol
UNODC
WCO
IAEA
IMO
SOLAS (SAFETY OF LIFE SEA)
POLAR CODE
MARPOL
MSC
MEPC
GHG Shipping Strategy
Guidelines on Precautionary Approach
Guidelines on underwater noise
MARPOL Special Areas, Particularly Sensitive Areas and Routing measures
Risk and impact assessment of discharge waters from EGCS
Guidelines for Voyage Planning
ANTI-FOULING CONVENTION
BALLAST WATER MGT CONV
OIL POLLUTION & HNS
FAO
COFI
FAO COMPLIANCE AGREEMENT
Code of Conduct for Responsible Fisheries
Voluntary Guidelines on the Marking of Fishing Gear
CAPE TOWN AGREEMENT
PORT STATE MANAGEMENT AGREEMENT
CITES
CONV ON THE INT'L TRADE OF ENDANGERED SPECIES
COP
Decisions and Resolutions
FISHERIES SUBSIDIES AGREEMENT
WTO
FISHERIES & AQUACULTURE
SHIPPING
UN CONVENTION ON THE LAW OF THE SEA (UNCLOS)
UN FISH STOCKS AGREEMENT
WOA
DOALOS
LC/LP
LC/LP COPs
Guidelines for the disposal of specific waste streams, CCS, marine geoengineering, etc.
LONDON CONV & PROTOCOL ON PREVENTION FROM DUMPING
DUMPING OF WASTE OR OTHER MATTER
CMS
CONV ON ALBATROSSES & PETRELS
CONV ON MIGRATORY SPECIES
COP
Resolutions
MOP
Ramsar
RAMSAR CONV ON WETLANDS OF INT'L IMPORTANCE
COP
Decisions
CBD
COP
CONV ON BIOLOGICAL DIVERSITY
CARTAGENA PROT
NAGOYA PROT
MOPs
Decisions - E.g. Global Biodiversity Framework
Ecologically or Biologically Significant Areas
TRADE
CONSERVATION
BBNJ AGREEMENT
UN Regular Process
Int'l Law Commission
UN GENERAL ASSEMBLY (UNGA)
ITLOS & other Dispute Resolution Mechanisms
Annual resolutions on Ocean and the LOS
Int'l court decisions
ENVIRONMENT - GENERAL & SCIENCE
1994 AGREEMENT
TOXIC CHEMICALS
Triple COP
COP
STOCKHOLM CONV
COP
BASEL CONV
COP
ROTTERDAM CONV
COP
MINAMATA CONV
IWC
Scientific Committee
COP
INT'L WHALING CONV
Resolution on Anthropogenic Underwater Noise
Guidelines for mitigation and monitoring of seismic surveys
UNESCO
WORLD HERITAGE CONV
WH Commission
WH Committee
IOC
Resolutions
Areas of Outstanding Universal Value
UNDERWATER CULTURAL HERITAGE CONV
UNEP
UNEA
Resolutions (e.g. negotiation of plastic treaty)
CLIMATE CHANGE
DEEP SEABED MINING
beyond national jurisdiction
OTHER OFFSHORE INSTALLATIONS
i.e oil and gas within national jurisdiction and renewable energy or other commercial activities within and beyond national jurisdiction
NO GLOBAL INSTITUTIONAL BODY
Regulations at regional level only
Standards at regional level and/or sector-driven
IRENA
MONTREAL
VIENNA CONV
MONTREAL PROT
ISA
Council
LTC
EXPLORATION REGULATIONS
Recommendations, Guidance and Guidelines (e.g. EIAs)
IPBES
Annual Plenary Meeting
UNFCCC
COP
UNFCCC
CMA
PARIS AGREEMENT
Implementation & Compliance Committee
Decisions and Declarations
UNECE
ESPOO CONV
KIEV PROT
AARHUS CONV
IPCC
Annual Plenary Meeting
ACRONYMS
CBD Conv. on Biological Diversity
CCALMR Commission for the Conservation of Antarctic Marine Living Resources
CITES Conv. on Int'l Trade in Endangered Species of Wild Fauna and Flora
Conv. Convention
CMA Meeting of the Parties (Paris Agreement / UNFCCC)
CMS Conv. on the Conservation of Migratory Species
COFI Committee on Fisheries (FAO)
COP Conference of the Parties
DOALOS Division for Ocean Affairs and the Law of the Sea (UN)
EIA Environmental Impact Assessment
FAO Food and Agricultural Organisation (UN)
IAEA International Atomic Energy Agency (UN)
IMO International Maritime Organisation
Interpol International Criminal Police Organisation
IOC Intergovt'l Oceanographic Commission
IOTC Indian Ocean Tuna Commission
IPBES Intergovt'l Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC Intergovt'l Panel on Climate Change
IRENA International Renewable Energy Agency
ISA International Seabed Authority
IWC International whaling Commission
LC/LP London Conv./Prot. on the Dumping of Wastes and Other Matter
LTC Legal and Technical Committee (ISA)
MEPC Marine Environment Protection Committee
MOP Meeting of the Parties
MSC Maritime Safety Committee
OECD Organisation for economic cooperation and development
OIE Office International des Epizooties
PPR Sub-Committee on Pollution Prevention and Response
RFB Regional Fisheries Bodies
RFMO Regional Fisheries Management Organisations
SDC Sub-Committee on Ship Design and Construction
UN United Nations
UNCLOS UN Convention on the Law of the Sea
UNDP UN Development Programme
UNEA UN Environment Assembly
UNECE UN Economic Commission for Europe
UNEP UN Environment Programme
UNESCO UN Educational, Scientific and Cultural Organisation
UNFCCC UN Framework Convention on Climate Change
UNODC UN Office on Drugs and Crime
WCPFC Western and Central Pacific Fisheries Commission
WCO World Customs Organisation
WH World Heritage
WOA World Ocean Assessment
WTO World Trade Organisation
LEGEND
Regional Organisation
International Organisation
Body/committee within an International Organisation or established by a Treaty
TEXT Lead organisation / sub-regime common name
Area of implementation under UNCLOS
Binding instruments
International and regional binding instruments - Not Yet in Force
Resolutions (incl. guidelines) and court decisions
Area-based measures and tools
Youna LYONS, ACOPS - 27 July 2025

1

Figure 3.1.1 Global Ocean Governance Framework and Developments DOI 10.5281/zenodo.16732422 ~~10.5281/zenodo.16488087~~

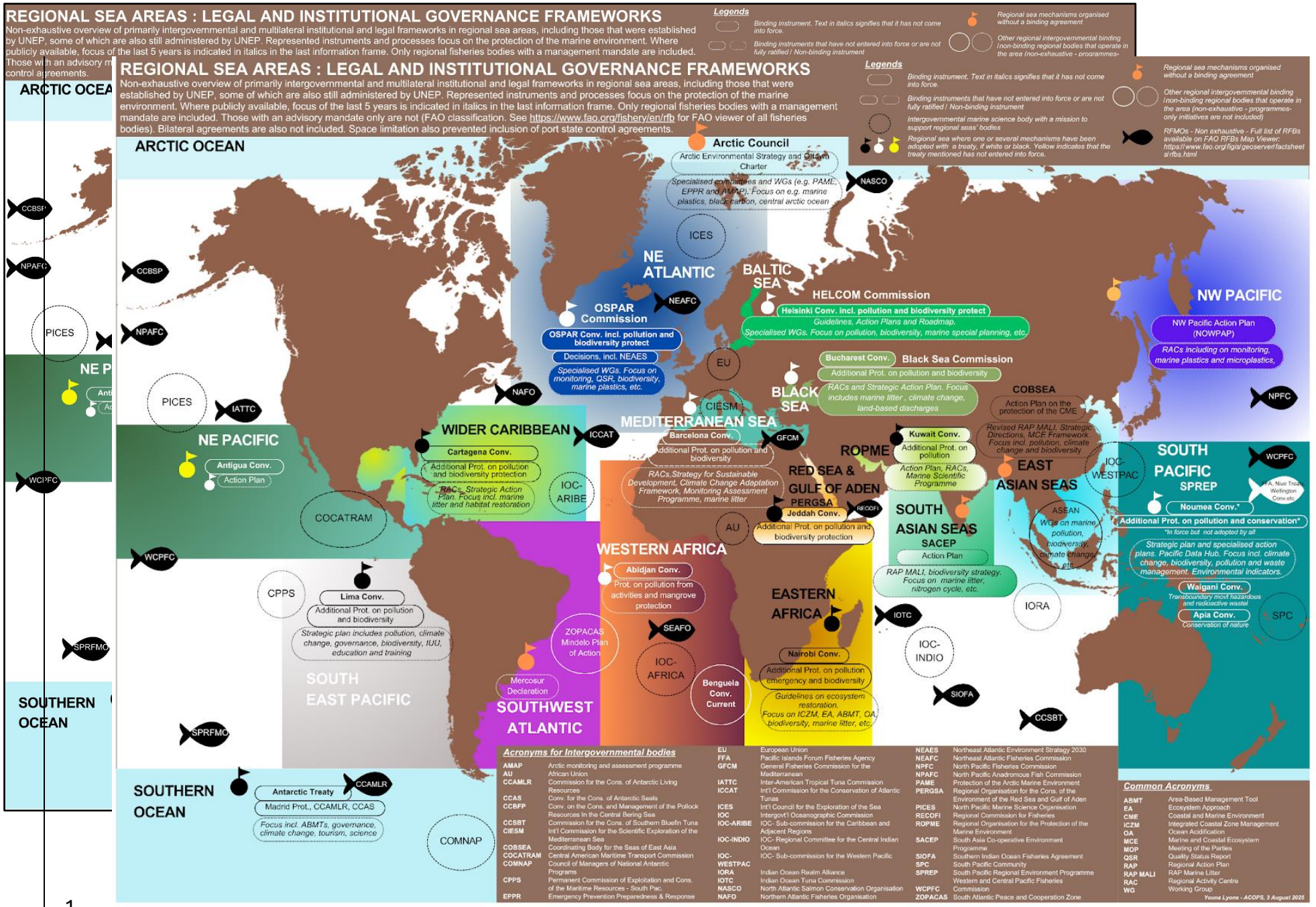

REGIONAL SEA AREAS : LEGAL AND INSTITUTIONAL GOVERNANCE FRAMEWORKS
Non-exhaustive overview of primarily intergovernmental and multilateral institutional and legal frameworks in regional sea areas, including those that were established by UNEP, some of which are also still administered by UNEP. Represented instruments and processes focus on the protection of the marine environment. Where publicly available, focus of the last 5 years is indicated in italics in the last information frame. Only regional fisheries bodies with a management mandate are included. Those with an advisory mandate only are not (FAO classification. See https://www.fao.org/fishery/en/rfb for FAO viewer of all fisheries bodies). Bilateral agreements are also not included. Space limitation also prevented inclusion of port state control agreements.
Legends
Binding instrument. Text in italics signifies that it has not come into force.
Binding instruments that have not entered into force or are not fully ratified / Non-binding instrument
Intergovernmental marine science body with a mission to support regional seas' bodies
Regional sea where one or several mechanisms have been adopted with a treaty, if white or black. Yellow indicates that the treaty mentioned has not entered into force.
Regional sea mechanisms organised without a binding agreement
Other regional intergovernmental binding /non-binding regional bodies that operate in the area (non-exhaustive - programmes-only initiatives are not included)
RFMOs - Non exhaustive - Full list of RFBs available on FAO RFBs Map Viewer: https://www.fao.org/figis/geoserver/factsheets/rfbs.html
ARCTIC OCEAN
Arctic Council
Arctic Environmental Strategy and Ottawa Charter
Specialised committees and WGs (e.g. PAME, EPPR and AMAP). Focus on e.g. marine plastics, black carbon, central arctic ocean
NASCO
ICES
NE ATLANTIC
BALTIC SEA
HELCOM Commission
Helsinki Conv. incl. pollution and biodiversity protect
Guidelines, Action Plans and Roadmap.
Specialised WGs. Focus on pollution, biodiversity, marine special planning, etc.
OSPAR Commission
OSPAR Conv. incl. pollution and biodiversity protect
Decisions, incl. NEAES
Specialised WGs. Focus on monitoring, QSR, biodiversity, marine plastics, etc.
NEAFC
NW PACIFIC
NW Pacific Action Plan (NOWPAP)
RACs including on monitoring, marine plastics and microplastics,
NPFC
CCBSP
NPAFC
PICES
EU
Bucharest Conv.
Black Sea Commission
Additional Prot. on pollution and biodiversity
RACs and Strategic Action Plan. Focus includes marine litter , climate change, land-based discharges
BLACK SEA
COBSEA
Action Plan on the protection of the CME
NAFO
IATTC
CIESM
MEDITERRANEAN SEA
Barcelona Conv.
Additional Prot. on pollution and biodiversity
GFCM
Revised RAP MALI, Strategic Directions, MCE Framework. Focus incl. pollution, climate change and biodiversity
NE PACIFIC
Antigua Conv.
Action Plan
WIDER CARIBBEAN
Cartagena Conv.
Additional Prot. on pollution and biodiversity protection
RACs, Strategic Action Plan. Focus incl. marine litter and habitat restoration
ICCAT
IOC-ARIBE
COCATRAM
WCPFC
ROPME
Kuwait Conv.
Additional Prot. on pollution
Action Plan, RACs, Marine Scientific Programme
RACs,Strategy for Sustainable Development, Climate Change Adaptation Framework, Monitoring Assessment Programme, marine litter
RED SEA & GULF OF ADEN
PERGSA
Jeddah Conv.
REDCFI
Additional Prot. on pollution and biodiversity protection
AU
EAST ASIAN SEAS
IOC-WESTPAC
SOUTH PACIFIC
SPREP
WCPFC
PFA, Niue Treaty, Wellington Conv.etc
Noumea Conv.*
Additional Prot. on pollution and conservation*
*In force but not adopted by all
Strategic plan and specialised action plans. Pacific Data Hub. Focus incl. climate change, biodiversity, pollution and waste management. Environmental indicators.
Waigani Conv.
Transboundary movt hazardous and radioactive waste
Apia Conv.
Conservation of nature
SPC
SOUTH ASIAN SEAS
SACEP
Action Plan
RAP MALI, biodiversity strategy. Focus on marine litter, nitrogen cycle, etc.
ASEAN WGs on marine pollution, biodiversity, climate change, etc
WESTERN AFRICA
Abidjan Conv.
Prot. on pollution from activities and mangrove protection
SEAFO
IOC-AFRICA
Benguela Conv. Current
EASTERN AFRICA
Nairobi Conv.
Additional Prot. on pollution emergency and biodiversity
Guidelines on ecosystem restoration. Focus on ICZM, EA, ABMT, OA biodiversity, marine litter, etc.
IOTC
IOC-INDIO
IORA
SIOFA
CCSBT
CPPS
Lima Conv.
Additional Prot. on pollution and biodiversity
Strategic plan includes pollution, climate change, governance, biodiversity, IUU, education and training
ZOPACAS Mindelo Plan of Action
SOUTH EAST PACIFIC
SOUTHWEST ATLANTIC
Mercosur Declaration
SPRFMO
SOUTHERN OCEAN
Antarctic Treaty
Madrid Prot., CCAMLR, CCAS
Focus incl. ABMTs, governance, climate change, tourism, science
CCAMLR
COMNAP
Acronyms for Intergovernmental bodies
AMAP Arctic monitoring and assessment programme
AU African Union
CCAMLR Commission for the Cons. of Antarctic Living Resources
CCAS Conv. for the Cons. of Antarctic Seals
CCBFP Conv. on the Cons. and Management of the Pollock Resources In the Central Bering Sea
CCSBT Commission for the Cons. of Southern Bluefin Tuna
CIESM Int'l Commission for the Scientific Exploration of the Mediterranean Sea
COBSEA Coordinating Body for the Seas of East Asia
COCATRAM Central American Maritime Transport Commission
COMNAP Council of Managers of National Antarctic Programs
CPPS Permanent Commission of Exploitation and Cons. of the Maritime Resources - South Pac.
EPPR Emergency Prevention Preparedness & Response
EU European Union
FFA Pacific Islands Forum Fisheries Agency
GFCM General Fisheries Commission for the Mediterranean
IATTC Inter-American Tropical Tuna Commission
ICCAT Int'l Commission for the Conservation of Atlantic Tunas
ICES Int'l Council for the Exploration of the Sea
IOC Intergov't Oceanographic Commission
IOC-ARIBE IOC- Sub-commission for the Caribbean and Adjacent Regions
IOC-INDIO IOC- Regional Committee for the Central Indian Ocean
IOC-WESTPAC IOC- Sub-commission for the Western Pacific
IORA Indian Ocean Realm Alliance
IOTC Indian Ocean Tuna Commission
NASCO North Atlantic Salmon Conservation Organisation
NAFO Northern Atlantic Fisheries Organisation
NEAES Northeast Atlantic Environment Strategy 2030
NEAFC Northeast Atlantic Fisheries Commission
NPFC North Pacific Fisheries Commission
NPAFC North Pacific Anadromous Fish Commission
PAME Protection of the Arctic Marine Environment
PERGSA Regional Organisation for the Cons. of the Environment of the Red Sea and Gulf of Aden
PICES North Pacific Marine Science Organisation
RECOFI Regional Commission for Fisheries
ROPME Regional Organisation for the Protection of the Marine Environment
SACEP South Asia Co-operative Environment Programme
SIOFA Southern Indian Ocean Fisheries Agreement
SPC South Pacific Community
SPREP South Pacific Regional Environment Programme
WCPFC Western and Central Pacific Fisheries Commission
ZOPACAS South Atlantic Peace and Cooperation Zone
Common Acronyms
ABMT Area-Based Management Tool
EA Ecosystem Approach
CME Coastal and Marine Environment
ICZM Integrated Coastal Zone Management
OA Ocean Acidification
MCE Marine and Coastal Ecosystem
MOP Meeting of the Parties
QSR Quality Status Report
RAP Regional Action Plan
RAP MALI RAP Marine Litter
RAC Regional Activity Centre
WG Working Group
Youna Lyons - ACOPS, 3 August 2025

Figure 3.1.2 Regional Seas Governance Frameworks and Developments DOI 10.5281/zenodo.16732401~~10.5281/zenodo.16490698~~

~~The work of~~ Mmost regional seas frameworks ~~is organised through~~ operate through regularly revised strategic plans~~, that are regularly revised (e.g~~. such as the Mindelo Plan of Action in the South Atlantic Ocean~~, managing numerous) and are extensive, with dozens of~~ projects ~~handled~~ at varying ~~different~~ scales (Vivero and others, 2023; Boukhari, ب 2019). T~~However,~~ ~~t~~he number ~~and~~ nature and scope of intergovernmental institutions and associated mechanisms ~~and the scope of their~~ work vary (e.g. degrees of delegation ~~of regional analysis~~ to external institutions or consultants; Al Ayachi (2020)). The ~~substantive~~ scope of and level of details in regional regulations and guidelines ~~developed by regional bodies varies also~~ differ, with pollution sources and biodiversity being the most frequent topics~~common subject~~ of specific regional binding instruments (Figure 3.1.2). Sectoral agreements and arrangements established by regional grouping complement these efforts (e.g. binding and non-binding management and conservation measures adopted by~~standard setting by~~ regional fisheries bodies ~~under the FAO or~~, CCAMLR MPAs~~, compliance and enforcement mechanisms under the Paris Memorandum of Understanding through port state control~~). The protection of marine biodiversity, threatened species and habitats has been a focus since the late 1990s (e.g. SPREP Strategic plan 2017-2024; OSPAR Northeast Atlantic Strategy 2030) while renewed scrutiny on MPAs and ABMTs, including OECM, is very clear (e.g. Medium Term Mediterranean Action Plan Strategy 2022-2027; Ross Sea Southern Ocean in Antarctica: Brooks, 2021).

Over the past~~In the last~~ five years, ~~common features of important~~ key developments~~development~~ have ~~included a~~ focused on marine plastic litter, biodiversity protection, assessment status and monitoring, including through the development of indicators (e.g. COBSEA, HELCOM and OSPAR Marine Litter Action Plan). Such developments can occur through the adoption of policy guidance and other non-binding documents (e.g. action plans) as well as the adoption of new binding instruments, amendments to existing instruments or a binding decision of the governing bodies if the regional regime allows (e.g. OSPAR Regional Action Plan for Marine Birds).

1.3 Interplay between institutions and processes

The multiplicityation of institutions and instruments at different governanceglobal, regional and sub-regional levels is a challenges to the adoption and implementation of consistent and complementary responses to marine environmental challengissues (e.g. Blasiak and Claudet, 2024 and Langlet and Vadrot, 2023 in the context of BBNJ; Fanning and Mahon, 2020). The multiplicity of mandates can also raise coordination difficulties, including in the presence of gaps between mandates. Examples include the management of cumulative adverse effects from activities managed under different sectoral regimes and adequate response to cross-cutting issues such as pollution from marine plastics, climate change and ocean acidification (Kim, 2012; Trevisanut and others, 2020; WOA III S5A.C10, S5B.C5 and S4.C6.sub5).

Political objectives frameworks such as Sustainable Development Goal 14 (UNGA 2015) and the 2022 Kunming-Montreal Global Biodiversity Frameworks set objectives and provide specific targets and tools for marine environmental protection, helping to drive and assess progress despitein the protection of the marine environment overall, irrespective of the institutional and legal fragmentation (CBD COP 16 L.30, 2024; SOI, 2014). A number of other mechanisms and processes that facilitate interplay and interactions between institutions and regimes, as well as the adoption of complementary norms, can fortunately be observed (Figure 3.1.3). In addition to procedural (formal and informal) interactions between sub-regimes, systemic integration approaches provide several substantive interaction mechanisms, from within the ocean regime complex as well as from outside (Maljean-Dubois, 2022; e.g. WOA III S4.C6.sub1). These processes and substantive developments support and enhance overall coherence and synergies in ocean governance through their transversal operation.

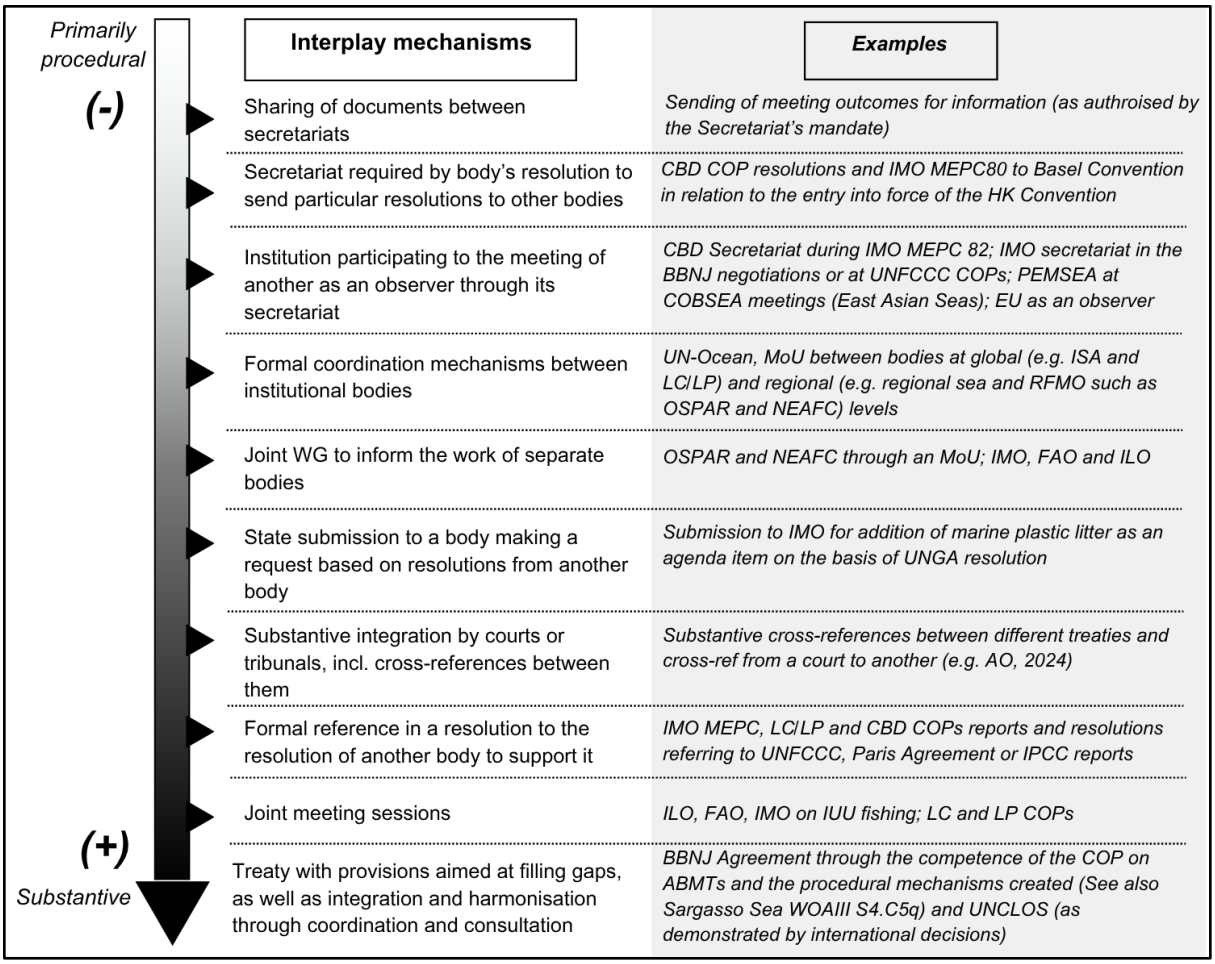


Figure 3.1.3 Ocean Governance Legal and Institutional Interplay Mechanisms

2. Transversal concepts, principles and means of implementation that underpin ocean governance

Ocean governance concepts, principles and means of implementation (hereafter concepts and approaches) have developed over time in different institutions of the ocean governance regime (sometimes in parallel), progressively penetrating the overall ocean governance regime complex~~.~~

. Despite persisting uncertainties on their contours, legal nature and practical application (Figure 3.2.1.), they are widely acknowledged to be framing and shaping ocean governance, including through influencing negotiations, and interpretation of international and regional instruments and mechanisms, as well as the development of national law and policy.

Some were expressly formulated at global level in UNCLOS. Many others developed later in various texts such as declarations and guidelines that contribute to the implementation of UNCLOS (e.g. Rio Declaration, 1992; CBD, 1992; FAO Code of Conduct for Responsible Fisheries, 1995; LP, 1996; VanderZwaag, 2019; Forteau, 2019; Zhang, 2021).~~To highlight theire significant overlap, articulation and/or circulation of key ocean governance concepts, principles, approaches and their means of implementation, this analysis adopts a management cycle perspective, focusing on policy and activity developments over the past five years and three overlapping and interconnected drivers of marine environmental protection (figure 3.2.1).~~ Parallel narratives, shaped in part by non-state actors, can also play a central~~fundamental~~ role in these processes, particularly in relation to the sustainable blue economy (Bennet and others, 2019; Germond-Duret and others, 2022), ocean health, blue justice (Bennet and others, 2021; Barros-Platiau and others, 2021; Jentoft and others, 2022), and maritime and food security~~. ((Germond-Duret and others, 2022; Bennet and others, 2019; Bennet and others, 2021; Barros-Platiau and others, 2021; Jentoft and others, 2022;(~~ Bueger and Mallin, 2023; Suárez-de Vivero, 2019; Sun, 2024; WOA III S5A.C1f, S5B.C2 and S5A.C1e). Overall, these concepts and approaches can be of a procedural and/or substantive nature, involve scientific, social and economic sciences as well as operationalise and reinforce an integrated approach

~~Despite persisting uncertainties on the contours, legal nature and practical application of the such transversal concepts, principles and means of implementations (Figure 3.2.1.), they are widely acknowledged to be framing and shaping ocean governance, including through influencing negotiations, and interpretation of international agreements as well as the development of national law and policy. They can be of a procedural and/or substantive nature, involve scientific, social and economic sciences as well as operationalise and reinforce an integrated approach.~~ To highlight their significant overlap, articulation and/or circulation, this overview adopts a management cycle perspective, focusing on policy and activity developments over the past five years and three overlapping and interconnected drivers of marine environmental protection, presented in the three sections below and illustrated in figure 3.2.1. This figure is not intended as an exhaustive representation of ocean governance.

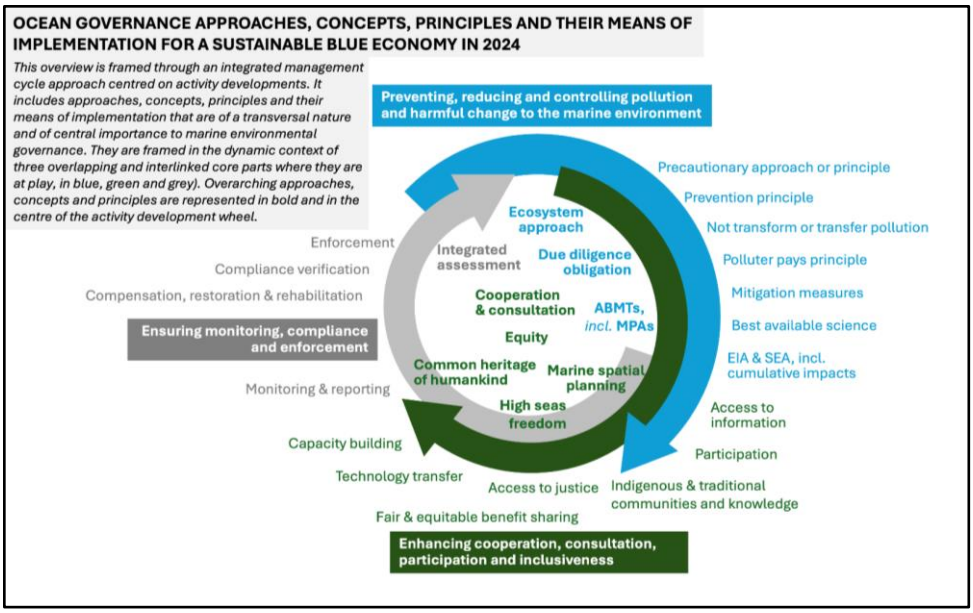


Figure 3.2.1- Ocean governance approaches, concepts, principles and their means of implementation for a sustainable blue economy in 2024

2.1 Preventing, reducing and controlling pollution and harmful change to the marine environment

~~**Most principles** and approaches relied on in the context of marine environmental governance were formulated at global level in UNCLOS, and developed in various texts such as dDeclarations and gGuidelines (e.g. Rio Declaration, 1992 and FAO Code of Conduct for Responsible Fisheries, 1995) and in the 1992 treaties adopted in 1992 and subsequently (e.g. CBD, 1992; LP, 1996) as well as subsequent ones. Many that are not expressly included in UNCLOS nevertheless contribute to the implementation of its provisions (VanderZwaag, 2019; Forteau, 2019; Zhang, 2021).~~

Implementation of the prevention, reduction and control of pollution of and harmful change to the marine environment (UNCLOS Part XII) brings into play several ocean governance concepts and approaches. The ***ecosystem approach*** is such a central approach included in a number of legal instruments since its inclusion in CCAMLR, 1982 and subsequent endorsement by the UNGA in 2002 (Moynihan Magsig, 2022; De Lucia, 2019; BBNJ, Art. 7 (f)). It has evolved as an umbrella concept (Figure 3.2.1) that articulates an integrated approach to ecosystem characteristics (e.g. scales and dynamics) and different sectors of activity (Long at al, 2015; Curtin and Prellezo, 2010; WOA III S5A.C1b) towards sustainable seas

(ITLOS, 2024). Stand-alone approaches, concepts and principles that are also embedded in the ecosystem approach have been extensively used in support of global policy and regulatory developments of the last five years. Examples include the ***precautionary principle/approach*** (Rio Declaration, Art. 15; UNFCCC, Art.3; BBNJ Agreement, Art. 7(e); UN Fish Stocks Agreement, Art. 6; LP, Art.3.1), the ***prevention principle*** (UNCLOS e.g. Art.194; Duvic-Paoli, 2018), the obligation to ***not transform or transfer pollution*** (UNCLOS Art. 195; BBNJ Agreement, Art. 7(l)); and, ***mitigation measures*** that are taken to prevent, reduce or control ~~prevent~~ harm to the marine environment and ecosystems (Vanderklift and others, 2022; see also e.g. WOA III S4.C4c, S4.C4g, S5A.C3a) from all sources, including climate change (Biermann and others, 2022).

Applicable across all branches of international law, the ***due diligence*** obligation (French and Stephen, 2014; Besson, 2023) has also had its content consolidated by decisions of several international tribunals until very recently and in a range of contexts: deep seabed mining beyond national jurisdiction (ITLOS, 2011), illegal, unreported, and unregulated (IUU) fishing (ITLOS, 2015), climate change impacts (ITLOS, 2024), the aquatic environment (ICJ, 2010) and the marine environment in general (PCA, 2016). Both customary (ICJ, 2010; Maljean-Dubois, 2021) and treaty-based (UNCLOS, 1982), the due diligence standard is recognised to vary with the risks involved (e.g. depending on the sensitivity of an ecosystem or the risks from the activity being undertaken; e.g. ITLOS, 2024) and to include, among other attributes, the use of ***best available science*** and the fulfilment of ***environmental impact assessments*** (EIAs). The need for best available science is commonly referred to by ocean governance instruments and institutions (e.g. UNCLOS, Part XIII; OSPAR NEAES; Polejack, 2021; WOA III S5A.C7, 7.4.2, 7.5) and enabled by scientific bodies established by treaty bodies such as the BBNJ Scientific and Technical Body (BBNJ Agreement, Art.49). The obligation to undertake EIAs to inform decision making has long been a procedural obligation under customary international law (ICJ, 2010; Craik, 2007; ITLOS, 2024; BBNJ, Art.7(i)) in addition to a direct obligation under UNCLOS (UNCLOS, Art.204), with other treaties providing particular substantive conditions in particular areas or sectors (e.g. Madrid Protocol, art. 10; CCAMLR, Art. IX; London Convention, 1972: Annex II, Madrid Protocol; BBNJ, Part IV; Doelle and Gunnar, 2020; WOA III S5A.C7, 7.4.1) and in ABNJ (including ***cumulative impacts***, BBNJ Agreement Art.1(6)).

Global policy targets on protected areas (SDG 14.5 and GBF Section H, Target 3) have pushed global policy and regulatory developments ~~of a third category of overarching ocean governance concepts that are central to the protection of the marine environment:~~ for all

area-based management tools (ABMTs) broadly, including ***marine protected areas*** (MPAs) (BBNJ, Part III). Amidst a call for tighter regulations in order to effectively protect their marine environment (e.g. Grorud-Colvert and others, 2021; Claudet and others, 2024; Pike and others, 2024), regional seas organisations and mechanisms continue adopting new instruments. The prospect of entry into force of the BBNJ Agreement is expected to further support this move whether through stimulating action of existing sectoral bodies or through the future adoption of new ABMTs by the bodies to be established (Kim, 2024; see also ISA study, 2024).

2.2 *Enhance* Cooperation, consultation, participation and inclusiveness

The foundational principles of ocean governance, including ***common heritage of humankind*** (formerly mankind), ***high seas freedoms***, ***cooperation and consultation*** among States have been further elaborated and reinforced in the context of ~~through~~ the development of more recent and interlinked marine environmental governance processes such as ***marine spatial planning (MSP)***, ***EIAs***, Strategic Environmental Assessments (SEAs), ***ABMTs***, ***participation and inclusiveness*** (figure 3.2.1).

The status of **the common heritage of humankind** relates to the seabed, ocean floor and the subsoil in ABNJ, as well as the associated resources, (UNGA 1970, UNCLOS Art.136 and 137; BBNJ Agreement Art.7 (b); WOA III S5A.C7, 7.6). It is characterised by five essential attributes: non-appropriation (UNCLOS, Art. 89), peaceful use (UNCLOS, Art. 88), rational exploitation of resources (UNCLOS, 150 (b); international management, and equitable distribution of benefits (Kiss, 1983; Oliveira and others, 2025; UNGA 1970; WOA III S5A.C7, 7.7.1). Some of these attributes, such as peaceful use and rational exploitation of resources, are also applicable to **high seas freedoms** (UNCLOS, Art.87; BBNJ Agreement Art.7(c)).

~~The status of **common heritage of humankind** relates to the seabed, ocean floor and the subsoil in ABNJ, as well as the associated resources, (UNGA 1970, UNCLOS Art.136 and 137; BBNJ Agreement Art. 7 (c); WOA III S5A.C7, 7.6) is characterised by five essential attributes that are also applicable to **high seas freedoms** (UNCLOS, Art. 87; BBNJ Agreement Art.7(c)): non-appropriation (UNCLOS, Art. 89), peaceful use (UNCLOS, Art. 88), rational exploitation of resources (UNCLOS, 150 (b); international management, and equitable distribution of benefits (Kiss, 1983; Oliveira and others, 2025; UNGA 1970; WOA III S5A.C7,, 7.7.1).~~ The principle of ***equity*** has evolved under differentiated treatment (UNCLOS, Art. 202-203, BBNJ Agreement, Art.7(d); WOA III S5B.C6 and S5B.C5) balanced by different provisions such as

capacity-building and technology transfer (UNCLOS, Part XIV; BBNJ Agreement, Part V; Vierros and Harden-Davies, 2020). In this context, ***fair and equitable sharing of benefit*** marks a normative clarification for marine genetic resources in ABNJ that can be traced back to developments under the CBD and the International Plant Treaty and the Nagoya Protocol (Morgera, 2024; Batista, 2024; Blasiak, 2018; WOA III S5A.C5, iii). Another significant development is the explicit inclusion of local, traditional and/or customary rights and knowledge of ***Indigenous Peoples***, as well as traditional and local communities who are knowledge holders on the ocean and coastal environments (BBNJ Agreement, Art.7(j)) into e.g. scientific information (Harden-Davies and Gjerde, 2019; IPBES, 2022). Consultation of ~~I~~indigenous P~~p~~eoples and traditional knowledge has been progressively embedded in a number of processes (e.g. Inuit Circumpolar Council becoming an observer to the IMO; see also IPBES, 2024; Golo and others, 2022; Rivers and others 2023; Strand and others, 2022; Niner and others, 2024; WOA III S5A.C9, 5).

Cooperation is required to implement measures of ocean governance and to settle disputes under UNCLOS (UNCLOS e.g. Art.123, 169, 197, 282). It is given particular texture in the context of e.g. transboundary environmental issues (ITLOS, 2001 and 2003), regional seas and due regard (PCA, 2016; Treves, 2019; Forteau, 2019). It is also associated with ***consultation***, including the gathering of input from a wide variety of relevant governance actors (BBNJ Agreement Art.8, 21; Kim, 2024; Craik, 2020). Cooperation and meaningful consultation further support ***access to information, participation and access to justice*** described together as "access rights" (e.g. Escazu Agreement, 2018: Art.2(a)). Recognised in environmental treaty provisions that include transparency obligations (e.g. UNCLOS Art.119(2), Art.4, 5 of the Aarhus Convention; Art.5, 6, 7.1, 8.1, 8.2 Escazu Agreement; Target 21, Global Biodiversity Framework, 2022; Art.32, 48 BBNJ Agreement, 2023; Strand and others, 2022; Sophie Shields and others, 2023), these rights are now generally ~~currently~~ viewed as the precondition to protect (WOA III S5A.C9, 5)and exercise various human rights related to a healthy environment (WOA III S5B.C2 and C3) and the duty to protect, preserve and restore the environment (Morgera, 2024; see also Preamble of the Aarhus Convention).

Cooperation and consultation are also central to ***marine spatial planning*** (MSP). Although other forms of planning exist, MSP is generally a planning tool of reference across international (e.g. UNESCO; IOC, 2021), regional (e.g. EU MSP Directive, OSPAR and HELCOM) and national ocean governance developments (Gerhardinger *et al.*, 2019; Johnson *et al.*, 2020; Stockbridge, Kuempe, 2024) ~~exemplifies the connection between international, regional, and national frameworks, reinforcing the interdependence inherent in ocean governance. National and~~

international processes and instruments must operate in a coordinated and complementary manner to ensure the effective protection of the marine environment. First envisaged to resolve marine and maritime uses conflicts in particular marine areas under national jurisdiction (Ehler and Douvere, 2009), MSP has since evolved (UNESCO-IOC, 2021; UNESCO-IOC, 2024) as a process of integrated approach which can anticipate conservation in ecologically sensitive areas and secure investments for economic development (Douvere, 2008) connecting stakeholders and supporting decision-making for marine use management (WOA III S5A.C1b, S5A.C1c and S5A.C1d), including in transboundary contexts (Gomes-Ballesteros and others, 2021; WOA III S5A.C9, 4).

2.3 *Enhancing* monitoring, compliance and enforcement

Integrated assessments are overarching governance tools to ensure monitoring, compensation, compliance and enforcement provided for in numerous international instruments with a view to ensuring effective protection and preservation of the marine environment (Cicin-Sain *et al.*, 1998). ***Reporting*** (e.g. CBD, Art. 26; London Protocol Art.9) and ***monitoring*** (e.g UNCLOS Art.204; OSPAR, Art.6; London Protocol, Annex 2; Antigua Convention, 2002 Art.3(h); Ramsar, Art.6(2)(e), CBD Art.7) typically focus on periodic measurement of environmental quality indicators or targets at different spatial and temporal scales to detect and document potential changes and impact of human activities (Gill and others, 2020), including with respect to specific sea areas, ecosystems and species. Marine environmental data collection, including traditional knowledge (Kumar and others, 2021) has been improving at global level (e.g. this WOA; UNESCO/IOC, 2024; other reports on specific aspects e.g. marine transport (UNCTAD), fisheries (FAO and RFMOs; WOA III S4.C4d); Rindorf and others, 2017; Stephenson and others, 2017) and nature's contributions to people including ecosystem services (IPBES, 2019), although it remains largely insufficient (e.g. for invasive species WOA III S4.C6.Sub1, liquids, solid and atmospheric inputs from land-based sources WOA III S4.C6.Sub5 and more generally WOA III S4.C2, 3). At regional level, examples of knowledge improvement include quality status reporting under OSPAR in the Northeast Atlantic (OSPAR Convention, Art.6) and the Barcelona Convention in the Mediterranean Sea (Barcelona Convention, Art.12).

Monitoring and reporting also provide useful baselines for marine environmental **compensation and restoration** (ITLOS, 2024; Mendis, 2022)**.** Compensation can provide redress or remediation through financial or material solutions (e.g. habitat restoration) when

environmental damage to people or nature cannot be fully avoided or mitigated and rests on the polluter pays principle. (López-Portillo, and others, 2017). **Restoration and rehabilitation** (ITLOS, 2024; GBF) can involve public and private actors (Ramírez-Monsalve and others, 2021) to return damaged ecosystems to their original state or to support ecosystem recovery and promote resilience from future harmful impacts (Van Tatenhove, 2021; Bayraktarov and others, 2016).

Growing focus on **compliance** (von Stein 2013 as cited in Lutmar & Carniero, 2018) and **enforcement** (Lutmar & Carniero, 2018) encompasses illegal activities (Febrica and Myers, 2024; Warikandwa, 2023) (e.g. FAO, 2021; 2022; Interpol, 2024; Lancaster and Erinosho, 2023; McCarthy and others, 2024; UNODC, 2024; WOA III S5A.C1a). Maritime security challenges can cause devastating environmental damage in addition to human and economic losses (Ho, 2006): e.g. explosion of a supertanker to block key straits or destruction of undersea pipelines releasing toxic substances (Sondakh, 2004; Richardson, 2004). Responses to these threats have included the adoption of standards by intergovernmental organisations such as the World Customs Organization to Secure and Facilitate Global Trade (SAFE Framework), as well as capacity building (e.g. World Customs Organization and Basel, Rotterdam, and Stockholm Conventions Secretariat; UNODC, 2021; 2023).

Conclusion

Over the last five years, substantive areas of concern in the work of relevant intergovernmental institutions have extended beyond traditional marine environmental pressures (e.g. pollution and fisheries), to more recent priorities (e.g. climate change mitigation and adaptation, marine plastics, monitoring and ocean observation) and non-traditional areas such as maritime security, migration by sea, human-rights based approach and food security. Overarching objectives such as a sustainable blue economy, ocean health, and blue justice are playing central roles in ocean governance developments.

The ocean governance overview provided in this section highlights the central role of both natural and social sciences, including the knowledge systems of Iindigenous Ppeoples and

local communities, and the importance of their integration in all stages of the policy cycle at all geographic scales.

References

Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters, 1998.

Abdenur, A. E. and Souza Neto, D. M (2014). Region-Building by Rising Powers: The South Atlantic and Indian Ocean Rims Compared. Journal of the Indian Ocean Region 10 (1): 1–17.

Al Ayachi, N. (2020). Environmental Challenges in the Atlantic Ocean and its Effects on Marine Policies, Casablanca: Dar Ifriqiya Charq. (In Arabic language) التحديات البيئية في المحيط الأطلسي وأثرها على السياسات البحرية.

Antigua Convention, 2002.

Barkin JS, Rashchupkina Y. Public Goods, Common Pool Resources, and International Law. American Journal of International Law. 2017;111(2):376-394. doi:10.1017/ajil.2017.9

Barros-Platiau, A. F., Gonçalves, L., & Oliveira, C. C. de. (2021). *A Década da Ciência Oceânica como oportunidade de justiça azul no Sul Global*. Conjuntura Austral, 12(59), 11–20.

Batista, P. D., *Proposal for a Global Regulation of Digital Sequence Information*, Max Planck Institute for Innovation & Competition Research Paper No. 24-10, 2024, available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4861106

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J. and Lovelock, C.E. (2016), The cost and feasibility of marine coastal restoration. Ecol Appl, 26: 1055-1074.

BBNJ Agreement 2023. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction, New York, 19 June 2023, C.N.203.2023.TREATIES-XXI.10 of regJuly 2023.

Besson, S. Due Diligence in International Law. The Hague Academy Special Editions, 2023.

Bennett, N. J., Cisneros-Montemayor, A. M., Blythe, J., Silver, J. J., Singh, G., Andrews, N., Calò, A., Christie, P., di Franco, A., Finkbeiner, E. M., Gelcich, S., Guidetti, P., Harper, S.,

Hotte, N., Kittinger, J. N., le Billon, P., Lister, J., López de la Lama, R., McKinley, E, Scholtens, J., Solås, A-M., Sowman, M., Talloni-Álvarez, N., Teh, L. C. L., Voyer, M., and Sumaila, U. R.(2019). Towards a sustainable and equitable blue economy. Nature Sustainability, 2(11), 991–993.

Bennett, N.Jl; Blythe, J.; White, C.S.; Campero, C. Blue growth and blue justice: Ten risks and solutions for the ocean economy, Marine Policy, Volume 125, 2021, 104387,

Biermann, F., Oomen, J., Gupta, A., Ali, S. H., Conca, K., Hajer, M. A., Kashwan, P., Kotzé, L. J., Leach, M., Messner, D., Okereke, C., Persson, Å., Potoc ˇ nik, J., Schlosberg, D., Scobie, M., & VanDeveer, S. D. (2022). Solar geoengineering: The case for an international non-use agreement. WIREs Climate Change, 13(3), e754.

Blanchard, C.; Harrould-Kolieb, E; Jones, E. and Taylor, M.L. The current status of deep-sea mining governance at the International Seabed Authority (2023). Marine Policy, 147: 105396.

Blasiak, R. and others. Corporate control and global governance of marine genetic resources. Science Advances**,** [S. l.], v. 4, n. 6, 2018.

Blasiak, R. and Claudet, J. Governance of the High Seas. Annual Review of Environment and Resources, 49, 2024, p. 549-572.

Boukhari, A. (2019). Environmental Governance in the Atlantic Ocean and its Effects on the Marine Resources. Riyadh: Dar Al Kitab Al Akadimi. (In Arabic language) الحوكمة البيئية في المحيط الأطلسي وأثرها على الموارد البحرية

Boyle, A. 'Further Development Of The Law Of The Sea Convention: Mechanisms For Change' (2005) 54 *ICLQ* 563.

Brander, S.M.; Senathirajah, K; Fernandez, M.O.; Weis, J.S.; Kumar, E.; Jahnke, A; Hartmann, N.B.; Alava, J.J.; Farrelly, T; Almroth, B.C.; Groh, K. J.; Syberg, K; Buerkert, J.S.; Abeynayaka, A; Booth, A.M.; Cousin, X.; Herzke, D.; Monclús, L; Morales-Caselles, C; Bonisoli-Alquati, A.; Al-jaibachi, R.; Wagner, M (2024). The time for ambitious action is now: Science-based recommendations for plastic chemicals to inform an effective global plastic treaty,

Science of The Total Environment, Volume 949, 174881.

https://pubmed.ncbi.nlm.nih.gov/39047828/

Brooks, C. M.; Bloom, E.; Kavanagh, A.; Nocito, E.S.; Watters, G.M.; Weller, J. (2021) The Ross Sea, Antarctica: A highly protected MPA in international waters,Marine Policy, Volume 134, 104795.

Bueger, C. and Mallin, Felix. (2023). Blue Paradigms. Understanding the intellectual revolution in global ocean politics. International Affairs, 99(4): 1719–1739, 2023.

Campanella, V. T. (Ed.). Routledge Handbook of Seabed Mining and the Law of the Sea. New York:Routledge Handbooks, 2024.

Campbell, Lisa M., Noella J. Gray, Luke Fairbanks, Jennifer J. Silver, Rebecca L. Gruby, Bradford A. Dubik, and Xavier Basurto. "Global oceans governance: New and emerging issues." Annual review of environment and resources 41, no. 1 (2016): 517-543. Available at: https://www.annualreviews.org/content/journals/10.1146/annurev-environ-102014-021121https://www.annualreviews.org/content/journals/10.1146/annurev-environ-102014-021121

Cicin-Sain, B. & Knecht, R. W. (1998). Integra- ted coastal and ocean management: concepts and practices. Washington: Island Press. ISBN: 1559636041.

Convention on Biological Diversity. *Kunming-Montreal Global Biodiversity Framework*, Montreal, 19 December 2022, CBD/COP/DEC/15/4. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

CBD, Draft decision on Cooperation with other conventions and international organizations. COP 16 L.30, 2024.

CBD, Sustainable Ocean Initiative, Action Plan for the Sustainable Ocean Initiative (2015-2020), 2014.

Convention on the prevention of marine pollution by dumping of wastes and other matters, 29 December 1972, United Nations, *Treaty Series*, vol.146, No. 15749.

Convention on wetlands of international importance especially as waterfowl habitat, 02 February 1972, United Nations, *Treaty Series*.

Convention for the protection of the marine environment of the North-East Atlantic, 22 September 1992, United Nations, *Treaty Series*, vol. 2354, No. 42279.

Claudet, J. and others (2024). Advancing ocean equity at the nexus of development, climate, and conservation policy. Nature Ecology & Evolution, 2024, ff10.1038/s41559-024-02417-5ff. ffhal-04579762f.

Craik, N. (2020). The duty to cooperate in the customary law of environmental impact assessment. International and Comparative Law Quarterly, 69(1), 239-260.

Craik, N. (2007). Deliberation and legitimacy in transnational governance: the case of environmental impact assessments. Victoria University of Wellington Law Review , 38(2), 381-402.

Curtin, Richard, and Raúl Prellezo. "Understanding marine ecosystem based management: a literature review." Marine policy 34, no. 5 (2010): 821-830.

https://doi.org/10.1016/j.marpol.2010.01.003

De Lucia, V., Iavicoli, V. (2019), From the Outer Space to Ocean Depths: "the 'SpacecraftCemetery' and the projection of the Marine Environment in areas Beyond national Jurisdiction", California Western International Law Journal, Vol. 49, No. 2, 20192019 .

Douvere, F. The importance of marine spatial planning in advancing ecosystem-based sea use management. Marine Policy, v. 32, n. 5, 2008. p. 762-771. DOI: https://doi.org/10.1016/j.marpol.2008.03.021.

Duvic-Paoli, L-A. *The Prevention Principle in International Environmental Law*. Cambridge University Press; 2018.

Ehler, C.; Douvere, F. Marine Spatial Planning: A step-by-step approach toward ecosystem-based management. Paris: UNESCO, 2009, 99 p.

Elisabeth M. Borgese, A Constitution for the Oceans: Comments and Suggestions Regarding Part XI of the Informal Composite Negotiating Text, 15 San Diego L. Rev. 371 (1978).

Escazu Regional Agreement on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, 2018.

Fanning, L. and Mahon, R. (2020) Governance of the Global Ocean Commons: Hopelessly Fragmented or Fixable? Available at: https://www.researchgate.net/publication/343919307_Governance_of_the_Global_Ocean_Commons_Hopelessly_Fragmented_or_Fixable

Food and Agriculture Organization of the United Nations (FAO) (2021). International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing, available from https://www.fao.org/fishery/en/publication/jobno/y1224e. Last accessed 30 May 2024.

FAO (2022). A policy and legal diagnostic tool for sustainable small-scale fisheries.

FAO (2023). Report of the Thirty-fifth Session of the Committee on Fisheries, Rome, 5–9 September 2022. FAO Fisheries and Aquaculture Report, No. 1391. Rome. https://doi.org/10.4060/cc3652en

FAO (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome. https://doi.org/10.4060/cd0683en

Febrica, S. and Myers, L. (2024). Policy Paper: US-Indonesia Maritime and Environmental Security Cooperation in the Sulu-Sulawesi Sea, available from. Washington: the Hollings Center. https://www.hollingscenter.org/wp-content/uploads/2024/06/Sulu-Sulawesi-Sea-Report.pdf

Forteau, M. (2019) The legal nature and content of 'due regard' obligations in recent international case law, *The International Journal of Marine and Coastal Law* 34, no. 1 (2019): 25-42.

French, D. and Stephens, T. (2014). International Law Association Study Group on Due Diligence in International Law, First Report, 7 March.

Garcia, Beatriz, Anita Foerster, and Jolene Lin (2021). Net zero for the international shipping sector? An Analysis of the Implementation and Regulatory Challenges of the IMO Strategy on Reduction of GHG Emissions. Journal of Environmental Law 33, no. 1: 85-112.

Gerhardinger, L. C., Quesada-Silva, M., Gonçal- ves, L. R., & Turra, A. (2019). Unveiling the gene- sis of a marine spatial planning arena in Brazil. Ocean and Coastal Management, 179, 104825. https://doi.org/10.1016/j.ocecoaman.2019.104825.

Germond-Duret, C., Heidkamp, C.P. and Morrissey, J. (2022) (In)justice and the blue economy. The Geographical Journal, 00, 184–192. Available from: https://doi.org/10.1111/geoj.12483

Golo, H. K., Ibrahim, S., and Erinosho, B. (2022). Integrating communities' customary laws into marine small-scale fisheries governance in Ghana: Reflections on the FAO Guidelines for Securing Sustainable Small-Scale Fisheries. *Review of European Comparative & International Environmental Law* (RECIEL) 31, 349–359. doi: 10.1111/reel.12478.

Gomes-Ballesteros, M., Cervera - Núñez, C., Campillos-Llanos, M., Quintela, L., Sousa, M., Marques, F.L. Alves, Murciano, C., Alloncle, N., Sala, P., Lloret, A., Simão, A.P., Costa, A.C., Carval , D, Bailly, D. Nys, C., H. Sybill, Dilasser, J. (2021) Transboundary cooperation and mechanisms for Maritime Spatial Planning implementation. SIMNORAT project

https://www.sciencedirect.com/science/article/abs/pii/S0308597X21000440

Grorud-Colvert, Kirsten, Jenna Sullivan-Stack, Callum Roberts, Vanessa Constant, Barbara Horta e Costa, Elizabeth P. Pike, Naomi Kingston and others. "The MPA Guide: A framework to achieve global goals for the ocean." Science 373, no. 6560 (2021): eabf0861.

Harden-Davies, H. R., & Gjerde, K. M. (2019). Building Scientific and Technological Capacity: Role for Benefit-Sharing in the Conservation and Sustainable Use of Marine Biodiversity beyond National Jurisdiction. Ocean Yearbook, 33, 377-400.

Hatje, V., R. L. B. Andrade, C. C. Oliveira, A. Polejack, and T. Gxaba (2021). Pollutants in the South Atlantic Ocean: Sources, Knowledge Gaps and Perspectives for the Decade of Ocean Science. Frontiers in Marine Science 8:644569.

Heike K. Lotze, Marine biodiversity conservation, Current Biology, Volume 31, Issue 19, 2021, Pages R1190-R1195, ISSN 0960-9822, https://doi.org/10.1016/j.cub.2021.06.084.

ICHR, Advisory Opinion OC-23/17 of November 15, 2017. https://www.corteidh.or.cr/docs/opiniones/seriea_23_ing.pdf

ICJ, *Pulp Mills on the River Uruguay (Argentina v. Uruguay),* judgement, 20 April 2010, *ICJ Rep 2010*, p.14.

ILC Report (2024). Chapter X, A/79/10, 75th Session.

Johnson, A.E.; McClintock, W.J.; Burton, O.; Burton, W.; Estep, A.; Mengerink, K.; Porter, R.; Tate, S. (2020).*Marine spatial planning in Barbuda: A social, ecological, geographic, and legal case study. Marine Policy*, Vol. 113.

IMO, Strategy on reduction of GHG emissions from ships. Res MEPC.377(80); IMO: London, 2023. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673

IPBES (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6522522 pp. 541

IPBES (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E., Frantzeskaki, N., Gosnell, H., Gurung, J., Lambertucci, S., Leventon, J., Liao, C., Reyes García, V., Shannon, L., Villasante, S., Wickson, F., Zinngrebe, Y., and Perianin, L. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382230

Interpol. (2024). Pollution crime. Available at: https://www.interpol.int/en/Crimes/Environmental-crime/Pollution-crime

Intergovernmental Oceanographic Commission (2021). *Ocean governance and marine spatial planning*. IOC Policy Brief No. 5, p. 8. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000375723

ITLOS (2024). Request for an Advisory Opinion submitted by the Commission of Small Islands States on Climate Change and International Law, May. 21.

ITLOS (2001).Request for the Prescription of Provisional Measures under Article 290, Paragraph 5, of the United Nations Convention on the Law of the Sea), Ireland v. United Kingdom, Order, Case No. 10, Order 2001/5, Nov. 13.

ITLOS (2003). Land Reclamation in and around the Straits of Johor (Malaysia v. Singapore), Order of 10 September 2003, ITLOS Reports 2003

ITLOS (2011). Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area. Advisory opinion of the Seabed Disputes Chamber of the International Tribunal for the Law of the Sea, February 1..

ITLOS (2015). Request for an advisory opinion submitted by the Sub-Regional Fisheries Commission (SRFC), Advisory Opinion of April 2 .

ISA (2024). A review of the contribution of ISA to the objectives of the 2023 Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdictions. https://www.isa.org.jm/wp-content/uploads/2024/06/The_contribution_of_ISA_to_the_BBNJ_objectives.pdf

IUCN (1995). The Law of the Sea: Priorities and Responsibilities in Implementing the Convention. Part I. L.A. Kimball. United Nations Convention on the Law of the Sea: A Framework for Marine Conservation. Part II. D.M. Johnston, P.M. Saunders & P. Payayo. Conservation and Management of the Marine Environment. A Marine Conservation and Development Report. IUCN, Gland, Switzerland. vi + 155 pp.

https://portals.iucn.org/library/sites/library/files/documents/MRN-015.pdf

Jentoft, S.; Chuenpagdee, R; Said, A.B; Isaacs, M (2022). Blue Justice: Small-Scale Fisheries in a Sustainable Ocean Economy. Volume 26, MARE Publication Series, Ed. Springer Nature.

Kim, R.E(2024). The Likely Impact of the BBNJ Agreement on the Architecture of Ocean Governance. Marine Policy, 165: 106190.

Kim, R.E (2012). Is a New Multilateral Environmental Agreement on Ocean Acidification Necessary?. Review of European Community and International Environmental Law, 21: 243-258.

Kim, R.E. (2024). The likely impact of the BBNJ Agreement on the architecture of ocean governance. Marine Policy, 165, p.106190.

Kiss, A.C. (1983). La notion de patrimoine commun de l'humanité. Académie de droit international, 175, 103 e s3.

Klein, N. (2014) Maritime Space. In Handbook of Governance and Security, ed. James Sperling Cheltenham: Edward Elgar, p. 388-407.

Koh, T.B., 'A Constitution for the Oceans' (1983). Final Act of the Third United Nations Conference on the Law of the Sea. Introductory Material on the Convention and the Conference. New York, United Nations, xxxiii–xxxvii.

Koh, T.T.B. (1983). A Constitution for the Oceans' remarks adapted from statements made by the President on 6 and 11 December 1982 at the final session of the Conference at Montego Bay reproduced in The Law of the Sea. *Official Text of the United Nations Convention on the Law of the Sea with Annexes an Index. Final Act of the Third United Nations Conference on the Law of the Sea. Introductory Material on the Convention and the Conference* (United Nations, New York) xxxiii–xxxvii.

Kumar, A., Kumar, S., Komal, Ramchiary, N., & Singh, P. (2021). Role of traditional ethnobotanical knowledge and indigenous communities in achieving sustainable development goals. Sustainability, 13(6), 3062.

Lancaster, A. and Erinosho, B. (2023). Strengthening linkages between SDG 14 & SDG 16: contributing to the development of a legislative guide to combatting pollution crime, and its annex, 14 December.

Langlet, A. , Vadrot, A.B.M. (2023), Not 'undermining' who? Unpacking the emerging BBNJ regime complex. Available at: https://www.sciencedirect.com/science/article/pii/S0308597X22004195

Long, Rachel D., Anthony Charles, and Robert L. Stephenson. (2015) Key principles of marine ecosystem-based management. Marine Policy 57): 53-60.

https://www.sciencedirect.com/science/article/pii/S0308597X1500024X

Lutmar, C. and Carneiro, C.L., (2018). Compliance in International Relations, In: World Politics Online Publication, June 2018. Available at: https://edisciplinas.usp.br/pluginfile.php/4424948/mod_resource/content/1/Lutmar%20and%20Carneiro%202018.pdf

Madrid Protocol.

Mahon, R. and Fanning, L. (2019). Regional ocean governance: Polycentric arrangements and their role in global ocean governance. *Marine Policy*, *107*, 103590.

Maljean-Dubois (2022). Circulations de normes et réseaux d'acteurs dans la gouvernance internationale de l'environnement. Available at: https://books.openedition.org/dice/2585

Mann Borgese, Elisabeth (1975) , A Constitution for the Oceans. In: Borgese, E. M. and Kreiger, D. (eds). The Tides of Change: Peace, Pollution and the Potential of the Oceans, Mason/Charter, 340.

Mangalagiu, D., Baker, E., Fidelman, P., Gonçalves, L.R., Harris, P., Hollway, J., Kim, R.E., and Rice, J. Oceans and Coastal Policy (2019). Chapter 14. In: P. Ekins, J. Gupta, and P. Boileau (Eds): Global Environment Outlook - GEO-6: Healthy Planet, Healthy People. Cambridge University Press, 2019.

Marjo K. Vierros, Harriet Harden-Davies, Capacity building and technology transfer for improving governance of marine areas both beyond and within national jurisdiction, Marine Policy, Volume 122, 2020, 104158.

Mazzega, P. and others, Ocean governance: on the recognition of institutions named in International environmental law, In: Oliveira, C.C. and others, A função do direito na gestão sustentável dos recursos minerais marinhos. Rio de Janeiro, Editora Processo, 2021, p. 77-109.

McCarthy, AH., Steadman, D., Richardson, H., Murphy, J., Benbow, S., Brian, JI., Brooks,H., Costa-Domingo, G., Hazin, C., McOwen, C., Walker, J., Willer,DF., Abdi, M., Auster,PJ., Bealey, R., Bensted-Smith, R., Broadburn, K., Carvalho, G., Collinson, T., Erinosho, B., Fabinyi, M., Febrica, S., Forbi, WN., Garcia, SM., Goad, D., Goldsworthy, L., Govan, H., Heaphy, C., Hiddink, JG., Hosch, G., Kachelriess, D., Kinch, J., Lancaster, AMSN., Le Manach, F., Matthews, T., Ortiz, AM., Morgan, A., Motta, H., Murua, H., Namboothri, N., Ndiritu, E., Passfield, K., Pilcher, NJ., Portus, JO., Rguez-Baron, JM., Robertson, M., Sharma, A., Suazo, CG., Tamini, LL., Vilata-Simón, J., Mukherjee, N. (2024). Destructive Fishing: an expert-driven definition and exploration of this quasi-concept. *Conservation Letters*.

Mendis, Nishara. (2022). Exploring the emerging international concept of the 'duty of ecosystem restoration'. South Asian Journal of Environmental Law and Policy, 1(1), 45-60.

Morgera, E. (2024). Participation of Indigenous Peoples in Decision Making Over Deep-Seabed Mining". American Journal of International Law (AJIL) Unbound. 118:93-97.

Morgera, E., McQuaid, K., La Bianca, G., Niner, H., Shannon, L., Strand, M., Rees, S., Howell, K., Snow, B., Lancaster, A. M. S., & Sauer, W. (2023). Addressing the Ocean-Climate Nexus in the BBNJ Agreement: Strategic Environmental Assessments, Human Rights and Equity in Ocean Science. The International Journal of Marine and Coastal Law, 38(3), 447-479.

Moynihan, M. R. (2022). An Ecosystem Approach in International Environmental Law Relevant to Transboundary Freshwater Ecosystems. Chinese Journal of Environmental Law, 6(2), 125-154.

Naidoo, A. and others (2021). Polycentric Regional Ocean Governance Opportunity in the Benguela Current Convention. Available at:

https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2021.703451/full

Niner, H.J., Wilson, D., Hoareau, K., Strand, M., Whittingham, J., Mcgarry, D., Bolanle, E., Ibrahim, S., Tshiningayamwe, S., Febrica, S., Lancaster, A.M.S.N., Prokic, M.. (2024). Reflections on the Past, Present, and Potential Futures of Knowledge Hierarchies in Ocean Biodiversity Governance Research. Frontiers in Marine Science.

Noumea Convention.

Nyman, E. (2020). Climate Change and Ocean Governance: Politics and Policy for Threatened Seas. Global Environmental Politics, 20 (3): 120–121.

Oliveira, C.C.; Bombaka, H.M.; Barros-Platiau (2025). The principle of Common Heritage of Humankind as a bridge between deep seabed mining and biodiversity conservation. In: Liu, N. and Scott, S.V. (eds). The Law of the Sea and the Planetary Crisis, Routledge, London.

Oral, N. (2023). A 50-year reflection on global ocean governance for protection of the marine environment. In: Borg, S; Attard, F. G.; Fremeaux, Vella, P. M. . Research Handbooks in Environmental Law series, Handbook on Ocean Governance Law,, Northampton : Edward Elgar Publishing; 2023, pp. 10-23.

Oral, N. (2015), 'Forty Years of the UNEP Regional Seas Programme: from past to future' in Rosemary Rayfuse (ed) Research Handbook on International Marine Environmental Law (Edward Elgar 2015) 339.

Pike, E. , Maccarthy ,J. Hameed, S., Harasta, N., Grorud-Colvert, K., Sullivan-Stack, J.,Claudet, J., Horta E Costa, B., Gonçalves, E., Villagomez, E. , Morgan, L., (2024), Ocean Protection Quality is Lagging Behind Quality: Applying a Scientific Framework to Assess Real Marine Protected Area, Available at: https://hal.science/hal-04588181/

Permanent Court of Arbitration (PCA) (2016), The South China Sea Arbitration, The Republic of Philippines v. The People's Republic of China. (The Chinese government neither accepts nor recognizes so-called award on South China Sea arbitration. See http://english.scio.gov.cn/pressroom/2023-07/13/content_92131216.htm

Polejack, A., Gruber, S. & Wisz, M.S. (2021). Atlantic Ocean science diplomacy in action: the pole-to-pole All Atlantic Ocean Research Alliance. Humanities and Social Sciences Communications, 8:52, https://doi.org/10.1057/s41599-021-00729-6. - https://www.nature.com/articles/s41599-021-00729-6)

1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 16 November 1996, *International Legal Materials*, 1997, vol. 36, 1.

Rayfuse, R., Jaeckel, A., & Klein, N. (2023). International Marine Environmental Law in the 21st Century. In R. Rayfuse, A. Jaeckel, & N. Klein (Eds.), Research Handbook on International Marine Environmental Law. Edward Elgar Publishing. (pp. 2-32)

Rindorf and others, 2017. Moving beyond the MSY concept to reflect multidimensional fisheries management objectives. Marine Policy, 85, 33–41.

Rio Declaration on Environment and Development, Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3-14 June 1992, A/CONF.151/26 (Vol.1).

Rivers, N., Strand, M., Fernandes, M., Denning, M., Lemahieu, A., Nonyane, C.L., Benkenstein, A., Snow, B. (2023). Pathways to integrate Indigenous and local knowledge in ocean governance process: lessons from the Algoa Bay Project, South Africa. Frontiers in Marine Science.

Scheiber H.N and Paik J-H (2013), Regions, Institutions, and Law of the Sea: Studies in Ocean Governance, Brill.

Shields, S., Longo, A., Strand, M., & Morgera, E. (2023). Children's Human Right to Be Heard at the Ocean-climate Nexus. The International Journal of Marine and Coastal Law, 38(3): 545-580.

Stephenson and others, (2017). Food for Thought Practical steps toward integrating economic, social and institutional elements in fisheries policy and management. ICES Journal of Marine Science, 74(7), 1981–1989. doi:10.1093/icesjms/fsx057

https://academic.oup.com/icesjms/article/74/7/1981/3787887

Stephenson, R. L., Paul, S., Pastoors, M. A., Kraan, M., Holm, P., Wiber, M., ... & Benson, A. (2016) Integrating fishers' knowledge research in science and management. *ICES Journal of Marine Science*, *73*(6), 1459-1465.

Stockbridge, J.; Kuempe, C.D. (2024). *Marine spatial planning for a blue economy in Australia*. The Blue Economy Cooperative Research Centre. Available at: https://blueeconomycrc.com.au/wp-content/uploads/2024/07/BECRC_MSP_Milestone-Report-1_A4_e050724.pdf

Strand, M., Morgera, E., Ntona, M., Kenny, A., Sauer, W., Gaebel, C., Lavelle, J and Snow, B. (2022). Advancing participation in the conservation & sustainable use of marine biodiversity of areas beyond national jurisdiction (BBNJ) https://oneoceanhub.org/wp-content/uploads/2022/08/Policy-brief_7_R1_BBNJ-_OOH.pdf.

Strand, M., Rivers, N., Snow, B. (2022). Reimagining Ocean Stewardship: Arts-Based Methods to 'Hear' and 'See' Indigenous and Local Knowledge in Ocean Management. *Frontiers in Marine Science*

Suárez-de Vivero, J.L.; Mateos J.C.R.; Corral, D.F.; Barragán, M.J.; Calado, H.; Kjellevold, M.; Miasik, E.J (2019).Food security and maritime security: A new challenge for the European Union's ocean policy,Marine Policy, Volume 108, 103640.

Sun, L., Zhang, W., Hu, Z. and others (2024). Food security under global economic policy uncertainty: fresh insights from the ocean transportation of food. Marit Econ Logist 26, 414–435).

Tanaka, Y. (2023). The International Law of the Sea (4th ed.). Cambridge: Cambridge University Press.

Tanaka, Y. (2023b). Basic Principles of International Marine Environmental Law. In:. Rayfuse, R; Jaeckel, A. & Klein, N., (Eds.), Research Handbook on International Marine Environmental Law. Edward Elgar Publishing, pp. 81-103.

Taylor Prue, 'The Common Heritage of Mankind: Expanding the Oceanic Circle' in Dirk Werle and others (eds), *The Future of Ocean Governance and Capacity Development: Essays in Honor of Elisabeth Mann Borgese (1918-2002)* (Brill Nijhoff, Leiden, 2019), 142–150.

Treves, T (2019). Due Regard Obligations under the 1982 UN Convention on the Law of the Sea: The Laying of Cables and Activities in the Area. International Journal of Marine and Coastal Law, Vol. 34, Issue 2, pp. 167-194.

Trevisanut, S., Giannopoulos, N., & Roland Holst, R. (2020). Regime Interaction in Ocean Governance: Problems, Theories and Methods. Brill. https://doi.org/https://doi.org/10.1163/9789004422100

UNGA Resolution, 2749, (UNGA, 1970).

UN Fish Stock Agreement (1995).

UN Office on Drugs and Crime (UNODC). (2023). United Nations Convention against Transnational Organized Crime and the Protocols Thereto, https://www.unodc.org/unodc/en/organized-crime/intro/UNTOC.html

UNCLOS (1982) United Nations Convention on the Law of the Sea, adopted 10 December 1982, entered into force 16 November 1994, 1833 UNTS 397.

UNDESA (2021). Assessment of the impacts of the United Nations Ocean Conference Voluntary Commitments, Sustainable Development Goal 14. Available at: https://sdgs.un.org/sites/default/files/2022-01/DESA-Oceans-VCs.pdf

UNDODC. (2024). Legislative Guide on Combating Crimes in the Fisheries Sector. Available at: https://www.unodc.org/unodc/en/organized-crime/news/2024/official-launch-of-the-legislative-guide-on-combating-crimes-in-the-fisheries-sector-during-the-9th-our-ocean-conference.html;

UNEP (nd). Global Programme of Action for the Protection of the Marine Environment from Land-based Activity (GPA), Available at: https://sdgs.un.org/partnerships/global-programme-action-protection-marine-environment-land-based-activity-gpa

UNEP Regional Seas, Milestones of UNEP's Regional Seas Programme (2024)

https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme

UNESCO-IOC/European Commission (2021). MSP global International Guide on Marine/Maritime Spatial Planning. Paris, UNESCO. (IOC Manuals and Guides nº 89). Available at: https://unesdoc.unesco.org/ark:/48223/pf0000379196.

UNESCO/IOC. State of the Ocean Report, 2024.

UNFCCC., 9 May 1992, United Nations, *Treaty Series*, vol.1771, p. 107.

UNGA 2019-2024, United Nations General Assembly, Resolutions on Oceans and the Law of the Sea

UNGA, *Resolution 2749 (XXV) on Declaration of Principles Governing the Sea-bed and the Ocean Floor, and the Subsoil thereof, beyond the Limits of National Jurisdiction*, UN Doc A/RES/2749(XXV), 16th December 1970 ('*Resolution 2749*').

UNODC (2023). UNODC Guide on Pollution Crime and its Annex: Aphrodite Smagadi, UNEP, https://www.youtube.com/watch?v=yH4tl8k5JwA

UNODC. (2024). Fisheries crime, https://www.unodc.org/documents/about unodc/Campaigns/Fisheries/focus_sheet_PRINT.pdf

UNODC. (2024). Legislative Guide for the United Nations Convention against Transnational Organized Crime and the Protocols theretohttps://www.unodc.org/unodc/en/treaties/CTOC/legislative-guide.html

Van Tatenhove, J.P.M., Ramírez-Monsalve, P., Carballo-Cárdenas, E., Papadopoulou, N., Smith, C.J., Alferink, L., Ounanian, K. and Long, R. (2021). The governance of marine restoration: insights from three cases in two European seas. Restor Ecol, 29: e13288.

Vanderklift MA, H. D, Lovelock CE, Murdiyarso D, Raw J.L. and Steven A.D.L. (2022). A Guide to International Climate Mitigation Policy and Finance Frameworks Relevant to the Protection and Restoration of Blue Carbon Ecosystems. Front. Mar. Sci. 9:872064.

VanderZwaag, D. (2002). The precautionary principle and marine environmental protection: slippery shores, rough seas, and rising normative tides. Ocean Development & International Law, 33(2), pp.165-188.

VanderZwaag, D.L. (2019). Edging towards principled ocean governance: law of the sea and beyond. In The Future of Ocean Governance and Capacity Development (pp. 117-127), Brill Nijhoff.

Vince, J. and others (2017). Ocean governance in the South Pacific region: Progress and plans for action. Marine Policy.

Vivero, J. L. S., E. V. Marroni, J. C. Rodríguez Mateos, E. de Lima Figueiredo, and A. Rocha Violante (2023). Chapter 11. South 'Atlanticism'." In: Marine Spatial Planning in the Tropical Atlantic, edited by M. Bonnin and S. Lanco Bertrand. Marseille: IRD Éditions.

Warikandwa, T. V. (2023). Fighting fisheries crimes in the fisheries industry: Practical training reflections of the efficacy of Namibia's fisheries law enforcement. Cogent Social Sciences, 9(2).

World Trade Organisation. Agreement on Fisheries Subsidies, Geneva, 17 June 2022, WT/MIN(22)/33? WT/L/1144, https://docs.wto.org/dol2fe/Pages/SS/directdoc.aspx?filename=q:/WT/MIN22/33.pdf&Open=True.

Zhang, H. (2021). The Development of International Law of the Sea by International Courts and Tribunals: A Case Study of Due Diligence Obligation. The Korean Journal of International and Comparative Law 9, no. 1: 132-152.

Section 4: Change since the second World Ocean Assessment (introduction)

Sections 4 and 5 of WOA III specifically focuses on providing details of the changes that have occurred in the ocean since the WOA II, i.e. over a period between 2018 and 2023 and directly relate to chapters in WOA II. All relevant information (wherever relevant) is described with respect to different geographical ocean regions, which is a new aspect of the WOA III.

Section 4 includes: Chapter 1 (Drivers) of Section 4 , which covers the sameprovides an updated list of drivers fromas WOA II-. to allow for consistency across assessments and direct comparison between assessments, ; Chapter 2 (Scientific understanding), that focuses on the improvements and advancements in ocean science and technology, as well as broadly understoodincluding diverse human-ocean interactions/relationships. .; Chapters 3 (Trends in the physical and chemical state of the ocean), 4 (Biodiversity) and 5 (Habitats) provides an updates on changes in the physical and chemical state of the ocean since WOA II, .; In Chapter 4 a subchapter on cephalopods has been incorporated and in Chapter 5 a subchapter on 'Fjord Systems' has also been added. Further, the WOA II subchapter 'Open Ocean' has been replaced by the subchapter 'Pelagic Domain', which also includes shelf areas. while Chapter 4 (Biodiversity), and Chapter 5 (Habitats) updates the changes in the abundance, distribution and functional role of the marine taxa groups across the period 2018-2024. ; Chapter 5 (Habitats) XX; Chapter 6 (Pressures), provides an update cross-cutting analysis onon changes in pressures (e.g. erosion and sedimentation, cumulative effects) not covered explicitly in the chapters contained in section 5..

The section 4 chapters relate to chapters 4, 3, 5 6, 7 (chapters 1 to 5, respectively) and 13, 14, 22 and 25 (chapter 6) of WOA II.

Section 5 (Socio-ecological systems) of WOA III provides an integrated view of the social and ecological systems (coupled human-environment systems) of the ocean and the interactions between them. Therefore, the section describes the pressures that human activities are placing on the ocean, the social and economic conditions, including the demographic, institutional, and technological factors associated with these systems and the data, tools and information, including management approaches available for progressing sustainable pathways for human activities in the ocean.

Section 5 consists of two subsections, A) Sustainable and inclusive ocean economy (10 chapters), which tackles issues related to Pressures, Sustainability Pathways, Social Components and Sector relevant governance while subsection B) One Health (8 chapters), with issues regarding the role of ecosystems in the carbon cycle, widely understood health and well-being issues, equity and gender as well as ITLK.

All information (wherever relevant) is described with respect to different geographical ocean regions, which is a new aspect of the WOA III.

Section 4

Chapter 1: Drivers

Michael Elliott

Angel Borja

Bruce Glavovic

Razieh Ghayoumi

Thomas Maes

Thomas Therriault

(Summary and Keynote points have been removed)

(NB ~~the ref.~~The reference websites ~~are to become~~should be converted into footnotes~~; the~~, and chapter cross~~-~~referencing ~~is to~~should be added~~).~~)

1. Introduction

The adverse effects of human activities in the marine environment require ~~conceptually~~a conceptual understanding a cause-consequence-response framework based on knowing the basic human needs ~~from~~provided by the environment, the activities required to satisfy those needs and the pressures (the mechanisms of change) emanating from those activities (Elliott and Kennish, 2024). This encompasses both the natural and human realms and frameworks, i.e. the Socio-Ecological-Environmental~~-~~ System to better understand how changes manifest (Bograd and others, 2019; Smith and others, 2025). The prevention and mitigation of actual or potential adverse changes then require effective governance and management.

Marine-based human activity sectors include: physical restructuring of catchments, coastlines and the seabed; extraction of non-living and living resources; energy production ~~of energy~~; cultivation of living resources; transport, ~~urban~~urbanisation and industrial uses; tourism and leisure, and security and defence. ~~A tenth~~An additional sector of nature conservation~~/~~, protection and restoration may be ~~added~~included (ref. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/qsr2023-reference/)

Drivers are regarded widely (e.g. IPBES, IPCC, EEA, Regional Seas Conventions, etc.) as any natural or human-induced factor that directly or indirectly ~~changing~~changes the ecosystem (Millennium Ecosystem Assessment, 2003; Haines-Young and Potschin, 2018; IPBES, 2024; Elliott and Kennish 2024; Balvanera and others, 2019, 2020; Diaz and others, 2018; Hill and others, 2021; European Environment Agency, 2005; Blanco and others, 2014). Here, the human drivers having the greatest influence on the marine environment and its sustainability are:

(a) Population growth and demographic changes, the demand for resources (e.g. food, space, energy~~, etc.););~~;

(b) Economic activity, ~~e.g.~~as both the cause of, and reasons for, many of the activities leading to the pressures on the natural and social systems;

(c) Technological advances, as activities which may ~~be~~create both beneficial and adverse consequences;

(d) Changing governance structures and social, economic and geopolitical instability: these are both the responses as management measures but also the results of a demand for resources;

(e) Climate change, biodiversity loss and pollution~~:~~ resulting from the activities and effects of an increasing population and its demands for goods and benefits, and their production ~~and~~, transport and ability to fulfil ~~the~~ basic human needs (e.g. food, security, employment, recreation, etc.). The resulting pressures include the increase in atmospheric greenhouse gases, and contamination leading to pollution as an adverse effect on all levels of biological organisation. ~~This driver~~These drivers are also ~~includes~~influenced by demographic changes through climate migrants.

2. Drivers of change in the marine environment

2.1. Population growth and demographic changes

Although the global human population increased from 7 billion in 2011 to 8.2 billion in late 2024,[3] the growth rate has decreased, from 2.1 per cent in 1968 to 0.87 per cent in 2024~~.~~ ~~Global~~ but the global population is projected to reach 9.7 billion by 2050. The decrease in the growth rate results from a decreasing birth-rate, especially in the Global North, with lower mortality rates and increased life-span resulting from improved health. This is accompanied by an increasing average age of the global population (ref. https://www.worldometers.info/demographics/world-demographics/)

An estimated 37 per cent of the global population, i.e. 3.03 billion, lives within 100km of the coast, twice the overall average population density (Cosby et al., 2024). Around 11 per cent, approx. 900 million people, live on land that is less than 10 m above sea level, i.e. the low-elevation coastal zone (LECZ) (Barbier, 2015) and this is projected to rise to >1 billion by 2050.

This increasing urbanisation and industrialisation, including exploitation, is one of the most important trends at the coastal area. It also increases pressure on river catchments given the increased use of resources (water, food, physical resources, space), increased transport and energy use. These lead to the need to remove waste or to an uncontrolled discharge of waste (see Sections Chapter xx and xx).

2.2. Economic activity

Economic growth, as gross domestic product (GDP) per capita, has steadily increased globally (with very high geographical variability) although manufacturing has decreased and services have increased in specific areas (ref. See https://ourworldindata.org/economic-growth). Growth has slowed as a result of a declining trade volume, especially with global

shocks such as the COVID-19 pandemic and other, often ~~smaller~~ more localised shocks (e.g. the Icelandic volcano cloud, blockages in the Suez Canal, the war in Ukraine ~~war, etc.).~~). Global Economic growth was 2.9 per cent in 2019 but then reduced greatly to -3.4 per cent with the pandemic in 2020, then recovered to 5.8 per cent in 2021 and then approximately 3.3 per cent in 2022-2024. When averaged globally there is very high geographical variability~~)~~ (ref. https://www.statista.com/statistics/1102889/covid-19-forecasted-global-real-gdp-growth/).

Given that 41-45 per cent of global economic activities are concentrated at the coast (Patterson and Glavovic 2013), the increased coastal urbanisation and industrialisation has increased the demand for societal goods and benefits including energy and other resources, as well as changes in tourism and recreation. This in turn has increased the use of natural resources through extraction, production, consumption and waste generation. This may be termed the increasing industrialisation of the seas.

Total energy demand, as measured in million tons of oil equivalent (Mtoe), grew from 13,267 Mtoe in 2014 to 13,978 Mtoe in 2018 (ref. See https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html). Global energy consumption accelerated in 2023 (+2.2 per cent), faster than its average growth rate (+1.5 per cent/year) from 2010 to 2019 (ref https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html). At the same time, primary energy intensity, indicating energy use by the global economy, declined to 0.8 per cent in 2021 from an average 1.8 per cent in the previous decade (Ref. https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity).

The reduction in the GDP generated per unit energy used is the result of several short-term factors, such as the reduction in fossil fuel-based electricity generation together with an increase in less energy-intensive industries. Many countries have reduced fossil fuel use, especially the closure of coal-fired power plants, compared to renewable energies which have increased~~, with improved~~. Improved technologies ~~increasing~~have increased marine-based renewables, especially offshore wind power although other marine energy technologies (e.g. wave and current turbines) are at the prototype stage with their use increasing. In 2023, the global operational capacity for marine renewable energy (MRE) reached 527 megawatts (MW) while the cumulative capacity for emerging ocean technologies was 67.8 MW, with 41.4 MW for tidal-stream energy and 26.4 MW for wave energy (ref. https://www.oceanenergy-europe.eu/wp-content/uploads/2023/03/Ocean-Energy-Key-Trends-and-Statistics-2022.pdf) (see Chapters xx and xx). Mature marine energy generation technologies, in 2023, gave 8.8 GW of new installations bringing the total global offshore wind power capacity to 64.3 GW~~, showing year-on-year~~; this showed an annual growth of 16 per cent ~~and~~, representing 7 per cent of global energy production (ref. https://www.gwec.net).

The economic benefits from extracting marine biological resources (fish, shellfish and algae) are increasing with an increasing coastal population. ~~Mariculture~~~~Local scale~~ ~~m~~Mariculture is increasing ~~in local scale~~ and starting to move~~ing~~ offshore to floating cages as well as having inshore and estuarine/fjordic culture. Marine capture fisheries production has remained relatively stable in the last three decades, but the sustainability of fisheries

resources is of concern. The percentage of sustainable fished stocks has decreased to 62.3% in 2021 (https://doi.org/10.4060/cd0683en)~~have apparently decreased annually with 81.48 Mtonnes live weight in 2018, 80.09 in 2019, and 78.79 in 2020 (World Aquaculture Production 1991-2020 (ref. https://www.nature.org/content/dam/tnc/nature/en/documents/Provide-Food-and-Water-2023-Year-in-Review.pdf). The increasing wildHowever, the most recent assessment concludes that these fisheries are stable (SOFIA 20124; ref. https://www.fao.org/publications/home/fao-flagship-publications/the-state-of-world-fisheries-and-aquaculture/en)~~. Wild fishing and mariculture activities have an impact through overfishing, bycatch (the accidental taking of unwanted species and sizes), habitat loss, and transfer of pests and diseases~~, etc.~~ (Haas and others 2020) (see Chapters xx and xxx).

There are continuing demands and increases for nearshore coastal and marine aggregates and minerals extraction ~~together with an exploration potential for deep mineral mining~~; sand and gravel mining is mostly inshore for construction and beach nourishment and from 2012-2019, there was an increase in sand extraction with 4-8 billion tonnes extracted annually (see Chapters xx and xxx) [ref https://www.unep.org/news-and-stories/press-release/unep-marine-sand-watch-reveals-massive-extraction-worlds-oceans~~]; from 2012-2019 there was an increase in sand extraction with 4-8 billion tonnes extracted annually and there are now~~]. In addition, the exploration potential for offshore deep mineral mining has led to proposals for mining deeper resources of ferromanganese crusts, manganese nodules, seafloor sulphides, phosphorites and phosphates, and even marine diamond mining (ref. https://www.usgs.gov/centers/pcmsc/science/global-seabed-mineral-resources).

Marine biotechnology is an emerging global industry for food and feed, cosmetics, aquaculture, agriculture and chemicals, diversifying into industrial enzymes, functional foods, cosmeceuticals, pharmaceuticals, biomaterials, bioprocessing and medical devices. The global market for such products and processes is predicted to reach US$6.4 billion by 2025 (EMB, 2017). The 10 largest companies in 8 core ocean economy industries generate, on average, 45 per cent of each industry total revenues, and the 100 largest corporations account for 60 per cent of total revenues (Virdin and others, 2021).

The COVID-19 pandemic greatly impacted social, economic and environmental ocean aspects. Social lockdowns and travel restrictions decreased tourism and recreation in coastal areas, altering community dynamics that rely on ocean access for leisure and livelihood (UNESCO, 2021; Bennett and others, 2020). Economically, many fishing and tourism dependent industries and communities faced significant losses due to reduced demand and operational challenges, increasing unemployment and financial insecurity (FAO, 2020; IMO, 2020). Environmentally, ~~temporarily~~short-term reduced human activity ~~in the short-term~~ improved water quality, decreased marine pollution and human impacts, and improved biodiversity. However, the long-term consequences of increased discarded plastic waste from medical supplies and single-use items pose new challenges (Zhang and others, 2020; Cozzoloi and others, 2020; Harrison, 2020). While the pandemic highlighted the need for sustainable practices, it emphasised the vulnerability of ocean-dependent communities and ecosystems.

2.3. Technological advances

The growth of sustainable inclusive ocean economies, increasing urbanisation and the increasing industrialisation on land and at sea has been accompanied by marine technological advances each with their own activity-, pressures- and effects-footprints (Elliott and Kennish 2024). For example, fisheries technologies have both increased catches and helped to reduce by-catch. There have been technological advances in monitoring, surveillance and catch reporting, the use of AI and eDNA, in fisheries litter reduction, and in seabed scanning in relation to habitat change and resource extraction (e.g. seabed mining). Improved monitoring and control on fishing, including the use of AIS and VMS, aims to reduce illegal, unregulated and unreported (IUU) fishing (as required by SDG14) (Andriamahefazafy and others, 2022).

On land, urban and industrial energy production and use has changed through technological innovations thereby leading to greenhouse gas reduction. However, such reductions are not uniform across national, regional and global areas.

2.4. Changing governance structures and geopolitical instability

Governance ~~as~~is the framework by which an entity (country, company or organisation) is directed and controlled~~; hence~~. Hence, at a country level it includes the sum of policies, politics (including parliamentary action), public administration and legislation; plans and programmes should then achieve these policies using technical measures (Cormier and others, 2022; Glavovic, 2024). It is broader than, but an integral part of, management by governing the political, economic and societal realms. Marine management then operationalises governance by encompassing public and private realms with government implementing policies leading to laws which then ~~produce~~require rules and regulations (Glavovic, 2024; Elliott and others, 2025). Marine industries, in turn, ~~include~~adopt operational aspects ~~in~~to give economically and societally successful and sustainable businesses. Governance should be vertically integrated, from the local to the global and vice versa, and horizontally integrated across the sectors. In turn, each legal instrument then requires an administrative competent body, usually at national level, for implementation, again resulting in each country having a plethora of often overlapping statutory bodies (ref to chapters on management, governance and MPAs).

~~The global~~Global initiatives are underpinned by regional agreements, notably Regional Seas Conventions (RSC), some of which are promoted by UNEP, and many of which produce regular Quality Status Reports. Regional initiatives are underpinned by national laws and regulations which, despite differing global inequalities, are broadly similar across countries.

2.5. Climate change, Biodiversity Loss and Pollution

Climate both influences and is influenced by oceanic conditions and climate change ~~can be~~is regarded as a suite of exogenic unmanaged pressures in a marine area. While the causes of climate change emanate outside that area, requiring them to be managed globally, the consequences (e.g. increased storminess, erratic weather patterns, acidification) are within that area and so require local management, e.g. adaptation to relative ~~Sea Level Rise~~sea-level rise (see Chapter xx). The recent 2024 IPBES Nexus report [ref.

https://www.ipbes.net/nexus-assessment) emphasises the intertwined nature of biodiversity loss, climate change and public health, food, water and energy, among others. These ~~shape~~influence coastal livelihood and sustainability prospects~~ at the coast~~.

The IPCC special report on the ocean and cryosphere in a changing climate (IPCC, ~~2022; IOC-UNESCO, 2024), shows the~~2019) and the 6th Assessment Report (AR6 ref. https://www.ipcc.ch/assessment-report/ar6/), shows global climate change trends and future projections under different GHG scenarios (the so-called~~ RCP~~ SSP scenarios (See Chapter xx)). Global CO_2 emissions increased from 30.4 $GtCO_2$ in 2010 to 37.55 $GtCO_2$ in 2023. This has decreased polar and altitudinal ice-cover and sea oxygen levels, and increased ocean acidification and extreme events (e.g. coral bleaching, see Chapters xx and xx).

The loss of Arctic sea-ice is opening navigation routes and hence access to previously inaccessible resources as well as providing increased vectors of non-indigenous species (NIS) (see Chapter on non-indigenous species). There will also be an increased demand for resources, such as water for agriculture in increasingly arid areas and the movement of fish stocks polewards. Climate change ~~is~~and its increasing marine pressures are increasing human population migrations, not least from arid interior areas to coastal areas, but also from vulnerable coastal areas~~, thereby increasing marine pressures~~.

Biodiversity loss both reflects and indicates ocean health decline and hence is a driver for associated changes such as a loss of ecosystem services and the resulting societal goods and benefits (UNEP, 2020). It also weakens ecosystem resistance and resilience to threats (e.g. climate change, pollution, NIS input, overfishing), further accelerating ocean health decline (UNEP, 2020).

Contamination and pollution (e.g. plastic waste, agricultural runoff, sewage~~,~~ and ~~chemical contaminants~~chemicals) are major contributors to the decline of ocean health (UNEP, 2021). Nutrient pollution from agricultural runoff and urban and industrial discharges causes eutrophication, resulting in harmful algal blooms that deplete oxygen in the water, cause fish kills and create abiotic 'dead zones' (UNEP, 2016). Plastic pollution creates significant environmental concerns. The ocean water column is a major, transitory sink for microplastics, forming a suspended concentration (Harris and others, 2023). This and the ~~increasing~~increasingly large major ocean floating plastics gyres have led to negotiations on a legally~~ -~~binding treaty to cover the full life-cycle of plastics by 2024 (Maes and others, 2023).

Additionally, plastics and harmful chemicals (e.g. heavy metals and pesticides) are bioaccumulating, disrupting reproduction and growth, and entering the food chain to impact larger organisms, including humans (Maes and others, 2020; Elliott and Kennish, 2024). This degrades critical habitats (e.g. coral reefs and mangroves), reducing biodiversity and essential ecosystem services (e.g. coastal protection and carbon storage) (Halpern et al, 2008; Harris and others, 2021). Furthermore, increased CO_2 emissions have led to ocean acidification, negatively affecting shell-forming organisms and disrupting marine ecosystems. As such, pollution poses a significant threat to ecosystem health, resistance and resilience, requiring effective pollution management and mitigation.

3. Key region-specific issues or aspects associated with drivers

There are geographical variations in all drivers described here especially between the Global North and South but also in economic wealth, population demographics, technological status and susceptibility (e.g. from climate change and geopolitical instability~~).~~ and resulting impacts).

3.1. Population growth and demographic changes

Fertility rates and hence population growth in high-income regions, notably the Global North, continue to be lower than those in middle-income and low-income regions especially in equatorial and Global South areas (Baxter and others, 2017). However, fertility rates coupled with an ageing demographic, even in high income countries, creates challenges although population growth in these countries ~~is countered by~~partly results from economic and climate change migrants (legal and illegal entries). There is high population growth in sub-Saharan Africa, Central and Southern Asia and Eastern and South-Eastern Asia; the average in the least developed countries (see http://unohrlls.org/about-ldcs) was 2.3 per cent over the period 2015–2020, over twice the rate globally. This influenced achieving sustainable development and the conservation of coastal and marine areas, especially in areas vulnerable to climate change, climate variability and ~~Sea Level Rise~~sea-level rise (UNDESA, 2019).

Migration to coastal areas (Ekoh and others, 2023) requires increased adaptation of coastal cities to climate change (Wannewitz and others, 2024). Although globally not uniform ~~globally~~, the increase in the number of global coastal megacities from 25-33 in 2018 to 44-45 in 2023 puts greater populations at the risk of flooding, erosion, subsidence and increased storminess and storm surges.

In 2022, the global Total Fertility Rate (TFR) was 2.3, the same as the global fertility replacement rate for 2010–2015, hence creating the significant milestone where the global fertility rate equals the global replacement rate.

3.2. Economic growth

The 2008 global financial crash and then the 2020-2021 pandemic increased economic challenges and variable abilities of rich and poor countries to withstand such shocks; for example, political instability, the effects of conflicts and/or climate change have adversely affected economic growth. Changes to shipping routes, through opening-up Arctic routes, and accidents or piracy, affect global trade (e.g. diversions from the Suez Canal).

It is notable that, together with ~~the~~ increased economic growth globally, coastal and estuarine urbanisation and industrialisation have increased disproportionally but with inter- and intra-national discrepancies. Increasing wealth in some areas and an increasing middle class, especially in the Global South, increased tourism and recreation with increasing coastal development and infrastructure. In 2024, global international tourism reached 97 per cent of pre-pandemic levels and had increased in some areas (UN Tourism Press Release May 2024). Similarly, agricultural changes and deforestation produced demographic changes.

3.3. Technological advances

Marine technological advances, especially in Areas Beyond National Jurisdictions (ABNJ), expand sustainable inclusive ocean economies and exploitation ~~including~~of marine resources. This includes increased aquaculture and renewable energy extraction moving offshore and proposed deep sea mineral mining. ~~International~~Effective international governance, such as through the International Seabed Authority and UNCLOS ~~are~~, is required to enhance national cooperation and address international transboundary issues especially to obtain societal goods and benefits while at the same time protecting marine ecological structure and functioning. Technology transfer is needed between the most and least developed countries and regions to ensure sustainable development and exploitation of marine resources. This also includes increased monitoring of activity environmental pressures and impacts and the conservation of nature protection areas as actual or *de facto* MPAs (see Chapter xxx).

Recent technological developments occur for controlling ~~Sea Level Rise~~the consequences of sea-level rise, with increasing estuarine barriers and hard defences, nature-based solutions, habitat creation and set back ~~but~~of defences. However, the continued loss of mangroves and other protective vegetation reduces coastal protection from both sea-level rise and increasing storminess and storm surges. Where sea defence costs outweigh the value of assets being protected then communities are being encouraged to move back from the coast; however, a lack of financial capability in less-developed, low-lying areas (e.g. the Sundarbans, India and Bangladesh), prevents such adjustment.

Fisheries extraction technological improvements reduce bycatch, and improved aquaculture technologies allow movement of mariculture and windfarms offshore; ~~moving~~a move from fixed to floating cages and turbines and underwater current turbines allow exploitation of deeper waters, i.e. increased marine industrialisation. Ocean carbon capture and storage technologies as well as CDR (CO_2 removal) are being trialled (GESAMP, 2019, 2025) as are hydrogen storage technologies for energy created by renewable sources.

The offshore oil and gas industry is undergoing a major transformation as fields are exhausted or deemed unnecessary. Injection techniques extract remaining oil and gas but the major transition is through decommissioning including decisions whether to remove, leave or topple the rigs and jackets in place, and leave or remove pipelines and cables. For example, oil and gas producing areas in the Gulf of Mexico, the North Sea and SE Asia are considering 'rigs to reefs' programmes (with advantages and disadvantages to local biodiversity) and investing in decommissioning technologies.

3.4. Changing governance structures and geopolitical instability

With increasing neoliberalism, the Democracy Index (ref. https://www.eiu.com/n/campaigns/democracy-index-2020/) indicates that nationalism and protectionism continue to increase with notable politically-motivated real or threatened trade tariffs and agreements. The Index fell from 5.55 in 2014, 5.44 in 2019 to 5.37 in 2020, largely driven by the regional deterioration of conditions in Latin America and sub-Saharan Africa. This is the lowest global score since the first index ~~started~~ in 2006, has significantly

deteriorated and occurred largely, but not solely, through government-imposed restrictions on individual civil liberties worldwide in response to the COVID-19 pandemic.

The 2020 global score decline reflected declines in the average regional scores worldwide, but by especially large decline in the 'authoritarian regime'-dominated regions of Sub-Saharan and North Africa and the Middle East where scores declined by 0.09-0.10 between 2019 and 2020. The average regional scores declined during the lifetime of the Democracy Index: in Western and Eastern Europe both by 0.06, that for Asia and Australasia, the region which has made the most democratic progress, by 0.05, for the Latin American average by 0.04 in 2020, marking the fifth consecutive year of regression for the region, while that for North America fell by only 0.01 (reflecting a bigger decline of 0.04 in the US score but an improvement for Canada). There remain large regional differences: countries in Scandinavia, the far north of North America and the South-West Pacific had the highest indices, while those in sub-Saharan Africa, the Middle East and parts of Asia had the lowest.

These changes impact adopting global, regional and national treaties, agreements and legal instruments thereby affecting economic growth, technological developments and use, and ocean governance and hence the use and users of the marine environment.

The OECD Better Life Index (OECD, 2020) shows societal quality based on 11 topics (housing, income, jobs, community, education, environment, civic engagement, health, life satisfaction, safety and work-life balance) as indicators of the ultimate drivers of basic human needs and improved human health and welfare. Between 2010-2020, and following the 2008 financial collapse, overall longevity, income, employment and life satisfaction have increased~~ and there is greater life satisfaction~~, with fewer in overcrowded households. However, there are large and widened inequalities within and between countries, in resources for future well-being (in economic, natural and social capital) and in health outcomes and environment. Coastal and marine natural, economic and social risks, especially climate change, biodiversity loss and threats to democratic processes, are threatening future well-being.

Legal instruments and agreements (respectively hard and soft law) are increasingly required for areas outside, between and within national waters as well as globally through UNCLOS. As such, horizontal and vertical integration in marine ~~governance~~legal instruments and organisations are increasing with a transfer of expertise especially with an increase in the number and influence of multinational regional seas conventions. These blocs increase the ability to tackle transboundary issues aiming for coherence and equivalence across jurisdictional boundaries (Elliott and others, 2023). Geopolitical instability varies with country, including some of the largest economies and superpowers.

The governance of marine nature conservation and restoration areas varies regionally and geographically. ~~Despite~~There are geographical disparities in their adoption despite the increase in nature conservation designations and other areas of designated importance (Area Based Management Tools (ABMTs~~), including~~). These include Marine Protected Areas (MPAs), ~~Ecologically and/or Biologically Sensitive Areas (EBSA),~~and Other Effective Conservation Measures (OECMs), ~~etc.~~among others,~~)~~ and their expansion beyond territorial waters, ~~there are geographical disparities in their adoption~~ (see Chapter xx). In addition,

Ecologically and Biologically Significant Areas (EBSAs), while not designations in themselves, provide crucial scientific guidance for identifying areas of ecological value and are increasingly de facto designated areas for conservation (e.g. Canada).

3.5. Climate change, Biodiversity and Pollution

The climate change suite of pressures shows considerable geographical variability with many areas warming, ocean acidification and ~~Sea Level Rise~~sea-level rise and biodiversity patterns changing with species migrations, ultimately affecting societies (see Chapters xx and xx). National responses to climate change are shaped by policy priorities, including alignment with international climate agreements such as the Paris Accord and domestic approaches to the energy transition~~are influenced by whether the ruling party or leadership supports or opposes the Paris COP15 Accord and the energy transition~~.

Climate change effects vary geographically~~-~~ and create hotspots defined according to their vulnerability and the rate of change of their climatic conditions (Fan and others, 2021). These include marine and coastal areas, e.g. the Arctic, western Africa, central east coast of South America (Brazil to Uruguay), Antarctica, Indonesia and South-East Asia, the Persian Gulf and the Red Sea, and the eastern China area. These areas appear to be warming more quickly and are exposed to species migrations and other consequences of climate change.

The above hotspots have to cope regionally and nationally with the consequences of climate change whereas the causes have to be addressed globally and by coordinated action. This includes China, US, India, Europe, Russia and ~~the US account~~Brazil which in 2023 accounted for the majority of GHG emissions (~~IPCC 2022~~UNEP 2024).

Coastal areas, deltas and estuaries are especially vulnerable to increasing in marine storminess, storm surges, catchment rainfall changes, marine heatwaves and hurricane frequency. These, coupled with stressors from increasing coastal urbanisation and industrialisation, cause infrastructure destruction; hence, there is the need to focus on natural hazards that become risks when they affect human welfare. For example, the annual numbers of hurricanes in the North Atlantic Ocean were: 2-9 in the 1980s; 3-11 in the 1990s; 3-15 in the 2000s; 2-12 in the 2010s; 7-13 in 2020-2023 (ref. https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=northatlantic).

4. Outlook

Coastal urbanisation and industrialisation and ocean industrialisation, and economic repercussions, are projected to continue increasing in all geographical areas, thereby providing food, shelter, employment, well-being, enjoyment, etc. as well as stressors. Informal settlements will proliferate around many cities in the Global South together with the exposure of low-lying coasts to ~~Sea-Level Rise~~sea-level rise and climate-compounded risk in coming decades and centuries (Barbier, 2015). Those activities each have a footprint on the natural system leading to increasing pressures-footprints and even larger effects-footprints (Elliott and others, 2020). Activities are accompanied by increased technological exploitation of ocean resources, including wind and wave energy, biotechnology resources and minerals; the latter necessary for batteries in electric vehicles.

The suite of climate change pressures, state changes and impacts on human welfare will continue at the present rate even if GHG production decreases ~~(IPCC 2022).~~. Technological advances to increase adaptation to global warming using methods in, below or above the oceans may increase beyond the development stage (GESAMP 2019, 2025). Increasing coastal defences will be required to combat storm surges, flooding and erosion. The effects of climate change will impact the structure and functioning of ecosystems and ultimately the creation and use of societal goods and benefits.

As well as geopolitical instability, national, regional and global demographics will change with economic migration, varying fertility rates and notable aging populations in the Global North and an increasingly youthful population in the Global South~~,~~; these all ~~impacting~~will impact coastal and marine ecosystems and the extraction of marine resources. Governance changes at the local, national, regional and global levels need to be vertically integrated (from the local to the global and vice versa) and horizontally integrated across the main sectors of sustainable inclusive ocean economies. Governance instruments require coordination and funding to deliver marine use sustainably and stressors will require monitoring, modelling and management. Many national administrative and statutory bodies will be increasingly responsible to protect marine areas and species, through several nature conservation designations, including in ABNJ.

The BBNJ Agreement, likely to enter into force at some point, will play a crucial role in governing ABNJ. While UNCLOS primarily upholds the principle of freedom of the high seas, the BBNJ Agreement is designed to ensure the sustainable use and conservation of marine biodiversity in these areas. Its implementation, including capacity-building and transfer of marine technology, and ABMTs are expected to enhance cooperation among stakeholders, reinforcing collective responsibility in addressing challenges in ABNJ.

The sustainable inclusive ocean economies have been minimally estimated at $1.5 trillion per year, projected to double by 2030, with total ocean assets (natural capital) estimated to be $24 trillion (ref https://thecommonwealth.org/bluecharter/sustainable-blue-economy). This will be delivered through existing and new technologies, especially with renewable energy generation replacing fossil fuel extraction; the latter experiencing the economic and environmental challenges of decommissioning. Shipping will be able to exploit new Arctic polar sea-routes (specifically the Northern Sea Route and North-west Passage) due to increased ice-free periods; however, this will expose formerly pristine areas to pollution threats and increase NIS spread. Short-sea transport, and especially inshore ferry routes, may use ~~of~~ alternative fuels (stored energy in batteries).

The marine system and its ecosystem structure, function, services and goods and benefits are subject to local, national, regional and global risks and hazards including shocks. These create, modify and disrupt the drivers, activities and pressures discussed here. Most notably the COVID-19 global pandemic in 2020-2021 had major economic adverse repercussions although some activities were reduced temporarily (e.g. fishing, tourism, maritime transport and supply chains, and manufacturing) resulting in decreased contamination and greenhouse gas emissions (ref. See https://www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter/). However, economies have

mostly recovered and in some sectors (e.g. international travel and tourism), the activity is now back to pre-covid levels. The short, medium and long-term effects of the pandemic on marine ecosystems and the uses and users of the seas have yet to be fully realised.

5. Key remaining knowledge and capacity-building gaps

The drivers, activities and pressures described here interact and although the single effects are well known conceptually and qualitatively, if not quantitatively, the cumulative synergistic and antagonistic effects are poorly understood (Korpinen and others, 2019). Spatially and temporally quantifying activity-, pressures- and effects-footprints is still lacking but needed to quantify the overall human footprint on the marine system.

A holistic, integrated assessment, management and governance system is needed for the sustainable use and protection of the marine environment as a social-ecological system (Elliott and Kennish, 2024; Bograd and others, 2019; Smith and others, 2025). This ensures national, regional and global economies are protected, and the well-being of the growing populations is assured. Hence the importance of delivering the Ecosystem-Based Approach, operationalised by Ecosystem-based Management (EBA/EBM) and the Precautionary Approach. These are supported by adopting fit-for-purpose monitoring systems linked to quantitative indicators; ~~this~~these will indicate what management is required but also whether management has been effective (Elliott and others, 2025) (see Chapter xx). Despite this, EBM is only one of several approaches as governance imperatives (Glavovic, 2024).

The prediction of effects relies on detailed field and laboratory science coupled to modelling, including end-to-end models linking natural functioning and socio-economic outputs. Furthermore, monitoring and management systems should be effective in all regions and areas. This detailed science then needs to inform policy and vice versa. Transferring marine science and management technologies and approaches across geographic areas, and especially from the Global North to the Global South, will have positive outcomes. In particular, such capacity building will create sustainably managed global oceans and seas.

Crucial in this wider context is the need to engage with marginalised groups, Indigenous Peoples, gender and other inequities and injustices as these realities drive unjust and unsustainable development. Hence, overcoming the drivers and root causes of unjust and unsustainable coastal and ocean development is not a technical problem but a socio-economic and political challenge.

References

Andriamahefazafy, M., Touron-Gardic, G., March, A., Hosch, G., Palomares, M.L.D., Failler, P., 2022. Sustainable development goal 14: To what degree have we achieved the 2020 targets for our oceans? *Ocean & Coastal Management,* **227**: 106273.

Balvanera, P., and others, 2020. The science-policy interface on ecosystems and people: challenges and opportunities. Ecosystems and People, 16(1) 345–353, https://doi.org/10.1080/26395916.2020.1819426

Balvanera, P., Pfaff, A., Viña, A., García-Frapolli, E., Merino, L., Minang, P. A., Nagabhatla, N., Hussain, S. A., and Sidorovich, A. A., 2019. Chapter 2.1. Status and Trends – Drivers of Change. In: Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (pp. 49-200). Brondízio, E. S., Settele, J., Díaz, S., and Ngo, H. T. (eds). IPBES secretariat, Bonn, Germany. DOI: https://doi.org/10.5281/zenodo.3831881

Barbier, E.B., 2015. Climate change impacts on rural poverty in low-elevation coastal zones. Estuar. Coast. Shelf Sci., 165, A1-A13.

Baxter, D., and others, 2017. Population aging and the global economy: weakening demographic tailwinds reduce economic growth. In *Berkeley Forum on Aging and the Global Economy*. Issue brief No. 1.

Bennett, N.J., and others, 2020. The COVID-19 pandemic and its impacts on coastal and marine tourism: A case study from the Great Barrier Reef. *Tourism Management Perspectives*, 35, 100746.

Blanco, G., and others, 2014. Chapter 5: Drivers, trends and mitigation. In *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5*. Cambridge University Press.

Bograd, S.J., Kang, S., Di Lorenzo, E., Horii, T., Katugin, O.N., King, J.R., Lobanov, V.B., Makino, M., Na, G., Perry, R.I., Qiao, F., Rykaczewski, R.R., Saito, H., Therriault, T.W., Yoo, S., Batchelder, H., 2019. Developing a Social–Ecological–Environmental System Framework to Address Climate Change Impacts in the North Pacific. *Frontiers in Marine Science* 6:333.

Cormier, R., Elliott, M., Borja, Á., 2022. Managing Marine Resources Sustainably – The 'Management Response-Footprint Pyramid' Covering Policy, Plans and Technical Measures. Front. Mar. Sci. 9:869992. https://doi.org/10.3389/fmars.2022.869992

Cosby, A.G., Lebakula, V., Smith, C.N. and others, 2024. Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. *Sci Rep* **14**, 22489. https://doi.org/10.1038/s41598-024-73287-x

Cozzoli, F., and others, 2020. COVID-19 and the Environment: A Global Overview. *Environmental Science and Pollution Research*.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P.W., Van Oudenhoven, A.P.E., Van Der Plaat, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C.A., Hewitt, C.L., Keune, H., Lindley, S., Shirayama, Y., 2018. Assessing nature's contributions to people. Science 359, 270-272. https://doi.org/10.1126/science.aap8826

Ekoh, S.S., Teron, L., Ajibade, I., -2023. Climate change and coastal megacities: Adapting through mobility. Global Environmental Change, 80, 102666. https://doi.org/10.1016/j.gloenvcha.2023.102666

Elliott, M., Borja, A., Cormier, R., 2020. Activity-footprints, pressures-footprints and effects-footprints – walking the pathway to determining and managing human impacts in the sea. Marine Pollution Bulletin, 155: 111201; https://doi.org/10.1016/j.marpolbul.2020.111201.

Elliott, M., Borja, Á., Cormier, R., 2023. Managing marine resources sustainably – ecological, societal and governance connectivity, coherence and equivalence in complex marine transboundary regions. Ocean & Coastal Management, 245: 106875; https://doi.org/10.1016/j.ocecoaman.2023.106875

Elliott, M., Borja, Á., Cormier, R., 2025. Managing marine resources sustainably – But how do we know when marine management has been successful? Ocean & Coastal Management, 265: 107623; https://doi.org/10.1016/j.ocecoaman.2025.107623

Elliott, M., Kennish, M.J., 2024. Chapter 6.1. A Synthesis of Anthropogenic Impacts and Solutions in Estuarine and Coastal Environments. In: Kennish, M.J., Elliott, M., (Eds.) Volume 6, Treatise on Estuarine & Coastal Sciences, 2nd Edition., Elsevier, Amsterdam, pp 1-56. https://doi.org/10.1016/B978-0-323-90798-9.00126-8

EMB (European Marine Board), 2017. Marine Biotechnology. Advancing innovation in Europe's bioeconomy. EMB Policy Brief, n 4. https://www.marineboard.eu/sites/marineboard.eu/files/public/publication/EMB_Policy_Brief_4_Marine_Biotechnology_Web_v12.pdf

European Environment Agency, 2019. *The European Environment — State and Outlook 2020, Knowledge for Transition to a Sustainable Europe*. EEA Report, 9/2005. Copenhagen: European Environment Agency.

Fan, X., Miao, C., Duan, Q., Shen, C., Wu, Y., 2021. Future climate change hotspots under different 21st century warming scenarios. Earth's Future, 9, e2021EF002027. https://doi.org/10.1029/2021EF002027

Food and Agriculture Organization (FAO), 2020. The Impact of COVID-19 on Fisheries and Aquaculture. Rome.

GESAMP, 2019. High level review of a wide range of proposed marine geoengineering techniques. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/ UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.

GESAMP, 2025. The State of the Science for Marine Carbon Dioxide Removal (mCDR) – A Scientific Summary for Policy-Makers. Paris, UNESCO-IOC. (IOC Technical Series, 209) downloaded from https://unesdoc.unesco.org/ark:/48223/pf0000393817

Glavovic, B., 2024. Chapter 7.18. Governance Experiences and Prospects in Estuarine and Coastal Communities. In: Glavovic, B.C., Beaumont, N.J. (Eds.), Volume 7: Management, Governance and Socio-economics, Treatise on Estuarine and Coastal Science (2nd. Ed.), p413-447. Doi: https://doi.org/10.1016/B978-0-323-90798-9.00129-3

Haas, B., and others, 2020. Factors influencing the performance of regional fisheries management organizations. *Marine Policy*, vol. 113.

Haines-Young, R., Potschin, M., 2018. *Common International Classification of Ecosystem Services (CICES) V5.1 Guidance on the Application of the Revised Structure*. www.cices.eu

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., 2008. A Global Map of Human Impact on Marine Ecosystems. *Science*, 319(5865), 948-952. DOI:10.1126/science.1149345

Harris P.T., Westerveld, L., Nyberg, B., Maes, T., Macmillan-Lawler, M., Appelquist, LR., 2021 Exposure of coastal environments to river-sourced plastic pollution. Science of The Total Environment 769: 145222; https://doi.org/10.1016/j.scitotenv.2021.145222

Harris, P.T., Maes, T., Raubenheimer, K., Walsh, J.P., 2023. A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution Peter T. Continental Shelf Research Volume 255, 15 February 2023, 104947; https://doi.org/10.1016/j.csr.2023.104947

Harrison, E., 2020. How COVID-19 has impacted ocean ecosystems. *World Economic Forum*.

Hill, H., Dıaz, S., Pascual, U., Stenseke, M., Molnar, Z., Van Velden, J., 2021. Nature's contributions to people: weaving plural perspectives. One Earth 4, July 23, p910-915, https://doi.org/10.1016/j.oneear.2021.06.009

International Maritime Organization (IMO), 2020. Impact of COVID-19 on the Maritime Industry.

IOC-UNESCO, 2024. State of the Ocean Report. *Paris, IOC-UNESCO. (IOC Technical Series, 190) https://doi.org/10.25607/4wbg-d349.*: 92 pp.

IPBES (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E., Frantzeskaki, N., Gosnell, H., Gurung, J., Lambertucci, S., Leventon, J., Liao, C., Reyes García, V., Shannon, L., Villasante, S., Wickson, F., Zinngrebe, Y., and Perianin, L. (eds.). IPBES secretariat, Bonn, Germany. DOI: https://doi.org/10.5281/zenodo.11382230

IPCC, 2022. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [~~H.-O.~~ Pörtner, ~~D.C.~~H.-O., Roberts, ~~V.~~D.C., Masson-Delmotte, ~~P.~~V., Zhai, ~~M.~~P., Tignor, ~~E.~~M., Poloczanska, ~~K.~~E., Mintenbeck, ~~A.~~K., Alegría, ~~M.~~A., Nicolai, ~~A.~~M., Okem, ~~J.~~A., Petzold, ~~B.~~J., Rama, ~~N.M.~~B., Weyer, N.M., (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp.

Korpinen, S., Klančnik, K., Peterlin, M., Nurmi, M., Laamanen, L., Zupančič, G., Murray, C., Harvey, T., Andersen, J. H., Zenetos, A., Stein, U., Tunesi, L., Abhold, K., Piet, G., Kallenbach, E., Agnesi, S., Bolman, B., Vaughan, D., Reker, J., Royo Gelabert, E., 2019. Multiple pressures

and their combined effects in Europe's seas. *ETC/ICM Technical Report 4/2019: European Topic Centre on Inland, Coastal and Marine waters*: 164 pp.

Maes, T., van Diemen de Jel, J., Vethaak, A.D., Desender, M., Bendall, V.A., van Velzen, M., Leslie, H.A., 2020. You Are What You Eat, Microplastics in Porbeagle Sharks from the North East Atlantic: Method Development and Analysis in Spiral Valve Content and Tissue. Front. Mar. Sci. 7:273. doi: 10.3389/fmars.2020.00273

Maes, T., Wienrich, N., Weiand, L., Cowan, E., 2023. A little less conversation: How existing governance can strengthen the future global plastics treaty. Cambridge Prisms: Plastics, 1, e22, 1–12 https://doi.org/10.1017/plc.2023.22

Millennium Ecosystem Assessment, 2003. *Millennium Ecosystem Assessment: Ecosystems and Human Well-Being: A Framework for Assessment*. Washington, D.C.: Island Press.

OECD, 2020. How's Life? 2020: Measuring Well-being, OECD Publishing, Paris, https://doi.org/10.1787/9870c393-en.

Patterson, M., Glavovic, B., 2013. From frontier economics to an ecological economics of the oceans and coasts. ~~Sustain Sci (2013)~~Sustainable Science 8:11–24 DOI 10.1007/s11625-012-0168-2

Smith, G., Atkins, J.P., Gregory, A., Elliott, M., 2025. The minimum complexity necessary: the value of a simple Social-Ecological systems analysis in holistic marine environmental management. Sustainable Futures, 9: 100476. https://doi.org/10.1016/j.sftr.2025.100476 .

UNDESA, 2019. *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423)*. New York: United Nations.

UNEP, 2021. From Pollution to Solution: A global assessment of marine litter and plastic pollution. United Nations Environment Programme, Nairobi.

UNEP, 2020. The United Nations Environment Programme's (UNEP) Report on Marine and Coastal Biodiversity (2020). New York: United Nations.

UNEP, 2024. Emissions Gap report 2024. New York, United Nations, https://www.unep.org/resources/emissions-gap-report-2024).

UNESCO, 2021. COVID-19 and the Ocean: Impact and Solutions. Paris.

United Nations Environment Programme (UNEP), 2016. Report on Marine Pollution. United Nations Environment Programme, Nairobi.

Virdin, J., Vegh, T., Jouffray, J.-B., Blasiak, R., Mason, S., Österblom, H., Vermeer, D., Wachtmeister, H., Werner, N., 2021. The Ocean 100: Transnational corporations in the ocean economy. *Science Advances,* **7**: eabc8041.

Wannewitz, M., Ajibade, I., Mach, K.J., Magnan, A., Petzold, J., Reckien, D., Ulibarri, N., Agopian, A., Chalastani, V.I., Hawxwell, T., Huynh, L.T.M., Kirchhoff, C.J., Miller, R., Musah-Surugu, J.I., Alverio, G.N., Nielsen, M., Nunbogu, A.M., Pentz, B., Reimuth, A., Scarpa, G., Seeteram, N., Canosa, I.V., Zhou, J., The Global Adaptation Mapping Initiative Team,

Garschagen M., 2024. Progress and gaps in climate change adaptation in coastal cities across the globe. Nature Cities: 1 - 610–619: https://doi.org/10.1038/s44284-024-00106-9

Zhang, Y., and others, 2020. Impacts of COVID-19 on the environment and human health. *Environmental Pollution*, 266, 115158.

Section 4

Chapter 2: Scientific understanding

Writing Team:

Antonio Di Natale (C.A.), Pavanee Annasawmy, Sophie Arnaud-Haond, Michéle Baqués, Jahson Berhane Alemu, Robert Blasiak, Erinosho Bolanle, Nene Bi Tra Boniface, Ian Butler, Ralf Doering Luigi Jovane, Samina Kidwai, Katrin Kleemann, Rob Middag, Colin Moffat, Fabiana da Silva Paula, Bing Qiao, Kedong Yin, Erica Wales, Peng Zhan; Katarina Viik (L.A.), Jörn Schmidt (L.A.)

4.2.1 Keynote points

- The~~re is only one~~ Ocean is a single and complex interconnected system, the planet's "life support system", ~~a complex~~combining biological, physical and chemical ~~system~~processes while interacting~~, interconnected~~ with the atmosphere. It hosts millions of species, many still unknown.
    - Managing human impacts on the Ocean is essential for preserving life on Earth, including humankind. Despite advancements, significant challenges persist, necessitating ongoing improvements to ensure ~~progress, challenges remain, requiring continuous improvements for~~ long-term sustainability.

4.2.2 Introduction

A comprehensive s~~S~~cientific understanding of the Ocean and its complex functioning (IOC-UNESCO, 2020) is ~~fundamental~~ essential for assessing human-induced impacts.

Evidence-based science underpins this effort, integrating disciplines, including marine biology, ecology, ethology, physical and biological oceanography, climatology, geology, marine chemistry, genetics, acoustics, economics, sociology, Ocean literacy, and traditional knowledge.

An integrated muldisciplinary approach ~~helps~~ addresses societal challenges, ~~provides a better~~improves the understanding of oceanic complexities, identifies knowledge gaps, enhances sustainable uses ~~of the Ocean~~, preserves spiritual values and ecosystem

services, and supports Sustainable Development Goal (SDG) 14. Advances from WOA II and WOA III are detailed in each chapter of this assessment.

~~However~~Nonetheless, the Ocean is increasingly threatened by ~~faces increasing threats:~~ acidification, warming (see S4.C3), euthrophication (see S4.C3), plastics pollution (see S4.C6sub5), deep-sea mining (S5A.C7), and anthropogenic noise (S4.C6.sub5.1). Persistent organic pollutants (see S4.C6sub3), heavy metals and radioisotopes (see S4.C6sub6) ~~derived~~ from ~~anthropogenic~~ human activities (see S4.C6s~~ub5~~), along with overfishing and illegal, unreported and unregulated (IUU) fisheries (see S4.C1sub2.3, S5A.C1a and S5B.C5) remain ~~serious~~ critical issues~~problems~~.

A ~~major~~ significant milestone was the ~~2023~~ adoption in 2023 of the Agreement for the Conservation and Sustainable Use of Marine Biological Diversity in Areas beyond National Jurisdiction (BBNJ), following ~~20 years~~two decades of negotiations. This marks significant progress toward better Ocean management.

Improving scientific knowledge is essential for enforcing the BBNJ Agreement and advancing SDG 14.

4.2.3 Advances in data, theories, technology, and models, including enhancing socioeconomic understanding

DOALOS-UNESCO-IOC Symposium in 2023[6] and multidimensional indications (Boero and others, 2019a, b; Qiao, 2024; IOC-UNESCO, 2024) provided useful science-policy discussions, supporting SDGs (particularly SDG 14) enhancements.

Advancements from WOA II to WOA III:

- IPC~~P~~C[7] Report (2023) improve~~d~~s data, forecasts and Ocean understanding.
- Technological improvements boosted knowledge of Ocean health, climate processes, and complex Ocean ecosystem.

[6] https://www.un.org/regularprocess/sites/www.un.org.regularprocess/files/summary_of_discussions_symposium_final_for_circulation.pdf

[7] Intergovernmental Panel on Climate Change (IPPC)

    - Combining in situ data with satellite remote sensing assimilation technology has produced consistent global meteorological dataset since 1958, improving physical oceanography (ECMWF[8], 2024; NOAA[9]) (see also S5A.C6).
    - Drones improve real-time data collection (Fillingham and others, 2023)(see also S4.sC5g, S5A.C2, S5A.sC3B, S5A.C9).
    - Artificial Intelligence (AI) progressively improves prediction capacity, though integrating partial AI models into existing broader numerical models remains challenging (Ebel and others, 2024). Improving data sharing remains essential.
    - Marine microbiomes studies in the most remote areas and assessing ecosystem health is now possible using new sequencing technologies and environmental DNA (Haddock and Choy, 2024)(see also S5A.C5).
    - Ocean warming is evident not only at the surface but also in depths below 2,000 m globally (Cheng and others, 2024; Johnson and Purkey, 2024).
- Improved taxonomical, genetic and ecological studies have expanded knowledge of deep-sea biodiversity. Newly identified species include 33 new Cephalopods, 7,252 invertebrates, and 3,502 fish (see S4.C5, S4.C4b, S4.C4c, and S4.C4d).
- Conservation status improved for, e.g. :
    - Eastern Atlantic bluefin tuna (ICCAT, 2022)
    - The southern bluefin tuna (CCSBT, 2023; ISSF, 2025)
    - Four subpopulations of loggerhead turtles (IUCN, 2023)
    - Mediterranean monk seal (Valsecchi, 2024).
    - ~~Mediterranean monk seal (Valsecchi, 2024).~~
- Improved management tools and initiatives: advancements in Marine Spatial Planning (see S1; S3; efforts to decarbonise shipping (Anonymous, 2023a) and reduce underwater noise and other eco-impacts are progressing (MEPC, 2023; Shuye and Lidong, 2024).
- Socio-economic studies improved for shipping, fisheries, marine aquaculture, oil extraction, coastal activities, and deep-sea mining (Benites and others, 2023; de Matos and others, 2023; Bin Hassan and others, 2024).

Policy and international activities:

- EU Missions: Restore our Ocean and Waters (2020) initiated hundreds of new projects, including the European Digital Twin of the Ocean (DTO), marking a significant step towards sustainable Ocean management (Könnölä and others, 2021). By combining real-time data, AI models, and simulations, DTOs create virtual representations of the ocean that can support better decision-making and ocean governance.
- The United Nations (UNGA, 2024) highlighted the importance of a well-structured marine geospatial information management infrastructure for sustainable Ocean development[10].

[8] European Centre for Medium-Range Weather Forecasts (ECMWF), https://www.ecmwf.int/

[9] National Oceanic and Atmospheric Administration (NOAA). https://www.star.nesdis.noaa.gov/data/star_docs/meetings/2018JPSSAnnual/Thursday/5_0_Garrett_LunctimeBB_DataFusion_v2.pdf

[10] https://www.un.org/Depts/los/doalos_publications/publicationstexts/MarineGeospatialInfoMgmt.pdf

4.2.4 Key region-specific changes

- **Arctic Ocean**
  The Arctic Council monitors climate change impacts, including rising sea level, altered density in the northern Atlantic, and slowing Gulf Stream (Piecuch and Beal, 2023). These changes drive species, including pathogens, to move from the Pacific into the Arctic and the Atlantic. Ice melt has also opened new shipping routes, raising pollution risks with significant environmental, social and economic implications.
- **North Atlantic Ocean, Baltic Sea and North Sea**
  OSPAR (Anonymous, 2023b) updated the status of North-East Atlantic, noting improvements since WOA II, such as decrease in concentrations of persistent organic pollutants. However, concerns remain, including Ocean acidification, noise pollution and declining status of marine birds (see S4.C4g). Climate change is probably the greatest pressure impacting plankton (see S4.C4a) and endangers coastal and benthic habitats. Protection of Sargasso Sea[11] is progressing (Mackey, 2021, Roe and others, 2022).

  The Baltic Sea assessesment (HELCOM, 2023) showed that climate change increases biodiversity loss risks and aggravates the impact of existing pressures.

- **Mediterranean Sea and Black Sea**
  The Mediterranean and the Black Sea host rich biodiversity but face growing pressures. Climate change and shipping drive increasing number of immigrant species (Galanidi and others, 2023), threatening local biodiversity and complicating management efforts. Studies now focus on oceanographic changes and their effects on distribution of fish species (Di Natale, 2024). Ongoing conflicts in the Black Sea hinder assessments.

- **South Atlantic Ocean and Wider Caribbean**
  Recent studies highlight climate change impacts on the Brazil Current, including altered heat transport, upper Oocean salinity shifts, deep Oocean freshening and intensification, and polewards shift of Brazil Current, affecting ecosystems changes (Franco and others, 2020; Chidichimo and others, 2023).

  Rising Caribbean Sea surface temperature have increased hurricanes frequency and intensity, threatening endangered corals and reefs (Hernández-Delgado and others, 2024) and boosting mass blooms and stranding of pelagic *Sargassum spp.* (Robledo and others, 2021).

[11] Mostly promoted by the Sargasso Sea Commission and various NGOs.

Along the margin, new seafloor morphologies and habitats have been discovered, including carbonate constructions, siliciclastic drifts and multiple submarine canyons systems (Steinmann and others, 2020; Alves and others, 2023; Jovane and others, 2024; Tagliaro and others, 2024). Challenges persist in controlling invasive species, offshore salmon farming and fisheries for shrimps and squids (Seto and others, 2023; de Carvalho-Souza and others, 2024).

Understanding of the Ocean system in the Gulf of Guinea has improved (De Esteban and others, 2023).

- **Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf**

  An anticyclonic gyre in the central Indian Ocean induces downwelling of nutrients, reducing productivity and mesopelagic organisms (Jena and others, 2013; Cherel and others, 2020). The Agulhas Current generates highly productive mesoscale eddies between Madagascar and Africa (Annasawmy and others, 2018; Vianello and others, 2020). The Indonesian Throughflow~~,~~ has been reassessed (Fritz and others, 2023).

  International research surveys have improved understanding of pelagic diversity, distribution, migration, trophic and biophysical interactions, and impact of warming temperatures (Ternon and others, 2014; Annasawmy and others, 2020a,b, 2022a,b, 2024a,b, 2025). Indian Ocean warming extends to 750 meters in depth, with deep cooling observed in the subtropics (Wenegrat and others, 2022). Plastic pollution remains an important threat (Woodall and others, 2015; Fürychová and others, 2024).

- **North Pacific Ocean**

  The North Pacific Marine Science Organization improved model approaches, using multidisciplinary components (Lew and others, 2024). ~~Reviewed e~~Ecosystem assessment methods (Hunsicker and others, 2022; Kobari and others, 2022) have been reviewed to enhance tools and capacity building, improving future regional Ocean understanding. Prediction models for large pelagic species have been included to now include long-term predictions under different environmental scenarios (Muhling and Chen, 2020).

  The China Ocean Agenda 21 has implemented the United Nations 2030 Agenda for Sustainable Development, which is promoting marine protection. In 2023, the Marine Environmental Protection Law was improved to integrate land-sea management (Information Office of the State Council, 2024).

- **Tropical (central) Pacific Ocean**

  This area is a major biodiversity hotspot, but also an area strongly affected by climate change.

  Many of the coral reefs in this region face repeated bleaching (i.e. Cook Islands, Great Barrier Reef) (Henley and others, 2024). The vaquita (*Phocoena sinus*), ~~the~~

mosta critically endangered marine speciesporpoise, nears continues to approach extinction in Baja California (Rojas-Bracho and Taylor, 2021;, IWC, 2023).
El Niño and La Niña complicate the understanding of climate change, impacting species distribution, especially tunas. The combined effects have environmental, economic and social impacts. New long-term models (Barrier and others, 2023) aid their management, using updated scientific understanding.
Marine litter and rising sea level are increasingly threaten islands and communities. ASEAN (Anonymous, 20251919) is developing new initiatives to facilitate the incluse use, management and conservation of oceanic resources and cooperation in the marine sector. promotes conservation, resilience, cooperation, capacity building and green shipping.

- **South Pacific Ocean**
  Pollution from many sources, climate change and El Niño are worsening marine environments (Atalah and Sanchez-Jerez, 2020). Concerns remain over regional and high-seas fishery management (FAO, 2024) and increasing deep-sea mining (Schofield, 2018). Plastic pollution and its impact on marine life are increasing (Muñoz-Pérez and others, 2023; Savoca and others, 2021). Oceanographic modelling is improving (e.g. FishMIP.org).
- **Southern Ocean**
  This remote region is difficult to study (Antonello, 2018; Howitt, 2024). Understanding is advancing through active/passive Ocean observation and modeling (Gray, 2024). Ocean circulation, crucial to global processes, and the carbon cycle, are driven by complex interactions of ice, sea level and oceanic processes across wide spatio-temporal scales (Bennetts and others, 2024; Gray 2024; de Souza and Morrison, 2024). Sea ice is a key component of the ecological web in this region (Swadling and others, 2023) (see S4,C5k).

4.2.5 Outlook for scientific understanding of the Ocean

The Due to Ocean's size and complexity, mean that our understanding of its functions and human impacts on the Ocean, although progressing, remains limited. The discovery of 'dark oxygen' in 2024 suggests many more secrets unknown (Sweetman and others, 2024).

Climate change tipping points (e.g. phase change in the Labrador Sea, sub-polar gyre and/or phase change in the Atlantic Meridional Overturning Circulation (AMOC) require further study. Our uUnderstanding of. cCumulative impacts must become will benefit from a mainstream approach, for example, adopting a four-dimensional Ocean approach. The complexity of marine biodiversity, including microbial communities, is much broader and complex than we currently understanood.

Autonomous and biomimetic underwater vehicles, autonomous surface vehicles and uncrewed surface vehicles to gather marine data are revolutionizing high-resolution marine

data collection. Sailing vessels opportunistically collect marine data and water samples during oceanic races in remote areas.

Advanced modelling~~, machine learning~~ and AI are enhancing the scientific understanding of the Ocean. Environmentally driven prediction models for large pelagic fish reveal large-scale oceanic changes (Petrik and others, 2020).

~~A key emerging challenge is underwater noise impacts from fixed and floating offshore wind farms on migratory pelagic species (Hendon and others, 2024).~~

New analytical techniques improve knowledge of nanoplastics distribution, role and pathological effects on marine life and humans (Catarino and others, 2022; Zaki and Aris, 2022; Chaoli and others, 2024).

~~Environmentally driven prediction models for large pelagic fish reveal large-scale oceanic changes (Petrik and others, 2020).~~ Improved seafloor mapping, a flagship programme of the Ocean Decade (~~GEBCO~~Seabed 2030, 2025~~4~~), advances understanding of benthic and deep environments for management and conservation.

A key emerging challenge is underwater noise impacts from fixed and floating offshore wind farms on migratory pelagic species (Hendon and others, 2024).

Gradual warming increases risks for I~~i~~ndigenous Peoples and coastal communities (IPCC, 2023). Cross-disciplinary and trans-disciplinary studies could improve by ~~must~~ expanding them to support informed decisions integrating biological, environmental, social and economic approaches for a sustainable Ocean providing a more holistic approach to SDG 14.

4.2.6 Key remaining knowledge gaps

Despite the Ocean's importance, SDG 14 remains the least funded among all UN SDGs (Conrad and others, 2022), affecting oceanic research. IOC-UNESCO (2024) and this Assessment identifi~~ed~~y key gaps:

- Seafloor mapping remains limited to 27.3~~8~~% (~~GEBCO~~Seabed 2030, 2025~~4~~).

- We understand little of the v~~V~~ulnerability of marine biodiversity, species genetics, microbial communities, particularly in the deep sea, to climate change and emerging economic activities.
- Our understanding of m~~M~~icrobial diversity and its role and function in biogeochemical processes is still very limited.
- Faster ~~C~~climate change impacts on Ocean circulation and cumulative effects on the Ocean-Atmosphere interface and on marine communities and species, including population dynamics.
- Marine and coastal ecosystem-based management can be supported by scaling up collaboration and data collection~~must scale up~~ to address multiple stressors.
- Research output is often under represented from the global south, with reduced capacity building reletive to the global north.
- ~~Climate change effects on marine communities and species, including population dynamics.~~
- Our understanding of p~~P~~ersistent organic pollutants (POPs) and emerging unregulated pollutants, along with cumulative health effects on living species, is still limited.
- Our understanding of u~~U~~nderwater anthropogenic noise impacts on marine species and migrations is very limited.
- Our knowledge of c~~C~~hemical and biological processes of polymetallic seafloor deposits is poor.
- Our understanding of p~~P~~lastics and nanoplastics dynamics in the Ocean and their biological effects is extremely poor.
- Sustainable Ocean Plans require stronger evidence-based decision-making and national o~~o~~ceanic accounting systems.
- Climate resilient ~~o~~oceanic economy projects need better conservation and socio-economic integration for local communities.
- Scaling up climate mitigation, including renewable energy and coastal ecosystem management is essential.
- Marine carbon dioxide removal (mCDR) feasibility, impacts, and policies require urgent study.
- Risk assessment tools for coastal communities and marine industries need development.
- Investment in O~~o~~cean science and digital representation requires new financial models.
- Greater effort is needed to preserve and catalogue I~~i~~ndigenous Peoples', traditional and local knowledges ~~must be preserved and catalogued~~.
- A large unknown proportion of historical scientific information is not yet available digitally and remains inaccessible to those that need the information.
- ~~Past scientific knowledge should be digitized for accessibility~~.
- ~~Advance multidisciplinary Ocean management must expand, integrating climate change, and strengthening~~ Regional Fishery Management Organisations (RFMOs) lack the integration of multidisciplinary Ocean management, and how to address climate change.

4.2.7 Key remaining capacity building gaps

Sectorial gender gaps are decreasing, but persist in some areas (see S5B.C6). Regional capacity gaps remain (Potter and Pearson, 2023). Partnerships and cooperation are transversal tools for improving capacities.

Uniformity in infrastructure distribution needs improvement, including specialised multidisciplinary scientific capacity, remote sensing tools, modern oceanographic instruments, autonomous vessels, research ships, and modern land-based support laboratories. Ocean data would benefit from increased or improved calibration ~~must be calibrationed~~ with in situ~~y~~ measurements. Despite advances in modelling and forecasting, capacity gaps between advanced and developing economies remain significant. AI might help.

Gaps in biodiversity knowledge persist due to declining taxonomic expertise (Boero, 2001; Löbl and others, 2023) and underutilization of international funding (Boero, 2010), limiting marine biodiversity research.

The Ocean Decade (Arbic and others, 2024) identified several capacity gaps in the Ocean science, including: language barriers, underrepresentation of marginalised groups (women, people with special needs, early career professionals, I~~i~~ndigenous P~~p~~eoples, etc.), and limited data accessibility. A more open data-sharing system can reduce capacity gaps. The Decade Coordination Office (DCO) for Ocean Data Sharing (ODS) is a crucial tool for collaboration and improving access to Ocean science data (Anonymous, 2023c).

4.2.8 Emerging issues

- **Recovery of existing scientific knowledge**

  Scientific and cultural Ocean knowledge, gathered over centuries, is scattered across thousands of documents around the world, often unavailable digitally. This knowledge is crucial for understanding marine environment evolution and historical exploitation of Ocean resources (Niner and others, 2024), is often not available digitally. While some organisations (e.g. Google, Digitation Centre of Western Australia, Digital Public Library of America) are making efforts on recovering and publishing this information, ~~National efforts should focus on recovering and publishing annotated references of these studies by research area,~~ ensuring accessibility (see also Kaspar and others, 2015; Di Natale, 2022), there are still large amounts of information that is not accessible. Although limited to information from the most recent decade, improving the Ocean Literacy programme in the Ocean Decade also will assist with this process. ~~The Ocean~~

~~Literacy programme in the Ocean Decade should play a key role in knowledge recovery.~~

- **~~Traditional knowledge of l~~indigenous Peoples' and local coastal communities knowledges**

  Coastal, island, and ~~l~~indigenous Peoples' communities hold ancient cultural knowledge about the Ocean, including marine species, seasonality and natural phenomena (Vierros and others, 2020; Pardie and Campion, 2022; Strand and others, 2022)(seeS5A.C7; S5; S5A; S5B.C2 and particularly S5B.C8). Traditional boat-building techniques and marine gear design stem from ancient experiences of global coastal communities. This precious knowledge risks disappearing if not urgently recovered for future generations and for current management (Kaiser and others, 2019). Ethno-anthropologists are essential in this effort. Preserving this knowledge not only safeguards history but also supports future marine research, providing essential baselines for long-term environmental assessments and policy development.

- **A new paradigm: Ocean Rights**

  The principles of Ocean Rights were presented to the UNGA in 2023, after extensive international discussions. In 2024, the International Tribunal of the Law of the Sea issued an Advisory opinion about the obligation to protect and preserve the marine environment. A legal paradigm shift is needed to ensure the Universal Declaration of Ocean Rights by 2030[12], safeguarding the planet's "life support system". This innovative approach will provide a comprehensive legal framework for the UN bodies and stakeholders, aligning with existing Universal Declarations (Bennett and others, 2024).

4.2.9 References

Alves, Daniel P.V. and others. Oceanographic exchanges between the Southern and Northern Atlantic during the Cenozoic inferred from mixed contourite-turbidite systems in the Brazilian Equatorial Margin. Marine Geology, vol. 456, No. 106975, 2023

Annasawmy, Pavanee, and others. Micronekton diel migration, community composition and trophic position within two biogeochemical provinces of the South West Indian Ocean: Insight from acoustics and stable isotopes. Deep-Sea Research, Part I, Oceanographic Research Papers, vol. 138, pp. 85-97, 2018.

Annasawmy, Pavanee. and others. Micronekton distribution as influenced by mesoscale eddies, Madagascar shelf and shallow seamounts in the south-western Indian Ocean: an acoustic approach. Deep-Sea Research Part II: Topical Studies in Oceanography, vol. 176, 2020a.

[12] https://www.earthlawcenter.org/ocean-rights and https://www.theoceanrace.com/en/ocean-rights

Annasawmy, Pavanee, and others. Stable isotope patterns of micronekton at two shallow seamounts of the south-western Indian Ocean. Deep-Sea Research Part II: Topical Studies in Oceanography, vol. 176, 2020b.

Annasawmy, Pavanee, and others. Mercury concentrations and stable isotope ratios (δ13C and δ15N) in pelagic nekton assemblages of the South-western Indian Ocean. Marine Pollution Bulletin, vol. 174, 113151, 2022a.

Annasawmy, Pavanee, and others. Trace elements and δ15N values in micronekton of the south-western Indian Ocean. Marine Pollution Bulletin, vol. 184, 114053, 2022b.

Annasawmy, Pavanee, and others. Environmental variability shapes trophic and resource partitioning between epipelagic and mesopelagic biomes in oceanic provinces: Implications in a globally changing ocean. Progress in Oceanography, vol. 229, 103339, 2024a.

Annasawmy, Pavanee, and others. Impact of an eddy dipole of the Mozambique channel on mesopelagic organisms, highlighted by multifrequency backscatter classification. PLOS ONE, vol. 19, n. 9, e0309840, 2024b.

Annasawmy, Pavanee, and others. Unraveling major questions in micronekton ecology and their role in the biological carbon pump through integrative approaches and autonomous monitoring. In: Frontiers in Ocean Observing: Marine Protected Areas, Western Boundary Currents, and the Deep Sea. Kappel, Ellen S., and others (eds), Oceanography, vol. 38, suppl. 1, 1-6, 2025 .

Anonymous. ASEAN 2045: our shared future. Outlook on the Indo-Pacific. Final, ASEAN Secretariat, Jakarta: 1-155, 20251~~9~~. https://asean.org/wp-content/uploads/2025/05/ASEAN-2045-Our-Shared-Future.pdf ~~https://asean.org/wp-content/uploads/2021/01/ASEAN-Outlook-on-the-Indo-Pacific_FINAL_22062019.pdf~~

Anonymous. COP26: Clydebank Declaration for Green Shipping Corridors. UK Department of Transport, 2023a https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors

Anonymous. Quality Status Report (QSR). OSPAR, 2023b. https://www.ospar.org/work-areas/cross-cutting-issues/qsr2023

Anonymous. Decade Coordination Office for Ocean data Sharing. IOC-UNESCO, Paris, 2023c. https://oceandatasharing-dco.org/

Antonello, Alessandro. The Southern Ocean, in: Oceanic Histories, David, Armitage, and others, eds., (Cambridge University Press), pp. 296–318, 2018

Arbic, Brian K., and others. Ocean Decade Vision 2030 White Papers – Challenge 9: Skills, Knowledge, Technology, and Participatory Decision-Making for All. UNESCO-IOC, Paris, The Ocean Decade Series, No. 51.9, pp. 1-27, 2024.

Atalah, Javier, and Sanchez-Jerez, Pablo. Global assessment of ecological risks associated with farmed fish escapes. Global Ecology and Conservation, vol. 21, e00842, 2020.

Barrier, Nicholas, and others. Mechanisms underlying the epipelagic ecosystem response to ENSO in the equatorial Pacific ocean. Progress in Oceanography, vol. 213, 103002, pp. 1-16, 2023

Benites, Mariana, and others. 2023. Controls on the chemical composition of ferromanganese crusts from deep-water to the summit of the Rio Grande rise, South Atlantic Ocean. Marine Geology, vol. 462, 107094, 2023.

Bennett, Nathan J., and others. 2024. The human right to a clean, healthy and sustainable ocean. npj Ocean Sustainability, vol. 3, No. 19, 2024.

Bennetts, Luke G., and others. Closing the loops on Southern Ocean dynamics: From the circumpolar current to ice shelvesand from bottom mixing to surface waves. Reviews of Geophysics, vol. 62, No. 3, e2022RG000781, pp. 1-62, 2024.

Bin Hassan, Muhammad, and others. Magnetization of ferromanganese crusts: Geochemical and magnetic insights from Rio Grande Rise and Tropic Seamount, Geochemistry, Geophysics, Geosystems, vol. 25, No. 6, pp. 1-23, e2023GC011210, 2024.

Boero, Ferdinando. Light after dark: The partnership for enhancing expertise in taxonomy. Trends in ecology & evolution, vol. 16, No. 5, p. 266, 2001.

Boero, Ferdinando. The Study of Species in the Era of Biodiversity: A Tale of Stupidity. Diversity, vol. 2, No. 1, pp. 115-126, 2010.

Boero, Ferdinando, and others. The Cells of Ecosystem Functioning: Towards a holistic vision of Marine space. Advances in Marine Biology, vol. 82, pp. 129-153, 2019a.

Boero, Ferdinando, and others. Navigating the Future V: Marine Science for a Sustainable Future. Position Paper 24 of the European Marine Board, Ostend, Belgium, pp. 1-203, 2019b.

Catarino, Ana I., and others. 2022. Micro- and nanoplastics effects in a multiple stressed marine environment. Journal of Hazardous Materials Advances, vol. 7, 100119, 2022.

CCSBT, Report of the Twenty Eight Meeting of the Scientific Committee. Jeju island, Republic of Korea, pp. 1-91, 2023. https://www.ccsbt.org/sites/default/files/userfiles/file/docs_english/meetings/meeting_reports/ccsbt_30/report_of_SC28.pdf

Chaoli, Shi, and others. Emergence of nanoplastics in the aquatic environment and possible impacts on aquatic organisms. Science of The Total Environment, vol. 906, 167404, 2024.

Cheng, Lijing, and others. 2024. New Record Ocean Temperatures and Related Climate Indicators in 2023. Advances in Atmospheric Sciences, . vol. 41, pp. 1068–1082, 2024.

Cherel, Yves, and others. Micronektonic fish species over three seamounts in the southwestern Indian Ocean. Deep Sea Research, Part II: Topical Studies in Oceanography, vol. 176, pp. 104777, 2020.

Chidichimo, Maria Paz, and others. Energetic overturning flows, dynamic interocean exchanges, and ocean warming observed in the South Atlantic. Communication Earth Environ, vol. 4, No. 10, 2023.

Conrad, Jillian, and others. SDG14 Financing Landscape Scan: Tracking Funds to Realize Sustainable Outcomes for the Ocean. White Paper, World Economic Forum, Cologny, Switzerland, pp. 1-26, 2022. https://www3.weforum.org/docs/WEF_Tracking_Investment_in_and_Progress_Toward_SDG14.pdf

de Carvalho-Souza, Gustavo F., and others. How to deal with invasive species that have high economic value?. Biological Conservation, vol. *292*, pp.110548, 2024.

De Esteban, Marcial Cosme, and others. Mapping marine habitats in the Gulf of Guinea: A contribution to the future establishment of Marine Protected Areas in Principe Island. Regional Studies in Marine Science, vol. 57, p. 102742, 2023.

de Matos, Caroline Silva, and others. Chemical-mineralogical characterization of critical elements into ferromanganese crusts. Journal of Materials Research and Technology, vol. 25, pp. 5633-5649, 2023.

de Souza, Gregory F., and Morrison, Adele K. The Southern Ocean hub for nutrients, micronutrients, and their isotopes in the global ocean. Oceanography, vol. 37, No. 2, pp. 46-59, 2024.

Di Natale, Antonio, ed. The Italian Annotated Bibliography on Tuna, Tuna-like and Billfish Species. Springer Nature, Switzerland, pp. XXI + 1-936, 2022.

Di Natale, Antonio. Factors to be taken into account for the albacore fishery in the Mediterranean Sea. Collective Volumes of Scientific Papers, ICCAT, SCRS/2024/068, vol. 81, No. 3, pp. 1-21, 2024.

ECMWF. ECMWF Global Data Monitoring Report. European Centre for Medium-Range Weather Forecasts, November, pp. 1-101, 2024.

Ebel, Patrick, and others. 2024 ESA-ECMWF workshop report: current status, progress and opportunities in machine learning for Earth system observation and prediction. Npj Climate and Atmospheric Science, vol. 7, No. 241, 2024.

FAO 2024. The State of World Fisheries and Aquaculture 2024. Blue Transformation in Action. Rome, FAO. Follesa, M.C., Carbonara, P. (eds.). 2019. Atlas of the maturity stages of Mediterranean fishery resources. Studies and Reviews. General Fisheries Commission for the Mediterranean. No. 99. Rome, FAO. 268 p.

Fillingham, Joe, and others. 2022 NOAA Science Report. National Oceanic and Atmospheric Administration, Silver Spring, Maryland, NOAA Technical Memorandum, NOAA Science Council vol. 5, pp. 1-81, 2023.

Franco, Bárbara C., and others. Subsurface Ocean Warming Hotspots and Potential Impacts on Marine Species: The Southwest South Atlantic Ocean Case Study. Frontiers in Marine Science, vol. 7, 2020.

Fritz, Magdalena, and others, Mayer M., Haimberger L., Winkelbauer S., 2023. Assessment of Indonesian Throughflow transports from ocean reanalyses with mooring-based observations. Ocean Science, vol. 19, No. 4, pp. 1203–1223, 2023.

Fürychová Barbora, and others. Microplastic analysis in abundant deep-seafish families of the Western Indian Ocean. VLIZ Marine Science Day, poster, 2024.

Galanidi, Marika, and others. Validated Inventories of Non-Indigenous Species (NIS) for the Mediterranean Sea as Tools for Regional Policy and Patterns of NIS Spread. Diversity, vol. 15, No. 9, pp. 962, 2023.

~~GEBCO. General Bathymetric Chart of the Ocean. 2024. https://www.gebco.net/.~~

Gray, Alison R. The Four-Dimensional Carbon Cycle of the Southern Ocean. Annnual Review of Marine Science, Vol. 16, pp. 163-190, 2024.

Haddock, Steven H.D., and Choy, Anela C. Life in the Midwater: the Ecology of Deep Pelagic Animals. Annual Review of Marine Science, vol. 17, pp. 383-416, 2024.

HELCOM. State of the Baltic Sea. Third HELCOM holistic assessment 2016-2021. Helsoinki Commission, HELCOM, Helsinki, Finland, Baltic Sea Environment Proceedings n°194, pp. 1-136, 2023.

Hendon, Read, and others. Offshore wind energy development and highly migratory species: ecological, fishery and management implications. SCRS/2024/092, Collective Volumes of Scientific Papers, ICCAT, vol. 81, No. 4, pp. 1-21, 2024.

Henley, Benjamin J., and others. Highest ocean heat in four centuries places Great Barrier Reef in danger. Nature, vol. 632: 320–326, 2024.

Hernández-Delgado, Edwin A., and others. Stronger Hurricanes and Climate Change in the Caribbean Sea: Threats to the Sustainability of Endangered Coral Species. *Sustainability*, vol. *16,* No. 4, pp. 1506, 2024.

Howitt, Rohan. Australasian Histories of Antarctica and the Southern Ocean World. History Compass vol. 22, No. 9, 2024.

Hunsicker, Mary E., and others. Eds. Report of Working Group 36 on Common Ecosystem Reference Points across PICES Member Countries. North Pacific Marine Science Organization, Sidney, BC, Canada, PICES Scientific Report, No. 64, pp. 1-155, 2022.

ICCAT. Report of the 2022 ICCAT Eastern Atlantic and Mediterranean Bluefin tuna stock assessment meeting. International Commission for the Conservation of Atlantic Tunas, Madrid, pp. 1-75, 2022. https://www.iccat.int/Documents/SCRS/DetRep/EBFT_SA_ENG.pdf

Information Office of the State Council. Marine ecological environment protection in China. Information Office of the State Council, The People's Republic of China, July (in Chinese), 2024. http://www.scio.gov.cn/zfbps/zfbps_2279/202407/t20240711_854789.html

International Tribunal for the Law of the Sea. Request for an Advisory Opinion Submitted by the Commission of Small Island States On Climate Change and International Law. Case 31, pp. 1-153, 2024. https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf

IOC-UNESCO. Global Ocean Science Report 2020 – Charting Capacity for Ocean Sustainability. Isensee, Kirsten, ed., UNESCO Publishing. Paris, pp 1-255, 2020.
IOC-UNESCO. Ocean Decade Vision 2030 White Papers. Challenge 1: Understand and beat marine pollution. Challenge 2: Protect and restore ecosystem and biodiversity. Challenge 3: Sustainably nourish the global population. Challenge 4: Develop a sustainable and equitable ocean economy. Challenge 5: Unlock ocean-based solutions to climate change. Challenge 6: Increase community resilience to ocean hazards. Challenge 7: Sustainability expand the Global Ocean Observing System. Challenge 8: Create a digital representation of the ocean. Challenge 9: Skills, knowledge, technology and participatory decisionmaking for all. Challenge 10: Restoring society's relationship with the ocean. UNESDOC Digital Library, 2024. https://unesdoc.unesco.org/search/e6c6ab51-9444-4325-9e72-a39d569b3ed0
IPCC, Intergovernmental Panel on Climate Change. Climate Change 2023. Synthesis Repoort, pp. 1-169, 2023. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf
ISSF, Status of the world fisheries for tuna. Mar. 2025. ISSF Technical Report 2025-01. International Seafood Sustainability Foundation, Pittsburgh, PA, USA, pp. 1-128, 2025. https://www.iss-foundation.org/about-issf/what-we-publish/issf-documents/issf-2025-01-status-of-the-world-fisheries-for-tuna-march-2025/
IUCN. Marine Turtles Red List Assessment. International Union for the Conservation of Nature, IUCN SSC Marine Turtle Specialist Group, 2023. https://www.iucn-mtsg.org/statuses
IWC. Extinction Alert (English lang): serious concern for the vaquita porpoise. IWC Scientific Committee, pp. 1-6, 2023. https://archive.iwc.int/pages/view.php?ref=20358&k=#
Jena, Babula, and others. Observation of oligotrophic gyre variability in the south Indian Ocean: Environmental forcing and biological response. Deep Sea Research, Part I, Oceanographic Research Papers, vol. 80, pp. 1–10, 2013.
Johnson, Gregory C., and Purkey, Sarah G. Refined Estimates of Global Ocean Deep and Abyssal Decadal Warming Trends. Geophisical Research Letters, vol. 51, No. 18, e2024GL111229, 2024.
Jovane, Luigi, and others. Mesophotic Hardground Revealed by Multidisciplinary Cruise on the Brazilian Equatorial Margin. MDPI, Mineral, vol. 14, No. 7, pp. 702, 2024.
Kaiser, Brooks A., and others. The Importance of Connected Ocean Monitoring Knowledge Systems and Communities. Frontiers in Marine Science, Sec. Ocean Observation, vol. 6, 2019.
Kaspar, Frank, and others. L, 2015. Data rescue of national and international meteorological observations at Deutscher Wetterdienst. Advances in Science and Research, vol. 2, No. 1, pp. 57–61, 2015.
Kobari, Toru, and others, Eds., 2022. Report of Working Group 37 on Zooplankton Production Methodologies, Applications and Measurements in PICES Regions. North Pacific Marine Science Organization, Sidney, BC, Canada, PICES Scientific Report. No. 63, pp. 1-164. https://meetings.pices.int/publications/scientific-reports/Report63/Rpt63.pdf

Könnölä, Totti, and others . . Mission Area: healthy Oceans, Seas, and Coastal and Inland Waters. Foresight on Demand Brief in Support of the Horizon Europe Mission Board. European Commission, Directorate General for Research and Innovation, Bruxelles, pp. 1-137, 2021.

Lew, Daniel K., and others, Eds. Report of Working Group 41 on Marine Ecosystem Services in the North Pacific. North Pacific Marine Science Organization, Sidney, BC, Canada, PICES Scientific Report No. 65, pp. 1-247, 2024. https://meetings.pices.int/publications/scientific-reports/Rpt65.pdf

Löbl, Ivan, and others. The Silent Extinction of Species and Taxonomists—An Appeal to Science Policymakers and Legislators. Diversity, vol. 15, No. 10, pp. 1053 (2023).

Mackey, Teresa. Saving the Sargasso Sea: the golden floating rainforest of the Atlantic. Sargasso Sea Commission, 2021. https://missionblue.org/2021/03/saving-the-sargasso-sea-the-golden-floating-rainforest-of-the-atlantic/

MEPC. Marine Environment Protection Committee (MEPC 80). International Maritime Organisation (IMO), 2023. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-80.aspx

Muhling, Barbara, and Chen, Siquing, Eds. Report of Working Group 34 on Ocean Conditions and the Distribution and Productivity of Highly Migratory Fish. North Pacific Marine Science Organization, Sidney, BC, Canada, PICES Scientific Report No. 61, pp. 1-29, 2020. https://meetings.pices.int/publications/scientific-reports/Report61/Rpt61.pdf

Muñoz-Pérez, Juan Pablo, and others. Galápagos and the plastic problem. Frontiers in Sustainability, No. 4, pp. 1091516, 2023.

Niner, Holly J., and others. Reflections on the past, present, and potential futures of knowledge hierarchies in ocean biodiversity governance research. Frontiers in Marine Science, vol. 11, 2024.

Pardie, Pamela Pardakie, and Campion, Benjamin Betey. The how in fishing and fish processing: traditional artisanal fishing and fish processing practices among the Ga people of Ghana. Maritime Studies, vol. 21, pp. 501–517, 2022.

Petrik, Colleen M., and others. Large Pelagic Fish Are Most Sensitive to Climate Change Despite Pelagification of Ocean Food Webs. Front. Mar. Sci., Sec. Global Change and the Future Ocean, vol. 7, pp. 588482, 2020.

Piecuch, Christopher G., and Beal, Lisa M. Robust Weakening of the Gulf Stream During the Past Four Decades Observed in the Florida Straits, Geophysical Research Letters, vol. 50, No. 18, e2023GL105170, 2023.

Potter, Ross W.K., and Pearson, Brodie C. Assessing the global ocean science community: understanding international collaboration, concerns and the current state of ocean basin research. Ocean Sustainability, npj, vol. 2, No. 1, pp. 1-12, 2023.

Qiao, Bing. The Four Dimensional Connotation Definition of Scientific Understanding of the Ocean and Human Practical Achievements. International Journal of Geosciences, vol. 15, pp. 557-566, 2024.

Robledo, Daniel, and others. Challenges and opportunities in relation to Sargassum events along the Caribbean Sea. Frontiers in Marine Science, Sec. Marine Ecosystem Ecology, vol. 8, pp. 699664, 2021.
Roe, Howard S.J., and others. The Sargasso Sea High Seas EBSA After Ten Years: Is It Still Relevant and How Has It Helped Conservation Efforts? Frontiers in Marine Science, Sec. Marine Affairs and Policy, vol. 9, 2022.
Rojas-Bracho, Lorenzo, and Taylor, Barbara. Vaquita. IUCN-SSC Cetacean Specialists Group. 2021. https://iucn-csg.org/vaquita/
Savoca, Matthew S., and others. Plastic ingestion by marine fish is widespread and increasing. Global Change Biology, vol. 27, No. 10., pp. 2188-2199, 2021.
Schofield, Clive. Chapter 7 Exploring the Deep Frontier: Deep Sea Mining Opportunities and Challenges in the Pacific. In: Global Commons and the Law of the Sea. Leiden, The Netherlands: Brill | Nijhoff. 2018.
Seabed 2030. Nippon Foundation-GEBCO Seabed 2030 Project. https://seabed2030.org/2025/06/21/seabed-2030-announces-millions-of-square-kilometers-of-new-seafloor-data-on-world-hydrography-day/ , 2025
Seto, Katherine L., and others. Fishing through the cracks: the unregulated nature of global squid fisheries. Science Advances, vol. 9, n. 10, 2023.
Shuye, Xue, and Lidong, He. The latest decarbonization trends at the United Nations Climate Change Conference and their implications for China's shipping industry [J]. World Shipping, 2024, vol. 47, No. 02, pp. 21-26, 2024. (in Chinese).
Steinmann, Lena, and others. Discovery of a giant cold-water coral mound province along the northern Argentine margin and its link to the regional Contourite Depositional System and oceanographic setting. Marine Geology, vol. 427, pp. 106223, 2020.
Strand, Mia, and others. Reimagining Ocean Stewardship: Arts-Based Methods to 'Hear' and 'See' Indigenous and Local Knowledge in Ocean Management. Frontiers in Marine Science, vol. 9, 2022.
Swadling, Kerrie M., and others. Biological responses to change in Antarctic sea ice habitats. Frontiers in Ecology and Evolution, Sec. Conservation and Restoration Ecology, vol. 10, pp. 1073823, 2023.
Sweetman, Andrew K., and others. Evidence of dark oxygen production at the abyssal seafloor. Nature Geoscience., vol. 17, pp. 737–739, 2024.
Tagliaro, Gabriel. CORE-VTRCC Cruise Report: Geophysical Acquisition and Seafloor Sampling along the Vitória-Trindade Ridge. Scientific Data, vol. 11, No. 1056, 2024.
Ternon, Jean-Francoise, and others. The Mozambique Channel: from physics to upper trophic levels. Deep Sea Research, Part II: Topical Studies in Oceanography, vol. 100, pp. 1-9, 2014.
United Nations General Assembly (UNGA). Preparatory process of the 2025 United Nations Conference to Support the Implementation of Sustainable Development Goal 14: Conserve and sustainability use of the oceans, seas and marine resources for sustainable development. Note by the Secretary General. UNGA, A/78/880, 2024. https://digitallibrary.un.org/record/862429?v=pdf

Valsecchi, Elena. Spot the Monk Observatory. 2024. https://www.spot-the-monk-observatory.com/spot-the-monk-data-map/

Vianello, Patrick, and others. Observation of amesoscale eddy dipole on the northern Madagascar ridge: Consequences for the circulation and hydrography in the vicinity of a seamount. Deep Sea Research, Part II: Topical Studies in Oceanography, vol. 176, pp. 104815 2020.

Vierros, Marjo K., and others. Considering Indigenous Peoples and local communities in governance of the global ocean commons. Marine Policy, vol. 119, pp. 104039, 2020.

Wenegrat, Jacob O., and others. A Century of Observed Temperature Change in the Indian Ocean. Geological Research Letters, vol. 49, No. 13, e2022GL098217, 2022.

Woodall, Lucy C., and others. Deep-sea litter: a comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. Frontiers in Marine Science, Sec. Marine Pollution, vol. 2, 2015.

Zaki, Muhammad Rozaimi Mohd, and Aris, Ahmad Zaharin ., 2022. An overview of the effects of nanoplastics on marine organisms. Science of The Total Environment, vol. 831, pp. 154757, 2022.

Section 4
Chapter 3: Trends in the physical and chemical state of the ocean

Lead: Vasily Smolyanitsky
Co-lead: Rafael González-Quirós
Coordinating Author: Penny Vlahos

Writing Team:
Penny Vlahos, Vasily Smolyanitsky, David N. Thomas, Sam Dupont, Niki Evelpidou, Jelena Knezevic, Manuel Vargas-YáñezManolo Vargas

Keynotes:

- Tracking changes in physical and chemical properties of ocean regions is critical to understanding the future of the planet, with its significant in terms of geopolitical and socioeconomic changesconsequences.
- These changes are underway, and nations will need to plan to adapt to them strategically to minimize damage to ecosystems and communities that rely upon them.
- Since the last WOA (WOA II- Chapter 5) the trends in the global ocean as a whole, continue to show accelerated warming, increases in sea level rise and surface salinities, and decreases in annual global sea ice coverage (particularly in the Arctic). Local variations exist.
- Since the last WOA (WOA II- Chapter 5), the trends continue to show accelerated warming and increases in sea level rise in the global ocean, whereas prominent regional increases in surface salinities (particularly in mid and southern Atlantic), and decreases in annual global sea ice coverage
- These changes are impacting global water circulation and air-sea-ice interaction processes while also leading to changes in nutrient distributions, species shifts (WOA III Chapter 4), and driving accelerating ocean hazards (WOA-III S5B.C4) and other cummulative effects including contaminants (WOA-III S4.C6).
- There will be significant changes on coastal ocean dynamics, associated with sea level rise, warming and shifts in circulation leading to significant impacts on regional communities over the next few decades.which will significantly impact regional communities over the next few decades.
- One of the most impactful changes anticipated is the frequent occurrence of ice-free Arctic Ocean in Septembers by mid before the 21st century.

3.1 Physical Trends

3.1.1 Ocean temperature (including ocean heat content)

The great capacity of the ocean to capture and store heat moderates the temperature of our planet. Over 90% of the heat absorbed by the Earth since 1955 has been absorbed or has been accumulated in the oceans.90 percent of the warming that has occurred on Earth since 1955 has happened in the ocean. Figure 1a illustrates the heat increase in the upper 2000 m of ocean since 1955 and indicates a continuous rise that peaks in 2023 (von Schuckmann et al., 2024). Sixteen percent of this increase occurred between 2018-2023 even though this is period represents only 7 percent of the time-period. This energy accounts for 30 to 50 percent of ocean sea level rise through thermal expansion. Additionally, this warming contributes to changes in

migration of oceanic species, damage to coral reef systems and the accelerated melting of ice sheets (S4.C5k, S5B.C4). While the Pacific Ocean holds the largest heat reservoir due to its vast size, ~~T~~the greatest warming has been observed in the ~~Atlantic~~ in most of the Atlantic Ocean and adjacent to the Southern Ocean parts of the Indian and western Pacific Oceans ~~(south of 50° N) and Southern Oceans~~ (Figure 1b) with notable cooling regions observed in the North Atlantic (~ 50–70° N) and in the northwest and southwest Pacific ~~though, the largest heat reservoir is in the Pacific Ocean due to its size with the major contrasting cooling regions in the North Atlantic (~ 50–70° N) and in northwest, and southwest Pacific~~ (Cheng et al., 2022, von Schuckmann et al., 2024). The ~~surface~~ ocean surface is where the most important heat exchange between the ocean and atmosphere occurs. Shifts in sea surface temperature (SST) translate to important differences in water evaporation rates, atmospheric heating and cooling, marine heat waves and thawing of sea-ice and broader impacts on continental climate as ~~addressed~~ discussed in WOA II.

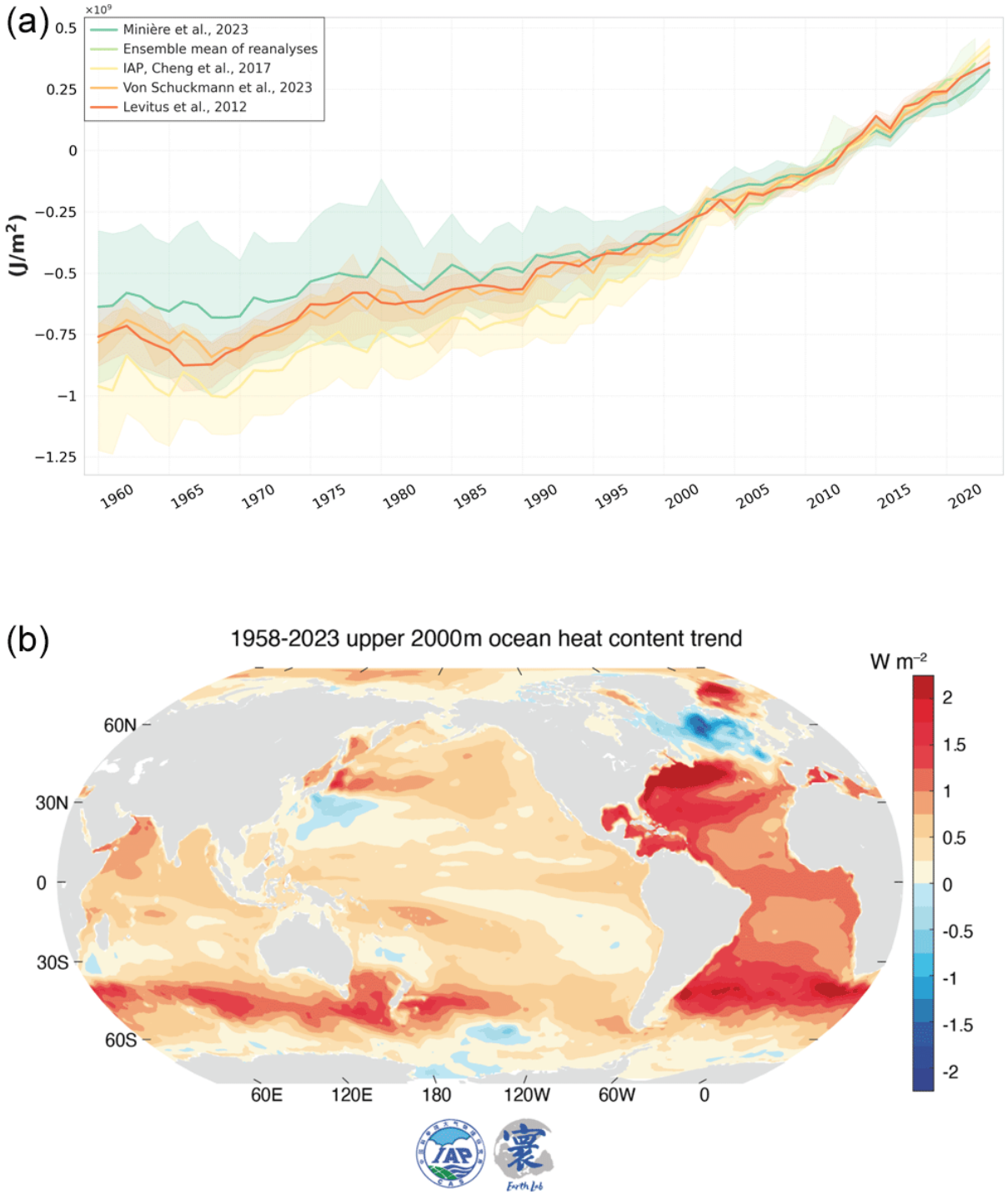
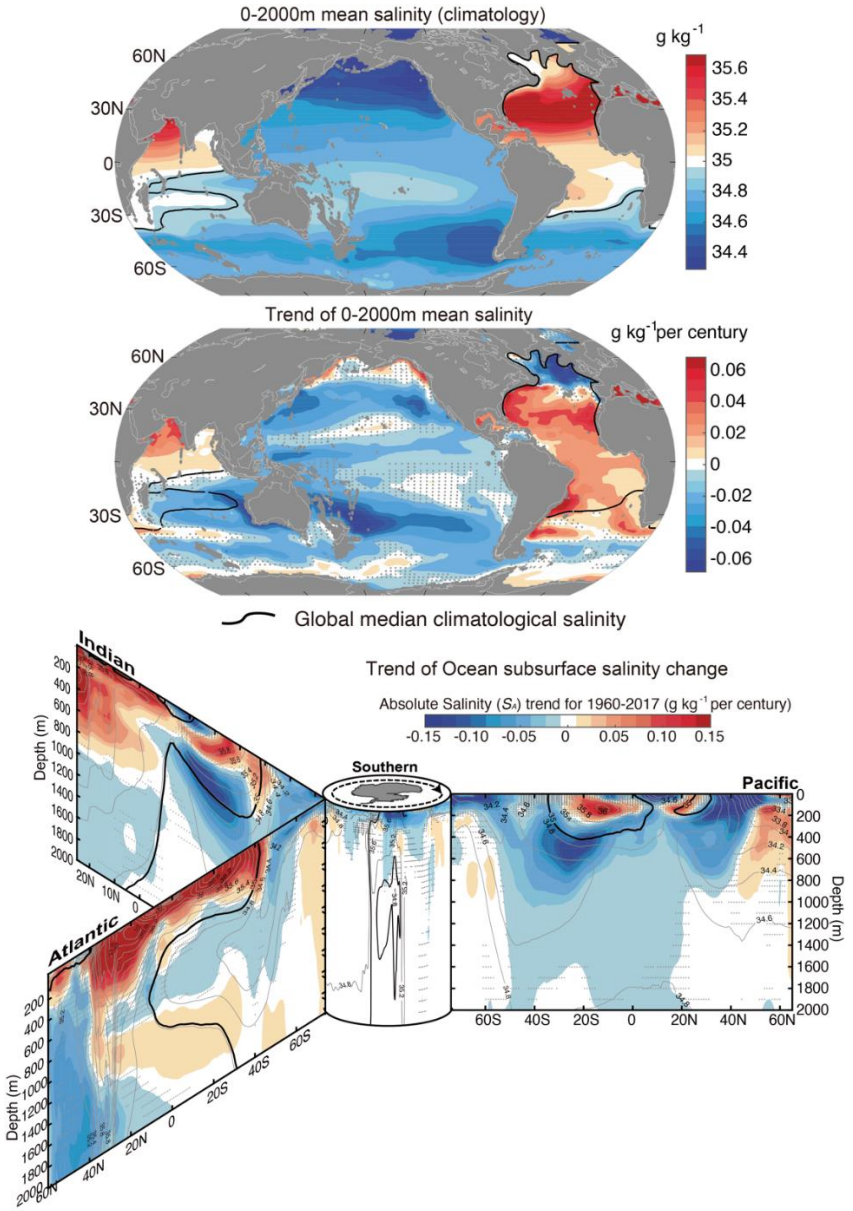


Figure 1. (a) Global mean ocean heat content (60° S–60° N) integrated from the surface down to 2000 m depth based on different products. Shaded areas indicate the uncertainty for each method respectively. The trend is estimated using a locally weighted scatterplot smoothing approach and amounts to 0.58 ± 0.13 W m−2 over the period 1960–2023 and 1.05 ± 0.17 W m−2 over the period 2005–2023. (b) Regional trend over 1960–2023 for ocean heat content in the upper 2000 m depth, in W m−2. (from von Schuckmann et al., 2024).

3.1.2 Ocean salinity

The warming climate is causing an intensification of the global water cycle due to increased rates of ocean evaporation. The impacts on salinity vary based on whether a region will experience greater net evaporation (raising salinity) or greater net precipitation (reducing salinities). The long term trends indicate that ~~over the past five years~~ there has been relative freshening or salinity decreases over the entire Pacific and North Atlantic and Southern Ocean, but salinity increases in the mid and southern Atlantic and Indian Oceans (Cheng et al., 2020). These trends are expected to continue throughout the century likely spanning in 0–1000 m layer (Figure 2, bottom) and further increase salinity by 4 to 8 percent in a world warmed by +2°C (expected year 2046).



~~Figure 2. Mean salinity climatology 0-2000m (top) shows the relatively fresh Pacific Ocean versus the salty Atlantic Ocean and northern Indian Ocean. The long-term trend (middle) has a remarkably similar pattern. (from Cheng et al. (2020).~~

Figure 2 Mean ocean salinity 0-2000m climatology (top), spacial distribution of its linear trend (mid) and 3D-distribution of linear trends averaged across three sections in each ocean basin (bottom) organized around the Southern Ocean in the centre. Reference period 1960-2017. (from Cheng et al. 2020).

3.1.3 Sea Level

Sea Lever Rise (SLR) is driven mainly by the combination of thermal expansion and the extended ice sheet melting. In some coastal zones, additional changes in storm surges and waves and local tectonic/isostatic processes may contribute to absolute sea level changes of up to a few mm per year. Locally, storm surges and waves may account for up to 10 percent of the sea-level rise (Jevrejeva et al. 2023). The coincidental occurrence of storm surge and spring tides, resulting in a storm-tides also adds a significant threat to coastal communities (Moftakhari et al, 2024). Rates of global mean SLR show increasing tendency, from 1.3-1.9 mm/yr during 1901-2015, 2.1 mm/yr for the first 10 years (1993–2002) of the altimetry era and 4.3 mm/yr for the last 10 years (2013–2023) with faster rates in the Indian Ocean and in some regions of the Pacific and Atlantic Ocean (Figure 3). Rates are projected to reach between 5.2 mm/yr (lowest CO_2 scenario), up to even 12.1 mm/yr (highest CO_2 scenario) during 2080-2100 (Fox-Kemper et al 2021). Sea level is not projected to rise uniformly by 2100, as **tropical areas seem more likely to undergo the largest changes**. Extreme sea level scenarios under storm conditions (as a combination of sea surface height associated with storm surge, wave, high tide and low probability sea level rise scenario) may reach 4.2 m by 2100, compared to 2.6 m in the period 1980-2014 (Jevrejeva et al, 2023). Overall, a significant proportion of the world's coasts will be inundated by 2100 though inundation will not be uniform, as countries with flat coasts will be more threatened (Vernimmen & Hooijer 2023). Further SLR concerns are addressed in the UN technical reports (UNFCCC, 2024).

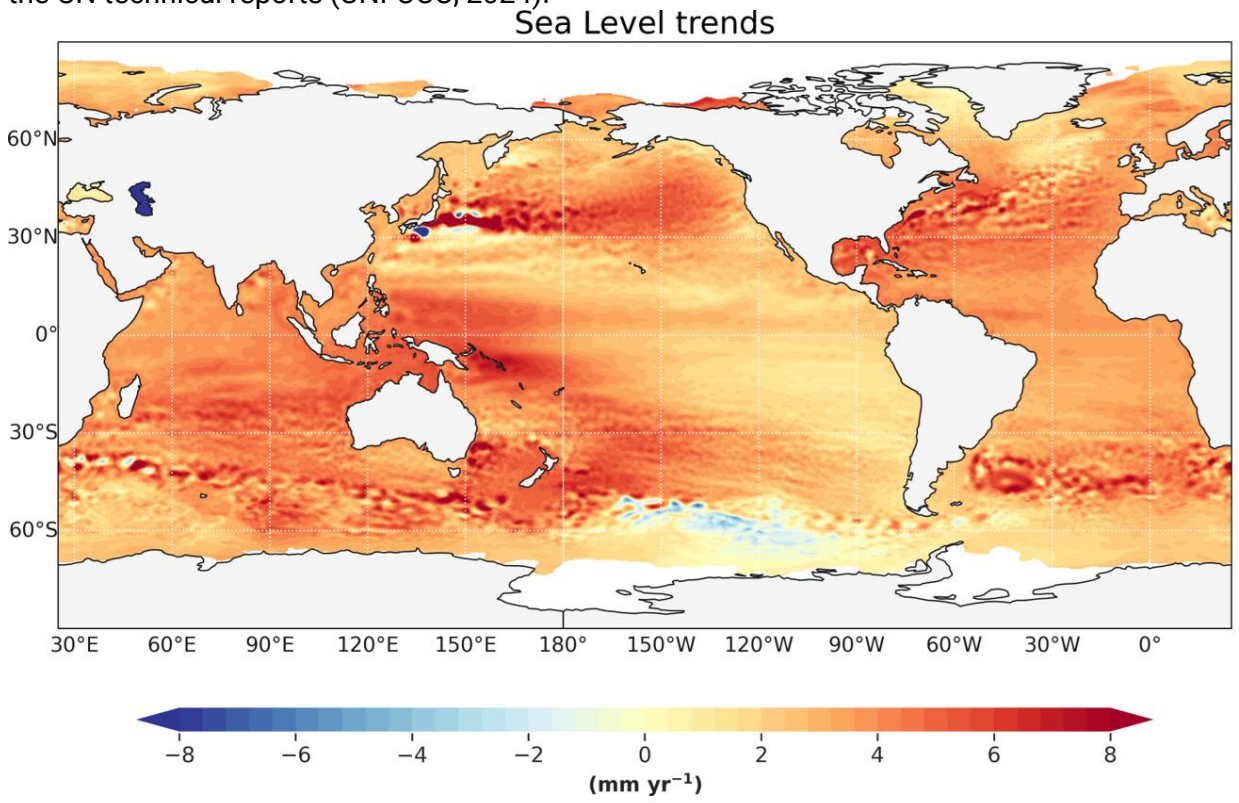


Figure 3. Regional sea level trends from January 1993 to June 2023 (adapted from von Schuckmann et al., 2024).

3.1.4 Sea Ice

The well-documented decrease in Arctic (more precisely, ~~Northern Hemisphere~~ Arctic Ocean and other Northern Hemisphere areas with seasonal ice cover) sea-ice extent continues (Meier et al. 2023, Stroeve et al. 2025) and in 2021-2025 seasonal ~~variability of~~ sea-ice extent remains close to the lowest in the satellite record from 1979 to present. Multiyear ice (>4 years old) area, ~~l extent~~, sea ice age, thickness and volume have remained consistently low since the 2010s and close to minimum values for period of observations from 1979 to 2025 ~~and ice parameters such as age, thickness and volume have remained consistently low since the 2010s and close to minimum values~~ with the marginal ice zone moving further north in summer ~~and further south again in winter~~ (Thoman et al. 2023), though significant regional and seasonal positive variations do occur. On March 22, 2025, the Arctic winter ice extent reached its minimum extent of 14.33 million km^2 which fell below the prior low of 14.41 million km^2 in 2017 (Figure 4). In the most recent climate predictions based on the Climate Model Intercomparison Project 6 (CMIP6) the earliest ice-free[13] conditions could occur in 2020–2030s under all emission trajectories and are likely to occur by 2050 (Jahn et al, 2024). Consistently, ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by mid-century (by 2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice free.

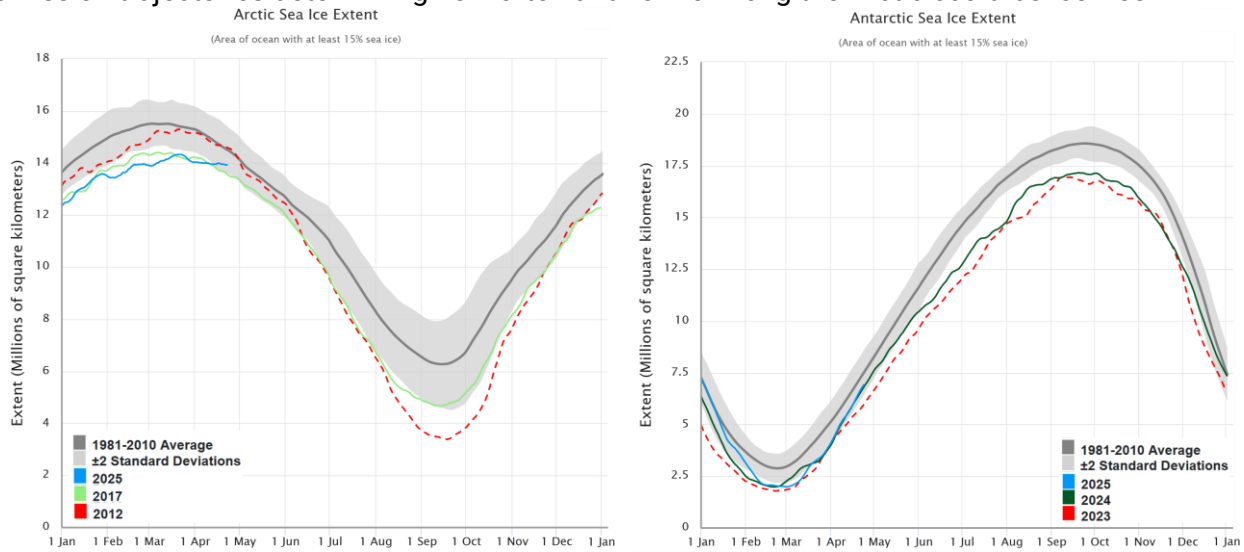


Figure 4: Arctic and Antarctic sea-ice average and extreme extents. The red dashed lines indicate current record minimum summer (Arctic, 2012) and minimum summer and winter (Antarctic, 2023) extents with gray line and zones in the time series indicating 1981-2010 average and +/-2 standard deviations range (https://nsidc.org/sea-ice-today).

[13] The term 'ice-free' used here should not be confused with a formal navigational term 'ice-free' of the relevant UN-bodies (WMO, IMO) ~~meaning 'No ice present. If ice of any kind is present this term should not be used'. As i~~Icebergs ~~or 'bergy waters'~~ will continue to be present within the domains of the Arctic and Southern Oceans, the term 'ice-free' navigationally is not applicable.

In contrast to Arctic sea-ice, the extent of sea ice in the Southern Ocean has only very recently (since 2021) shown significant decrease with the record minimum summer and winter sea ice observed in February and September 2023 (Purich and Doddridge, 2023). Southern Ocean declines in sea ice are most pronounced in regions south and west of the Antarctic Peninsula. The impacts of such decreases are widespread including changes in dense shelf water and associated Antarctic bottom water formation, increased heating of surface waters with subsequent changes in stratification/mixing dynamics. On March 1, 2025, Antarctic Sea ice reached its minimum extent of 1.98 million km^2, tying for second lowest extent with 2022-2024 in the 47-year satellite record (Figure 4).

3.1.5 Global ocean circulation patterns at all scales (including vertical and horizontal patterns such as stratification, boundary currents)

The potential decline of the Atlantic Meridional Overturning Circulation (AMOC) is a major concern related to ongoing changes in global circulation patterns. Previous results from the CMIP5 had predicted the slow-down of the AMOC and some of these models predicted an abrupt collapse during the twenty-first century. However, ~~the more recent Special Report on the Ocean and Cryosphere in a Changing. Climate (SROCC) (2019) and IPCC AR6 (2021) consider that~~ this weakening during the twenty-first century (Figure 5) has a medium to low confidence and none of the models in the CMIP6 predict the collapse of the AMOC during the present century. ~~Such an intense~~A weakening of the northward heat transport would result in a decrease of Sea Surface Temperature (SST) and Surface Atmospheric Temperatures (SAT) in the North Atlantic Subpolar Gyre (NA SPG) ultimately reducing the delivery of heat to Northern Europe. Swingedouw et al. (2021) estimated that the probability of this cooling was 45.5 percent in CMIP5, but it ~~had~~ has decreased to 36.4 percent in the CMIP6. On the contrary, Caesar et al. (2018, 2021) found that the AMOC was weakening and could reach a tipping point and an abrupt collapse during the mid-twenty first century (van Westen et al., 2024). This would result in significant climate shifts in the northern hemisphere (particularly Europe) and subsequently significant shifts globally due to the redistribution of ocean heat energy. Changes in AMOC circulation remains a research priority.

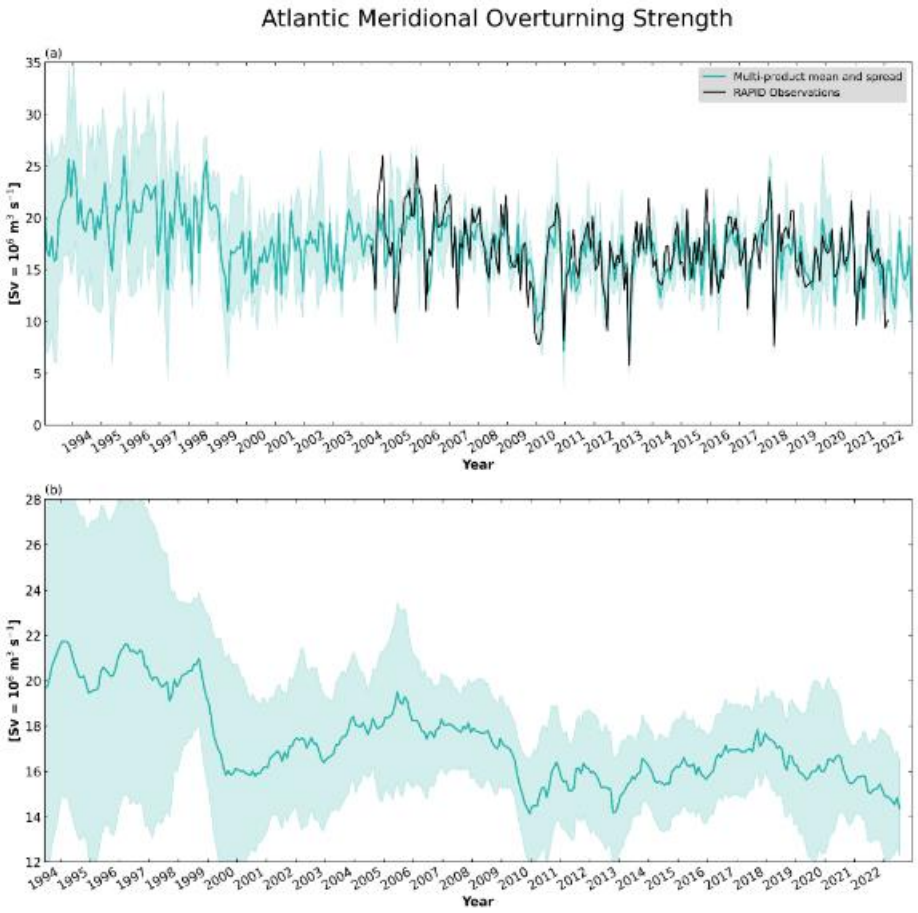


Figure 5: Temporal evolution of the Atlantic Meridional Overturning Circulation (AMOC) strength at 26.5° N obtained by integrating the meridional transport at 26.5° N across the Atlantic basin (zonally) and then cumulatively integrating over depth. Its maximum value in depth is the n taken as the strength in Sverdrups (Sv = 1 × 10^6 m^3 s^{-1}). The green line and shading (2 times the standard deviation) are based on product ref. OV.2 computed from product ref. OHC.8. The black line shows the observational record from the RAPID array (Moat et al., 2023). Panel (a) shows monthly mean values, and panel (b) shows interannual variations by applying a 12-month running mean (adapted from von Schuckmann et al., 2024).

These changes in the heat and freshwater transport in the North Atlantic are likely related ~~would likely be connected~~will translate to changes in the South Atlantic and the Indian Oceans. According to SROCC (2019), the Agulhas leakage, an inflow of anomalously warm and saline water from the Indian Ocean into the South Atlantic, intensified since 1960s contributing to the warming of the upper 300 m in the South Atlantic. The Agulhas leakage is likely to increase during the twenty-first century contributing to the slow-down of the AMOC (Loveday et al., 2015). This intensification of the Agulhas and Benguela Currents would be produced by an intensification of the westerlies in the Southern hemisphere and the southward displacement of the southern currents. However, this is also a result that should be analyzed carefully in the future. Majumder and Schmid (2018) used temperature and salinity profiles from Argo profilers, and Sea Surface Height (SSH) data to calculate the transport associated with the Agulhas Current and found no trends since 1993.

Against a backdrop of ocean warming, ~~declining sea-ice, induced freshening changes to Arctic Ocean oceanography~~ the freshening changes to Arctic Ocean oceanography, induced by declining sea-ice, are certain (reviewed by Timmermans & Marshall, 2020). Decreased summer sea ice, is resulting in reduced reflection of solar radiation back into space (reduced albedo), and an associated increase~~d~~ in surface ocean mixed-layer temperatures at a rate of about ~0.5°C per decade. Additional trends in increased heat advecting from the Pacific Ocean has triggered increased sea ice decline in the Chukchi Sea at the fastest rate of sea ice decline of the entire Arctic Ocean. The Atlantification of the Arctic Ocean, resulting from increased Atlantic water layer heat fluxes into the Eurasian basin, is resulting in reduced sea ice and changes in stratification (Polyakov et al., 2023, 2025). The total freshwater content of the Arctic Ocean continues to increase, especially in the Beaufort Gyre region (increase of liquid freshwater content from 2003 to 2018 by 40% relative to the climatology of the 1970s) as a result of persistent anticyclonic atmospheric wind forcing, sea ice melt, a wind-forced redirection of Mackenzie River discharge and a contribution of low salinity waters of Pacific Ocean origin via the Bering Strait ~~increase in freshwater content increase by 40% since 1970s~~, Proshutinsky et al., 2019). ~~The Beaufort Gyre is speeding up because of the increased heat entering the Pacific sector of the Arctic Ocean (MacKinnon et al. 2021).~~ In the Arctic shelf seas, there has been a decrease in freshwater content, combined with deeper mixed layers as winds drive surface freshwater offshore.

In general, there has been a freshening and warming of the Southern Ocean and an associated increased stratification of the uppermost 200 m since the 1970s. This potentially restricts the vertical exchange of heat, salt, nutrients and gases between surface, intermediate and deep waters (Carter, Bostock-Lyman & Bowen, 2022). Freshening of Antarctic shelf waters in the Southern Ocean surface waters has led to a freshening and contraction to Antarctic bottom water (AABW) formed in the Weddell Sea, Cape Darnley, the Adélie coast and Ross Sea. This trend is certain to have profound implications in slowing down deep ocean ventilation and global overturning circulation (Gunn et al. 2023; Lee et al. 2023; Li et al. 2023) and in turn on marine productivity, impacting fisheries. The societal implications of these changing resources are profound (Huntington et al. 2022; Stroeve et al. 2025).

3.2 Chemical Trends[14]

3.2.1 Ocean Acidification

About 20-30 percent of the carbon dioxide (CO_2) released by human activity into the atmosphere has been absorbed by the ocean leading to a ~~26 percent~~ increase in the average surface ocean acidity of 0.1 pH units since pre-industrial levels. The transport of CO_2 to the deeper ocean via currents and mixing is resulting in ocean acidification (OA) now surpassing a depth of 2000m in the North Atlantic and Southern Ocean (IPCC 2022). International initiatives such as the Global Ocean Acidification Observing Network (GOA-ON) are reporting large spatio-temporal variability in the carbonate chemistry in the coastal zones as consequences of biological activity, water

[14] Trends in contaminants are described in S4.C6.

mixing and run-off from land. As a consequence of biological activity, water mixing and run-off from land, results in large spatio-temporal variability in ~~the carbonate chemistry is increasingly documented in the coastal zones via the combined efforts of international initiatives such as the Global Ocean Acidification Observing Network (GOA-ON) and reporting to the Sustainable Development Goal 14.3~~. There is a large body of evidence reporting the negative impact of ocean acidification on marine species, ecosystems, and their associated services (S4.C4 and S4.C5). Species adaptation to changes in carbonate chemistry has been utilized as one of the representative stressors studied to understand species and ecosystem sensitivity (Vargas et al. 2022) in future marine conditions (Widdicombe et al. 2023). ~~This is addressed in Section 4, Chapter 4 of this report.~~

3.2.2 Changes in carbon

The ocean is the second largest carbon reservoir on Earth at 37 300 GtC (10^{15}gC) and holds over 60 times the carbon of the atmosphere (Devries, 2022). Ocean CO_2 uptake rates have tripled over the last 60 years to -2.7 ± 0.3 Pg C per year (over the period of 1990 through 2019) and are expected to continue increasing by -0.4 ± 0.1 Pg C per decade (Gruber et al. 2023). These values are impacted spatially and interannually by shifts in weather and climate. ~~For example, during El Nino years, the warmer surface waters of the Pacific result in a lower uptake of CO_2, weakening the ocean sink, and driving even higher atmospheric CO_2 levels.~~ It is expected that eventually, average net warming of surface waters will ~~attenuate~~ reduce the uptake rates of the ocean due to the reduction in solubility of CO_2 at higher temperatures.

Total alkalinty (TA) is a metric of the buffering capacity of the ocean or its ability to ~~attenuate~~ counter changes in pH and is dominated by inorganic carbon ~~carbon species including~~ (i.e. bicarbonate and carbonate). TA in subtropical regions has increased due to changes in the global water cycle (increased evaporation) and is expected to continue to do so. The northern hemisphere has more spatial variability in TA and salinity than the Southern Ocean due to fewer changes in salinity and the contribution by upwelling of TA enriched waters (Fine et al., 2017).

3.2.3 Dissolved oxygen

The trend of global deoxygenation in the oceans continues and is driven by a combination of lower ~~solubilities~~ solubility of oxygen associated with increasing water temperatures, intensified stratification (particularly in the open ocean) and ~~due to the intensification of~~higher nutrient additions to primarily coastal areas that drive bacterial activity and oxygen consumption. Figure 6 outlines the areas that have increasing oxygen minimum zones (blue) and coastal areas that are experiencing primarily anthropogenically driven hypoxia (red). Note, over the past 50 years the hypoxic zone area has increased by 4.5 million km^2 and the world's oceans continue to lose roughly 1 GtO_2 per year (Keeling and Garcia, 2002) decreasing by more than two per cent (4.8 ± 2.1 petamoles) since 1960 (Schmidtko et al, 2017).

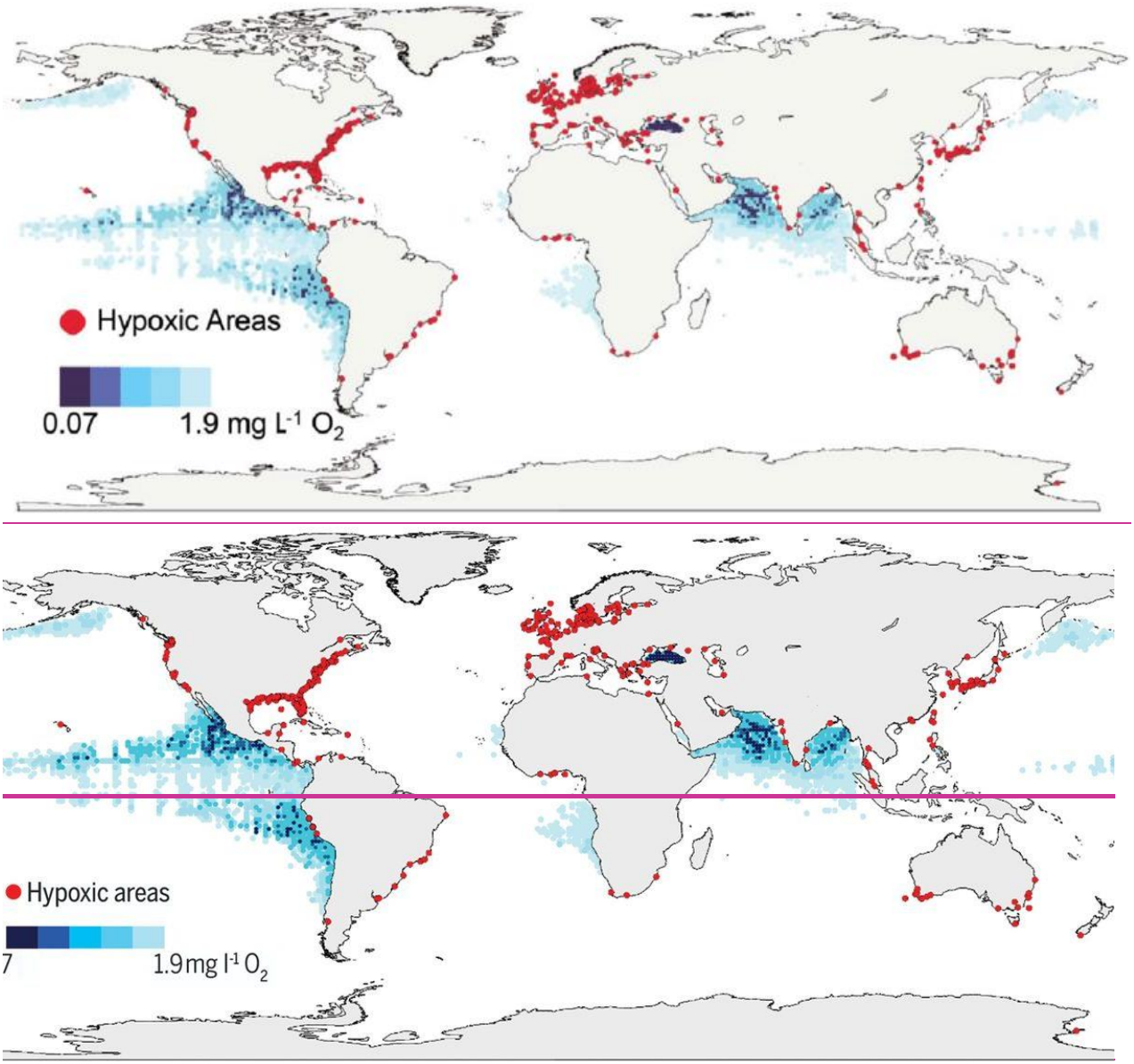


Figure 6: Ocean Minimum Zones (blue) and areas with coastal hypoxia (red) in the world's ocean (GO2NE, 2018, The Ocean is Losing its Breath: Declining Oxygen in the World's Ocean and Coastal Waters. Adapted after Isensee et al., 2015, Breitburg et al., 2018, including oxygen effects from Keeling and Garcia, 2002, Diaz and Rosenberg, 2008, Carstensen et al., 2014)
UNESCO

3.2.4 Nutrients

3.2.4.1 Nitrogen

Since 2018, changes in climate have significantly altered oceanic nitrogen dynamics, impacting phytoplankton productivity, carbon sequestration, and greenhouse gas emissions (S4.C4a and S4.C5n). Though ocean warming, changes in stratification and acidification are major influences on the ocean's nitrogen cycle, ocean deoxygenation is expected to have one of the

largest impacts on microorganisms involved in nitrogen transformation pathways (Hutchins and Capone, 2022). Adaptable anammox bacteria in oxygen-deficient zones (Zhao et al., 2024) highlight diverse responses and increased nitrogen fixation rates linked to higher diazotroph richness underscore biodiversity's role (Shao et al., 2023; Eriksson et al., 2023). Comparing recent studies with historical data like World Ocean Atlas II reveals differing trends across regions, emphasizing the need for ongoing monitoring to capture dynamic, regional responses to climate change (Pitcher et al., 2021) such as in the Southern Ocean, where regional variability in nitrogen dynamics and phytoplankton responses reflect localized impacts (Boyd et al., 2024). Understanding these complexities is crucial for predicting climate feedback and guiding effective mitigation strategies.

3.2.4.2 Phosphorus

Since 2018, studies have highlighted shifting oceanic phosphorus availability and cycling driven by climate change. Changes in ocean temperature, stratification, and circulation affect phosphorus availability and cycling (Chen et al. 2023. Further studies have demonstrated the significant role that phosphorus plays in nitrogen fixation by important groups of phytoplankton, with implications for marine productivity and ecosystems (Moisander et al. 2022, Boyd et al. 2024). These recent studies highlight deviations in contemporary phosphorus trends from historical baselines, emphasizing the need for updated monitoring to accurately predict future biogeochemical cycles.

3.2.4.3 Silica

Rising ocean acidification lowers the dissolution rate of biogenic silica and therefore increases the burial rate in sediments (Taucher et al 2022). This is expected to favor diatoms that require silicic acid to grow and account for near 40 percent of marine primary productivity in the short term. Over the long term (150 years) the increased burial of silica will lead to silica limitation which may then negatively impact diatom productivity and shift the primary production assemblages in the global surface ocean waters. The areas impacted greatest are expected to be those undergoing the fastest rates of acidification, particularly coastal zones where burial rates are greatest.

3.3 Gaps

There remain important uncertainties in mechanistic understanding of how ocean circulation will respond to warming and changes in freshwater inputs, especially ~~when downscaled to regional levels~~at regional scales. The ocean is an important distributer of heat on the planet and any changes in circulation patterns change how heat will be distributed. In addition to heat, circulation patterns determine where and when nutrients will be depleted and replenished, which translates to regional ecosystem dynamics, regional fisheries and regional economies. To improve our ability to predict future conditions and plan for and achieve some degree of resilience in response to changes we need to invest in observations (including long term time-series) and models in key regions and help communities prepare and adapt infrastructure planning. Among these are the areas that we know are changing most rapidly including the Arctic Ocean and Southern Ocean. We also need to identify ecosystem thresholds where key species are most at risk to avoid fisheries collapse. These efforts are critical to inform communities and to help guide adaptive management.

References

Boyd, P. W., Antoine, D., Baldry, K., Cornec, M., Ellwood, M., Halfter, S., Lacour, L., Latour, P., Strzepek, R. F., Trull, T. W., & Rohr, T. (2024). Controls on polar Southern Ocean deep chlorophyll maxima: Viewpoints from multiple observational platforms. *Global Biogeochemical Cycles, 38*(3), e2023GB008033. https://doi.org/10.1029/2023GB008033

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature, 556*(7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience, 14*, 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caínzos, V., Hernández-Guerra, A., McCarthy, G. D., McDonagh, E. L., Cubas Armas, M., & Pérez-Hernández, M. D. (2022). Thirty years of GOSHIP and WOCE data: Atlantic overturning of mass, heat, and freshwater transport. *Geophysical Research Letters, 49*, e2021GL096527. https://doi.org/10.1029/2021GL096527

Carter, L., Bostock-Lyman, H., & Bowen, M. (2022). Water masses, circulation and change in the modern Southern Ocean. In F. Florindo, M. Siegert, L. De Santis, & T. Naish (Eds.), *Antarctic Climate Evolution* (2nd ed., pp. 165–197). Elsevier. https://doi.org/10.1016/B978-0-12-819109-5.00003-7

Cheng, L., von Schuckmann, K., Abraham, J. P., et al. (2022). Past and future ocean warming. *Nature Reviews Earth & Environment, 3*, 776–794. https://doi.org/10.1038/s43017-022-00345-1

Cheng, L., Trenberth, K. E., Gruber, N., Abraham, J. P., Fasullo, J., Li, G., Mann, M. E., Zhao, X., & Zhu, J. (2020). Improved estimates of changes in upper ocean salinity and the hydrological cycle. *Journal of Climate*. https://doi.org/10.1175/JCLI-D-20-0366.1

Desbruyères, D. G., Mercier, H., Maze, G., & Daniault, N. (2019). Surface predictor of overturning circulation and heat content change in the subpolar North Atlantic. *Ocean Science, 15*, 809–817. https://doi.org/10.5194/os-15-809-2019

DeVries, T. (2022). The ocean carbon cycle. *Annual Review of Environment and Resources, 47*, 317–341. https://doi.org/10.1146/annurev-environ-120920-111307

Fine, R.A.; Willey, D.A.; Millero, F.J. Global variability and changes in ocean total alkalinity from Aquarius satellite data. Geophys. Res. Lett. 2017, 44, 261–267. https://doi.org/10.1002/2016GL071712

Fox-Kemper, B. (2021). Ocean, cryosphere and sea level change. In *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Gunn, K. L., Rintoul, S. R., England, M. H., et al. (2023). Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin. *Nature Climate Change, 13*, 537–544. https://doi.org/10.1038/s41558-023-01667-8

Gruber, N., Bakker, D. C. E., DeVries, T., et al. (2023). Trends and variability in the ocean carbon sink. *Nature Reviews Earth & Environment, 4*, 119–134. https://doi.org/10.1038/s43017-022-00381-x

Huntington, H. P., Zagorsky, A., Kaltenborn, B. P., et al. (2022). Societal implications of a changing Arctic Ocean. *Ambio, 51*, 298–306. https://doi.org/10.1007/s13280-021-01601-2

Hutchins, D. A., & Capone, D. G. (2022). The marine nitrogen cycle: New developments and global change. *Nature Reviews Microbiology, 20*, 401–414. https://doi.org/10.1038/s41579-022-00687-

IPCC (2019) *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. Weyer (Eds.). Cambridge University Press.

IPCC (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.). Cambridge University Press.

Jahn, A., Holland, M. M., & Kay, J. E. (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth & Environment, 5*, 164–176. https://doi.org/10.1038/s43017-023-00515-9

Jevrejeva, S., Williams, J., Vousdoukas, M. I., & Jackson, L. P. (2023). Future sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100. Environmental Research Letters, 18(2), 024037. https://doi.org/10.1088/1748-9326/acb9d4

Kelly, K. A., Drushka, K., Thompson, L., Le Bars, D., & McDonagh, E. L. (2016). Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports. Geophysical Research Letters, 43, 7625–7631. https://doi.org/10.1002/2016GL069789

Lee, S. K., Lumpkin, R., Gomez, F., et al. (2023). Human-induced changes in the global meridional overturning circulation are emerging from the Southern Ocean. Communications Earth & Environment, 4, 69. https://doi.org/10.1038/s43247-023-00727-3

Li, Q., England, M. H., Hogg, A. M., et al. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. Nature, 615, 841–847. https://doi.org/10.1038/s41586-023-05762-w

Loveday, B. R., Penven, P., & Reason, C. J. C. (2015). Southern Annular Mode and westerly-wind-driven changes in Indian-Atlantic exchange mechanisms. Geophysical Research Letters, 42, 4912–4921. https://doi.org/10.1002/2015GL064256

MacKinnon, J. A., et al. (2021). A warm jet in a cold ocean. Nature Communications, 12, 2418. https://doi.org/10.1038/s41467-021-22505-5

Majumder, S., Schmid, C., Moftakhari, H., Muñoz, D. F., Akbari Asanjan, A., AghaKouchak, A., Moradkhani, H., & Jay, D. A. (2024). Nonlinear interactions of sea-level rise and storm tide alter extreme coastal water levels: How and why? AGU Advances, 5(2), e2023AV000996. https://doi.org/10.1029/2023AV000996

Meier, W. N., et al. (2023). Sea ice. In R. L. Thoman, T. A. Moon, & M. L. Druckenmiller (Eds.), Arctic Report Card 2023 (pp. 39–48). NOAA Technical Report OAR ARC. https://doi.org/10.25923/5vfa-k694

Moftakhari, H., Muñoz, D. F., Akbari Asanjan, A., AghaKouchak, A., Moradkhani, H., & Jay, D. A. (2024). Nonlinear interactions of sea-level rise and storm tide alter extreme coastal water levels: How and why? AGU Advances, 5, e2023AV000996. https://doi.org/10.1029/2023AV000996

Moisander, P. H., Daley, M. C., Shoemaker, K. M., et al. (2022). Nitrogen fixation influenced by phosphorus and nitrogen availability in the benthic bloom-forming cyanobacterium Hydrocoleum sp. identified in a temperate marine lagoon. Journal of Phycology, 58(3), 377–391. https://doi.org/10.1111/jpy.13244

Piecuch, C. G., & Beal, L. M. (2023). Robust weakening of the Gulf Stream during the past four decades observed in the Florida Straits. Geophysical Research Letters, 50, e2023GL105170. https://doi.org/10.1029/2023GL105170

Pitcher, G. C., Aguirre-Velarde, A., Breitburg, D., Cardich, J., Carstensen, J., Conley, D. J., Dewitte, B., & Zhu, Z. Y. (2021). System controls of coastal and open ocean oxygen depletion. Progress in Oceanography, 197, 102613. https://doi.org/10.1016/j.pocean.2021.102613

Polyakov, I. V., et al. (2023). Fluctuating Atlantic inflows modulate Arctic atlantification. Science, 381, 972–979. https://doi.org/10.1126/science.adh5158

Polyakov, I. V., et al. (2025). Atlantification advances into the Amerasian Basin of the Arctic Ocean. Science Advances, 11, eadq7580. https://doi.org/10.1126/sciadv.adq7580

Proshutinsky, A., et al. (2019). Analysis of the Beaufort Gyre freshwater content in 2003–2018. *Journal of Geophysical Research: Oceans*, 124, 9658–9689. https://doi.org/10.1029/2019JC015281

Purich, A., & Doddridge, E. W. (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment, 4, 314. https://doi.org/10.1038/s43247-023-00961-9

Schmidtko, S., Stramma, L. & Visbeck, M. Decline in global oceanic oxygen content during the past five decades. *Nature* **542**, 335–339 (2017). https://doi.org/10.1038/nature21399

Shao, J., et al. (2023). Global oceanic diazotroph database version 2 and elevated estimate of global oceanic N_2 fixation. Earth System Science Data, 15(8), 3673–3709. https://doi.org/10.5194/essd-15-3673-2023

Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L. F., Sgubin, G., Mignot, J., & Menary, M. (2021). Atlantic Meridional Overturning Circulation response to climate change: A review. Annals of the New York Academy of Sciences, 1504, 187–201. https://doi.org/10.1111/nyas.14639

Stroeve, J. C., Notz, D., Dawson, J., Schuur, E. A. G., Dahl-Jensen, D., & Giesse, C. (2025). Disappearing landscapes: The Arctic at +2.7°C global warming. Science, 387(6734), 616. https://doi.org/10.1126/science.ads1549

Taucher, J., Bach, L. T., Prowe, A. E. F., et al. (2022). Enhanced silica export in a future ocean triggers global diatom decline. Nature, 605, 696–700. https://doi.org/10.1038/s41586-022-04687-0

Thoman, R. L., Moon, T. A., & Druckenmiller, M. L. (Eds.). (2023). Arctic Report Card 2023. NOAA Technical Report OAR ARC. https://doi.org/10.25923/5vfa-k694

Timmermans, M.-L., & Marshall, J. (2020). Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. Journal of Geophysical Research: Oceans, 125, e2018JC014378. https://doi.org/10.1029/2018JC014378

UNFCCC. (2024). WIM ExCom technical report on sea level rise. United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/WIM%20ExCom%20sea%20level%20rise.pdf

van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. Science Advances, 10, eadk1189. https://doi.org/10.1126/sciadv.eadk1189

Vargas, C. A., Cuevas, L. A., Broitman, B. R., San Martin, V. A., Lagos, N. A., Gaitán-Espitia, J. D., & Dupont, S. (2022). Upper environmental pCO_2 drives sensitivity to ocean acidification in marine invertebrates. Nature Climate Change, 12, 200–207. https://doi.org/10.1038/s41558-022-01261-w

Vernimmen, R., & Hooijer, A. (2023). New LiDAR-based elevation model shows greatest increase in global coastal exposure to flooding to be caused by early-stage sea-level rise. Earth's Future, 11(1), e2022EF002880. https://doi.org/10.1029/2022EF002880

von Schuckmann, K., Moreira, L., Cancet, M., Gues, F., Autret, E., Baker, J., Bricaud, C., Bourdalle-Badie, R., Castrillo, L., Cheng, L., Chevallier, F., Ciani, D., de Pascual-Collar, A., De Toma, V., Drevillon, M., Fanelli, C., Garric, G., Gehlen, M., Giesen, R., ... Zuo, H. (2024). The state of the global ocean. In K. von Schuckmann, L. Moreira, M. Grégoire, M. Marcos, J. Staneva, P. Brasseur, G. Garric, P. Lionello, J. Karstensen, & G. Neukermans (Eds.), 8th edition of the Copernicus Ocean State Report (OSR8). State of the Planet, 4-osr8, 1. https://doi.org/10.5194/sp-4-osr8-1-2024

Widdicombe, S., Isensee, K., Artioli, Y., Gaitán-Espitia, J. D., Hauri, C., Newton, J. A., Wells, M., & Dupont, S. (2022). Unifying biological field observations to detect and compare ocean acidification impacts across marine species and ecosystems: What to monitor and why. EGUsphere, 19, 101–119. https://doi.org/10.5194/egusphere-2022-119

Worthington, E. L., Moat, B. I., Smeed, D. A., Mecking, J. V., Marsh, R., & McCarthy, G. D. (2021). A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline. Ocean Science, 17, 285–299. https://doi.org/10.5194/os-17-285-2021

Zhao, R., Zhang, I. H., Jayakumar, A., Ward, B. B., & Babbin, A. R. (2024). Age, metabolisms, and potential origin of dominant anammox bacteria in the global oxygen-deficient zones. ISME Communications, 4(1), ycae060. https://doi.org/10.1093/ismeco/ycae060

Section 4 Chapter 4: Biodiversity (introduction)

The present chapter provides information on the state of biodiversity for nine important marine groups, ranging from phytoplankton to marine mammals. For the taxonomic groups that were included in the second World Ocean Assessment (WOA II), the focus is on changes observed since 2018. ~~The key change~~A key change in the 'Biodiversity' chapter (S4.C4) is the division of the subchapter ~~9 previously titled~~ 'Marine Plants and Macroalgae' ~~in the~~from WOA II into two distinct subchapters: ~~one 10 for~~ 'Marine Plants' and ~~the other for~~ 'Algae other than Phytoplankton'. WOA III introduces a new subchapter on Cephalopods (4B) to fill a gap identified in WOA II. ~~A new subchapter on 'Cephalopods' has been added to WOAIII to address a gap identified in WOAII.~~ This subchapter focuses on general information to establish a baseline of the current regional and global status. Subchapter ~~4A~~ 4A focuses on the highly diverse group of organisms including phytoplankton, zooplankton and marine microbes. It explores how plankton communities respond to both long-term environmental changes, and short-term climate-related extreme events. ~~expandsbuilds on phytoplankton biodiversity, highlighting~~ emphasizing ~~changes in the Arctic Ocean since WOA II, where warming and reduced sea-ice coverage have increased~~ led to ~~increased phytoplankton biomass, altered~~ shift in ~~community composition, phenology, and modified~~ distribution ~~patterns~~. Subchapter 4C, Marine Benthic Invertebrates, includes updated data ~~presents new information~~ on newly identified and threatened species, ~~accompanied by~~along with the newly developed maps ~~depicting~~ illustrating relevant human activities, associated pressures, and their spatial impacts. Subchapter 4D, ~~on~~ Fish ~~(4D) provides an update on~~offers insights into global marine fish taxonomy, biology, distribution, habitat, and conservation status. Subchapter on Marine Mammals (4E) highlights the alarming fact that over a quarter of marine mammal species, including those in freshwater ecosystems, are under threat. Chapter 4 also ~~contains information on~~covers recent changes in the biodiversity Marine Reptiles (4F), and Seabirds (4G). Subchapter on Marine Plants (4H), includes entirely new material on Sabkas (coastal salt flats) providing fresh insights into these unique ecosystems. Subchapter 4I, ~~on~~ Algae other than Phytoplankton outlines the current status of the red, green and brown macroalgae, ~~and any changes~~highlighting changes since 2018. Overall, this chapter ~~emphasizes~~underscores

discusses the need for the ~~urgent~~ need for conservation efforts and sustainable practices to safeguard marine biodiversity ~~protect marine life and its habitats~~.

Section 4

Chapter 4 Subchapter 4a Plankton

Dana E. Hunt; Amaranta Focardi; Inma Herrera; Nora Montoya; Guangyi Wang

Keynotes:

- Plankton are overwhelmingly the biomass-dominant organisms in the open oceans, thus their activity ~~and abundance both drives~~sets the rates of biogeochemical cycles and propagates to higher trophic levels.
- With short generation times, large population sizes and high diversity, the plankton are responsive to changing ocean conditions.
    - However, this responsiveness presents challenges in capturing changes at the appropriate spatial and temporal scales.
- As addressed in the Second WOA, plankton are predicted to alter their productivity, composition and distributions due to global change-driven alterations in temperature, nutrient fluxes, ocean acidification, among other factors (See WOAIII Chapter 3). However, in the absence of observable ecosystem tipping points, the period 2018-2023 largely continues previously-observed trends.
    - Here, we identify gaps in plankton responses to long-term environmental change, with little long-term data beyond phytoplankton and zooplankton that can be used to establish trends.
    - However, we identify stronger support for ~~l~~event-driven compositional and functional shifts in response to storms, fires, marine heat waves, etc.

- Current global observing networks and models still ~~largely neglect~~under sample the plankton ~~and fail~~or treat them as a “black box”, failing to capture their dynamics in the pelagic ~~ocean, but more specifically are undercharacterized~~oceans and particularly in dynamic coastal ecosystems (See WOAIII Chapter 9).

Introduction

Marine plankton comprise the majority of biomass in the open oceans, driving key biogeochemical cycles and supporting higher trophic levels by providing essential resources such as food and oxygen. Marine plankton (here excluding larvae of larger organisms) encompass a diversity of forms and functions, including viruses; bacterioplankton; archaea; phototrophic, heterotrophic, and mixotrophic microeukaryotes, as well as zooplankton. Prior United Nations World Ocean Assessments (WOAs) and the scientific literature have predicted plankton responses to long term global change, including temperature-driven poleward shifts and changes in community composition; decreasing phytoplankton cell size due to stratification; reduced transfer of carbon and energy to metazoan food webs and to the deep ocean; reductions in primary production at mid-latitudes and increases at the poles; loss of calcifying taxa due to ocean acidification; shifts toward carnivorous and gelatinous filter-feeding zooplankton, as well as high temperatures potentially driving localized extinctions/ or evolution in the tropics (Bopp et al., 2013; Beaugrand et al., 2019; Affairs, 2021; Heneghan et al., 2023; Knecht et al., 2023).

Many of these predictions and models, generally looking over the next ~100 years, have focused on primary producers, which tend to have more clearly-defined thermal niches and nutrient requirements compared to other plankton groups (Bopp et al., 2013). Particularly neglected are predictions for heterotrophic eukaryotes (e.g., fungi ~~and fungus-like protists (i.e.,~~ *Labyrinthulomycetes*) (Jones et al., 2022), that are generally not ~~included~~measured in time series ~~measurements~~ or molecular surveys. In addition to data gaps and ~~measurement biases~~biased methods [e.g., exclusion of fragile rhizarians in net samples (Soviadan et al., 2024) or specific taxa by molecular techniques], it can be difficult to determine whether ~~changes~~shifts in the plankton are driven directly by global change or indirectly through interactions with other trophic levels. For example, ~~as~~ phytoplankton serve as the base of the marine food web, thus alterations in their composition and physiology ~~can~~ propagate to bacteria and zooplankton ~~that consume their organic matter~~consumers (Hunt and Ward, 2015). While there is growing confidence in ~~our measurement~~measurements of ~~existing~~ environmental change and ~~predictions~~models of ~~the plankton's~~planktons' responses ~~to these environmental shifts~~ (Beaugrand et al., 2019), we lack unambiguous, empirical evidence that long-term climate pressures are reshaping plankton communities. ~~Across these organisms, changes~~Shifts in plankton abundance and community composition are assumed to be driven by temperature followed by ~~alterations in~~ nutrients and salinity ~~are generally assumed to drive plankton abundance and community characteristics~~ (Frémont et al., 2022). However, ~~difficulties in quantifying marine plankton responses to global change can be attributed to~~ many environmental

parameters co-vary and the same characteristics that make ~~them~~plankton good sentinels/~~indicators~~bioindicators for ecosystem change, such as short generation times and ~~large population sizes.~~responsiveness to environmental conditions make it difficult to identify the proximal drivers of community and biomass changes. Further complicating identification of long-term trends, plankton ~~rapidly respond to~~are also shaped by mesoscale physical and temporal forces, including seasonal changes, large-scale multi-year oscillations [e.g., El Nino Southern Oscillation (ENSO)], stochasticity and drift (Vellend, 2010).

~~During the period covered by WOAIII (2018-2023), research has highlighted the increasing prevalence of extreme events and their impacts on marine plankton. Therefore, in addition to assessing evidence for long-term trends, we also examine plankton responses to extreme events, including floods, storms, heat waves, etc., which may themselves be driven by global change or the event may add to underlying climate trends (e.g., a marine heat wave occurring in addition to long-term warming).~~

The environmental change since WOAII

Given the vast diversity in plankton phylogeny, trophic levels, form, and function, a comprehensive review of the predicted impacts of global change on marine plankton is beyond the scope of this WOA update~~.~~ (Dates: 2018-2023). Instead, we focus on the evidence of observed responses to (a) sustained changes in the environment (e.g., ocean warming) as assessed by time series, and (b) shorter-term climate-related extreme events (e.g., storms, fires). In addition to long-term trends, research has

highlighted the importance of extreme events including floods, storms, heat waves, etc., which may themselves be driven by global change or may add to underlying climate trends (e.g., a marine heat wave occurring in addition to long-term warming).

~~We place specific emphasis on the polar regions, as an area with an enhanced rate of change as well as sensitivity to chronic and acute climate impacts.~~

Long-term trends

Measuring changes in the plankton requires long-term time series to separate annual and interannual variability from global change-driven trends. Environmental ~~observation~~observations, experiments and models largely focus on phytoplankton due to their relatively simple nutrient requirements, abundant long-term data and ease of measurement. However, even trends in phytoplankton are somewhat mixed within general shifts toward smaller phytoplankton including cyanobacteria, (Table 1).

~~**Table 1 Predicted impacts of global change and extreme events on the plankton**~~

	Long term Global Change		Heat waves		Fires		Storms	
	abundance	community	abundance	community	abundance	community	abundance	community
Large zooplankton	Unresolved	Shifts in composition	Decreasing	Favoring smaller species	Neutral/Minor impact	Minor shifts	Decreasing	Favoring tolerant species
Small zooplankton	Unresolved	Shifts in composition	Increasing	Smaller species dominance	Minor increase	Minor shifts	Unresolved	Shifts in composition
Eukaryotic phytoplankton	Unresolved	Shifts in composition	Unresolved	Favoring smaller species	Increase	-	-	-
HABs	Unresolved	Unresolved	Increasing	-	-	-	Unresolved	
Cyanobacteria	Increasing	Shifts in composition	Increasing	Shifts in ecotypes	-	-	-	Shifts in composition
Fungi	-	Predicted shifts in composition	-	-	-	-	-	-
Bacterioplankton	Increasing	Shifts in composition	-	Shifts in composition	-	Shifts to tolerant groups	Potential increases	Minor changes

~~Unresolved represents unclear trends between different studies/ regions.~~

~~- Indicates inconclusive or non-existent data where we are unable to draw conclusions~~

Globally, phytoplankton blooms have increased in area by 13.2% and in frequency by 59% between 2003 and 2020, though with regional differences and compositional changes (Dai et al., 2023). Moreover, despite ~~predictions of decreased~~predicted decreases in tropical ocean primary production ~~in the tropical oceans~~, the Hawaii Ocean Time Series ~~(HOT)~~ shows ~~an~~ increasing ~~trend in~~ primary production, driven mainly by ~~increased in~~higher concentrations of cyanobacteria and picoeukaryotes (Kwon et al., 2022). Similarly, long-term trends in zooplankton reveals mixed responses, in some regions biomass has decreased, while in others, there have been increases in biomass and shifts in community composition (Pitois and Fox, 2006; Couret et al., 2023; Fernandez de Puelles et al., 2023).

Table 1 Predicted impacts of global change and extreme events on the plankton

	Long term Global Change		Heat waves		Fires		Storms	
	abundance	**community**	**abundance**	**community**	**abundance**	**community**	**abundance**	**community**
Large zooplankton	Mixed	Shifts in composition	Decreasing	Favoring smaller species	Neutral/Minor impact	Minor shifts	Decreasing	Favoring tolerant species
Small zooplankton	Mixed	Shifts in composition	Increasing	Smaller species dominance	Minor increase	Minor shifts	Mixed	Shifts in composition
Eukaryotic phytoplankton	Decreasing	Favoring smaller species	Mixed	Favoring smaller species	Increase	-	Potential increases	-
HABs	Mixed	Mixed	Increasing	-	-	-	Mixed	
Cyanobacteria	Increasing	Shifts in composition	Increasing	Shifts in ecotypes	-	-	-	Shifts in composition
Eukaryotic heterotrophs	-	Shifts in composition	-	-	-	-	-	-
Bacterioplankton	Increasing	Shifts in composition	-	Shifts in composition	-	Shifts to tolerant groups	Potential increases	Minor changes

Unresolved represents unclear trends between different studies/ regions.

- Indicates inconclusive or non-existent data where we are unable to draw conclusions

While it is generally assumed that temperature drives most plankton changes (Richardson, 2008), ~~some trends can be attributed to~~ other ~~aspects of global change.~~environmental factors

play a role in plankton dynamics. For example, a strengthening of the East Australia current ~~resulted in tropicalization of~~tropicalized temperate ~~cyano-~~cyanobacteria and heterotrophic bacteria and alteration of phytoplankton community composition (Ajani et al., 2016; Messer et al., 2020). Nutrients represent another key anthropogenic influence on the plankton~~; for example~~, harmful algal blooms (HABs) have increased in geographic range and frequency in coastal areas since the 1980s in response to increased riverine nutrient inputs (Glibert, 2020). Similarly, zooplankton community changes have been attributed to the combined increases in temperature and nutrients (Holland et al., 2023; Marques et al., 2024)~~. However, we have not identified long-term trends for fungi and other~~ or salinity and oxygen (Peña et al., 2019a). However, we did not find reports of long-term trends for eukaryotic heterotrophs as they are not measured in many time series (Xie et al., 2021). ~~Moreover~~To add further complication, viral abundances are ~~strongly~~rarely measured and are linked to their host, rendering it difficult to differentiate global change's direct impacts on viruses from ~~those on the~~shifts in host communities.

Short-term events:

This section examines a number of short-term extreme events which are themselves the products of global change (Table 1). **Marine heat waves**, persistent anomalously warm ocean temperatures, highlight the thermal sensitivity of plankton communities~~; however~~. However, observed changes in phytoplankton communities during heat waves may reflect ~~both~~a number of factors including warming and reduced nutrient inputs through stratification, such as a shift toward smaller phytoplankton ~~(Peña et al., 2019; Brown et al., 2024).~~(Peña et al., 2019b; Brown et al., 2024) or a shift

away from frustule-forming diatoms due to low silicate (Arteaga and Rousseaux, 2023). Zooplankton communities may also transition toward smaller, thermally-tolerant species, which can reduce grazing pressure on phytoplankton as well as total zooplankton biomass (Huỳnh et al., 2024). ~~In the North Pacific, marine heatwaves, have caused declines in large copepod populations, which are replaced by smaller, less energy-rich species, reducing food quality for higher trophic levels (Capuzzo et al., 2017).~~ Within the bacterioplankton, heat waves shifted the microbiome toward more thermally tolerant taxa and favour rare taxa (Brown et al., 2024.) Moreover, in one system, heat-wave induced bacterial community composition changes did not recover once temperatures return to seasonal averages (Larkin et al., 2020).

Wildfires: Although they are terrestrial in origin, fires can release growth-limiting resources (e.g., nitrogen, iron) through both wind and water-based dispersal that fuel phytoplankton blooms (Ardyna et al., 2022). While less is known about heterotrophs' responses to wildfires, they can increase marine organic matter (Coward et al., 2022), which could stimulate heterotrophic growth and remineralization of ~~additional~~ carbon dioxide.

Storms: Similarly, strong storms (e.g., tropical cyclones), can be multi-faceted disturbances that alter a number of environmental factors, making it difficult to identify the proximal drivers of shifts in the plankton. Somewhat surprisingly, these ~~tropical cyclones~~storms do not necessarily fuel dramatic or long-term changes in the

bacterioplankton, despite altered environmental factors, but appear to transiently drive shifts in the relative abundance of existing taxa and increase photosynthetic biomass, potentially favoring eukaryotic algae over cyanobacteria (Ares et al., 2020; Gronniger et al., 2022).(Ares et al., 2020; Gronniger et al., 2022; Johnson et al., 2025). Similarly, zooplankton are often resistant to tropical cyclone impacts, except when higher primary production fuels a zooplankton bloom (Topor et al., 2022). Although little is known about fungieukaryotic heterotrophs, salinity changes and terrestrial/phytoplankton detritus in coastal waters, can cause the transient blooms of specific micro-eukaryotes (Duan et al., 2018; Xie et al., 2021).

Other events: While we have focused on a number of discrete events as described above, additional factors such as ocean oscillations, deoxygenation, nutrient influxes, and changes in terrestrial influences (e.g., salinity, terrestrial organic matter) may also influence plankton dynamics. For example, harmful algal blooms resulting in fish kills have been linked to drought conditions influenced by the Southern Annular Mode (Mardones et al., 2021). Ocean deoxygenation (e.g. increases in oxygen minimum zones) are predicted to impact species, especially those sensitive to low oxygen levels, but without discernible impact on heterotrophic eukaryotes (Herrera et al., 2019; Li et al., 2024)increases in oxygen minimum zones) are predicted to impact organisms, especially those sensitive to low oxygen levels, but without discernible impact on heterotrophic eukaryotes (Herrera et al., 2019; Li et al., 2024). Due to the severe under-sampling of coastal oceans and the lack of baseline data needed to identify anomalies from a high-variability baseline, we are likely missing a number of critical events and responses among plankton.

Region-specific changes

~~For many oceans there is insufficient data to differentiate regional trends from those observed globally, in these cases we do not add attempt to add regional trends, even when data exists in these locations:~~ A full review of changes observed in plankton communities at the regional scale is beyond the scope of this subchapter due to the high diversity of plankton organisms and to the paucity of long-term monitoring programs. Ratnarajah and others (2023) have recently reviewed the global information from zooplankton long-term monitoring programs, that shows temperature related advancements in the seasonal peak and in poleward shifts of distribution of a few species or taxonomical groups (Table 2) in the North Atlantic and in the North Pacific oceans In the Southern Ocean, Antartic krill (*Euphausia superba*) and sapls showed poleward shifs. However, the seasonality of the pteropod *Limacina helicina* and the distribution of copepod species remained resilient to warming patterns and did not show apparent changes. The lack of patterns observed in other areas, can be partially explained by the limited number of long-term monitoring programs in areas beyond North America and western Europe and particularly in the global south. However, the overall absence of more examples of seasonal or geographical shifts in distribution across all regions can also be related with the reduced accessibility to the data from plankton long-term time series (see figure 3 in Ratnarajah and others, 2023). Although there have been significant improvements in automated or semi-automated analysis of plankton, the availability of detailed taxonomical analysis is further hampered by the

need of high levels of expert dedicated-time together with a decrease in the number of taxonomical experts in a particularly diverse and complex group of organisms. Following, there are other apparent patterns of change in other taxonomical groups at the regional scale observed since WOA II (2018-2023), which show the complexity of the plankton dynamics and the difficulties to observe conspicuous long-term trends at the global scale.

Table 2. Changes in phenology (days in advance per decade and days per increase by ºC of the seasonal peak) and in poleward shift of distribution observed in different zooplankton taxa. Data from Ratnarajah and others, 2023)

Ocean region	Phenology		Poleward shift (km / decade)
	More specific location	Species or group (Decade: Days in advance per decade; ºC: days in advance per increase by ºC); n.c., no change	
North Atlantic and adjacent seas	Central North Sea	Biomass of major zooplankton groups (Decade: 2.2 – 10; ºC: 11 – 52)	*Centropages chierchiae* (157-260) *Temora stylifera* *Calanus finmarchicus* (8-16)
	Narragansett Bay	*Mnemiopsis leidyi* (Deacade: 11; ºC: 49) *Acarti tonsa* (n.c.)	
	Gironde estuary	Several *Zooplankton and ichtyoplankton* species	
North Pacific Ocean	Subarctic Pacific Ocean	*Neocalanus plumchrus* (Decade: 14; ºC: 73)	
Southern Ocean	Palmer station, Antartica	*Limacina helicina antárctica* (n. c.)	*Euphausia superba* and salps (not estimated)

			Copepods (n.c.)

4.1 The Arctic Ocean- The most dramatic changes in the Arctic Ocean have been driven by warming and reduced sea ice cover (Ardyna and Arrigo, 2020); WOAIII Chapter 3). Increased open water has led to a 30% increase in net primary production, accompanied by the loss of sea-ice associated plankton (Hop et al., 2020; Ardyna et al., 2022). Furthermore, global change is increasing the "Atlantification" of the Arctic Ocean; for example, the poleward expansion range of *Emiliania huxley*, a calcifying coccolithophore (Oziel et al., 2020), among others. These changes in arctic phytoplankton communities and sea ice affect zooplankton phenology, production, and community composition (Wang et al., 2015); however, less is known about other plankton types. , such as e.g. ciliates (Wang et al., 2023)

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea- insufficient data to determine regional trends

Phytoplankton blooms have occurred 1 to 2 weeks earlier over the last 2 decades in the Baltic sea, associated to increased sunshine and decreased strong wind conditions. Higher temperatures were linked with earlier and decreasing diatom blooms and a higher proportion of dinoflagelates (Hjerne et al 2019). In the Black sea, shifts in the composition of the dominant species have been observed, together with an increase in the proportion of dinoflagellates, particularly in Autumn (Stelmakh and others, 2023). In the Mediterranean, diatoms

concentration is decreasing and cyanobacteria concentration is increasing and the whole Mediterranean Sea is shifting to an eastern Mediterranean state (Hourany and others, 2021).

~~**4.3 The South Atlantic Ocean and the Wider Caribbean-** insufficient data to determine regional trends~~

~~**4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf-** insufficient data to determine regional trends~~

~~**4.5** **The** **North** **Pacific Ocean-** insufficient data to determine regional trends~~

The warm anomaly in the Gulf of Alaska in 2014 reduced silica supply and led to a switch in community composition from diatoms to dinoflagellates, resulting in an increase in surface ocean chlorophyll during the Summer–Fall. A more dramatic change was observed in the equatorial Pacific, where the extreme warm conditions of the 2016 El Niño resulted in a major decline of about 40% in surface chlorophyll, which was associated with a nearly total collapse in diatoms (Arteaga and Rouseaux, 2023). The 2023 El Niño may have provoked similar dramatic effects, although its consequences on plankton are yet to be documented.

~~**4.6 The South Pacific Ocean-** insufficient data to determine regional trends~~

~~**4.7** **The Southern Ocean-** This region has experienced greater warming than other regions, resulting in phytoplankton blooms ~~likely~~ due to declines in sea ice and nutrient influxes (Ferreira et al., 2024). However, ~~observations~~ despite warming, mesozooplankton communities from the South Atlantic and West Antarctic Peninsula did not ~~find significant changes in mesozooplankton communities despite warming~~significantly change, suggesting possible

thermal resilience ~~(Tarling et al., 2018)~~(Tarling et al., 2018). ~~A~~This region is also subject to the influence of short-term events; a marine heat wave in the western Antarctic Peninsula showed a 60% decrease in microbial community biomass and a shift from a cryptophyceae-dominated community toward nanoflagellates and heterotrophic plankton (Latorre et al., 2023). ~~The~~Additionally, the Australian wildfires (2019-2020) were linked to months-long phytoplankton blooms in the Southern Ocean, potentially due to fertilization of ~~the~~ iron-limited waters (Tang et al., 2021).

Remaining key knowledge and capacity changes and any new gaps

~~In reviewing the literature, we noted a number of gaps that warrant attention from the scientific community. Here, w~~We advocate for long-term time series to capture both long-term trends and situate extreme events in context; to clarify whether these events result in statistically-discernible impacts on plankton and the persistence of altered plankton states. However, ~~most long-term time series are limited to~~ we make the ~~open ocean~~case that specific groups (notably, heterotrophic bacteria and ~~to surface waters, resulting in a lack of data from~~eukaryotes) and regions (e.g., ~~the coastal ocean~~ the global south and ~~deep-sea~~depths below the photic zone) are underrepresented relative to their biogeochemical importance. We also lack long-term data (as well as event-driven sampling) on bacterioplankton as well as heterotrophic eukaryotes. Considering these groups' critical functions in decomposing organic matter and secondary production, ~~climate change and extreme events can significantly impact~~and thus marine carbon cycling. However, we should not discount ~~the fact~~ that non-determinative factors, (e.g~~.~~., drift) shapes plankton communities; therefore, care should be taken when interpreting long-term

trends as being driven by global change or in predicting the reproducibility of short-term disturbance responses. ~~However, t~~To understand dynamics of the plankton within the context of climate variability and extreme events, long-term, high-resolution plankton observatories are needed, ideally across taxonomic groups, so that we can track transmission of impacts across food webs ~~can be better determined~~ (Hunt and Ward, 2015). ~~Furthermore, contextualizing extreme events requires long-term observations, to differentiate background variability; therefore~~Therefore, we advocate for sustained and even expanded support for plankton observatories in the face of changing climate.

References

Affairs, U.N.O.o.L. (2021) *The Second World Ocean Assessment*: United Nations.

Ajani, P.A., Hallegraeff, G.M., Allen, D., Coughlan, A., Richardson, A.J., Armand, L.K. et al. (2016) Establishing baselines: Eighty years of phytoplankton diversity and biomass in south-eastern Australia. *Oceanography and marine biology*: 395-420.

Ardyna, M., and Arrigo, K.R. (2020) Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change* **10**: 892-903.

Ardyna, M., Hamilton, D.S., Harmel, T., Lacour, L., Bernstein, D.N., Laliberté, J. et al. (2022) Wildfire aerosol deposition likely amplified a summertime Arctic phytoplankton bloom. *Communications Earth & Environment* **3**: 201.

Ares, Á., Brisbin, M.M., Sato, K.N., Martín, J.P., Iinuma, Y., and Mitarai, S. (2020) Extreme storms cause rapid but short-lived shifts in nearshore subtropical bacterial communities. *Environmental Microbiology* **22**: 4571-4588.

Arteaga, L.A., and Rousseaux, C.S. (2023) Impact of Pacific Ocean heatwaves on phytoplankton community composition. *Communications Biology* **6**: 263.

Beaugrand, G., Conversi, A., Atkinson, A., Cloern, J., Chiba, S., Fonda-Umani, S. et al. (2019) Prediction of unprecedented biological shifts in the global ocean. *Nature Climate Change* **9**: 237-243.

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M. et al. (2013) Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**: 6225-6245.

Brown, M.V., Ostrowski, M., Messer, L.F., Bramucci, A., van de Kamp, J., Smith, M.C. et al. (2024) A marine heatwave drives significant shifts in pelagic microbiology. *Communications Biology* **7**: 125.

Couret, M., Landeira, J.M., del Pino, Á.S., and Hernández-León, S. (2023) A 50-year (1971–2021) mesozooplankton biomass data collection in the Canary Current System: Base line, gaps, trends, and future prospect. *Progress in Oceanography* **216**: 103073.

Coward, E.K., Seech, K., Carter, M.L., Flick, R.E., and Grassian, V.H. (2022) Of sea and smoke: evidence of marine dissolved organic matter deposition from 2020 western United States wildfires. *Environmental Science & Technology Letters* **9**: 869-876.

Dai, Y., Yang, S., Zhao, D., Hu, C., Xu, W., Anderson, D.M. et al. (2023) Coastal phytoplankton blooms expand and intensify in the 21st century. *Nature* **615**: 280-284.

Duan, Y., Xie, N., Song, Z., Ward, C.S., Yung, C.-M., Hunt, D.E. et al. (2018) A High-Resolution Time Series Reveals Distinct Seasonal Patterns of Planktonic Fungi at a Temperate Coastal Ocean Site (Beaufort, North Carolina, USA). *Appl Environ Microbiol* **84**: e00967-00918.

Fernandez de Puelles, M.L., Gazá, M., Cabanellas-Reboredo, M., and O'Brien, T.D. (2023) Decadal Trends in the Zooplankton Community of the Western Mediterranean. *Water* **15**: 4267.

Ferreira, A., Mendes, C.R., Costa, R.R., Brotas, V., Tavano, V.M., Guerreiro, C.V. et al. (2024) Climate change is associated with higher phytoplankton biomass and longer blooms in the West Antarctic Peninsula. *Nature Communications* **15**: 6536.

Frémont, P., Gehlen, M., Vrac, M., Leconte, J., Delmont, T.O., Wincker, P. et al. (2022) Restructuring of plankton genomic biogeography in the surface ocean under climate change. *Nature Climate Change* **12**: 393-401.

Glibert, P.M. (2020) Harmful algae at the complex nexus of eutrophication and climate change. *Harmful algae* **91**: 101583.

Gronniger, J.L., Wang, Z., Brandt, G.R., Ward, C.S., Tsementzi, D., Mu, H. et al. (2022) Rapid changes in coastal ocean microbiomes uncoupled with shifts in environmental variables. *Environmental Microbiology* **24**: 4167-4177.

Heneghan, R.F., Everett, J.D., Blanchard, J.L., Sykes, P., and Richardson, A.J. (2023) Climate-driven zooplankton shifts cause large-scale declines in food quality for fish. *Nature Climate Change* **13**: 470-477.

Herrera, I., Yebra, L., Antezana, T., Giraldo, A., Färber-Lorda, J., and Hernández-León, S. (2019) Vertical variability of *Euphausia distinguenda* metabolic rates during diel migration into the oxygen minimum zone of the Eastern Tropical Pacific off Mexico. *Journal of Plankton Research* **41**: 165-176.

Hjerne O, Hajdu S, Larsson U, Downing AS and Winder M (2019) Climate Driven Changes in Timing, Composition and Magnitude of the Baltic Sea Phytoplankton Spring Bloom. Front. Mar. Sci. 6:482. doi: 10.3389/fmars.2019.00482

Holland, M., Louchart, A., Artigas, L.F., and Mcquatters-Gollop, A. (2023) Changes in Phytoplankton and Zooplankton Communities Common Indicator Assessment Changes in Phytoplankton and Zooplankton Communities. *OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic*.

Hop, H., Vihtakari, M., Bluhm, B.A., Assmy, P., Poulin, M., Gradinger, R. et al. (2020) Changes in sea-ice protist diversity with declining sea ice in the Arctic Ocean from the 1980s to 2010s. *Frontiers in Marine Science* **7**: 243.

Hourany, R., Mejia, C., Faour, G., Crépon, M., & Thiria, S. (2021). Evidencing the impact of climate change on the phytoplankton community of the Mediterranean Sea through a bioregionalization approach. Journal of Geophysical Research: Oceans, 126, e2020JC016808. https://doi.org/10.1029/2020JC016808

Hunt, D.E., and Ward, C.S. (2015) A network-based approach to disturbance transmission through microbial interactions. *Frontiers in Microbiology* **6**: 1182.

Huỳnh, T.H., Horváth, Z., Pálffy, K., Kardos, V., Szabó, B., Dobosy, P., and Vad, C.F. (2024) Heatwave-induced functional shifts in zooplankton communities result in weaker top-down control on phytoplankton. *Ecology and Evolution* **14**: e70096.

Johnson, Z.I., Hunt, D.E., and PICO, C. (2025) The Piver's Island Coastal Observatory – a decade of weekly+ observations reveal the press and pulse of a changing temperate coastal marine system. *Frontiers in Marine Science* **12**.

Jones, E.G., Ramakrishna, S., Vikineswary, S., Das, D., Bahkali, A.H., Guo, S.-Y., and Pang, K.-L. (2022) How do fungi survive in the sea and respond to climate change? *Journal of Fungi* **8**: 291.

Knecht, N.S., Benedetti, F., Hofmann Elizondo, U., Bednaršek, N., Chaabane, S., de Weerd, C. et al. (2023) The impact of zooplankton calcifiers on the marine carbon cycle. *Global Biogeochemical Cycles* **37**: e2022GB007685.

Kwon, E.Y., Sreeush, M., Timmermann, A., Karl, D.M., Church, M.J., Lee, S.-S., and Yamaguchi, R. (2022) Nutrient uptake plasticity in phytoplankton sustains future ocean net primary production. *Science Advances* **8**: eadd2475.

Larkin, A.A., Moreno, A.R., Fagan, A.J., Fowlds, A., Ruiz, A., and Martiny, A.C. (2020) Persistent El Niño driven shifts in marine cyanobacteria populations. *PLoS One* **15**: e0238405.

Latorre, M.P., Iachetti, C.M., Schloss, I.R., Antoni, J., Malits, A., de la Rosa, F. et al. (2023) Summer heatwaves affect coastal Antarctic plankton metabolism and community structure. *Journal of Experimental Marine Biology and Ecology* **567**: 151926.

Li, J., Xie, N., Liu, X., Bai, M., Hunt, D.E., and Wang, G. (2024) Oxygen levels differentially attenuate the structure and diversity of microbial communities in the oceanic oxygen minimal zones. *Science of The Total Environment* **948**: 174934.

Mardones, J.I., Paredes, J., Godoy, M., Suarez, R., Norambuena, L., Vargas, V. et al. (2021) Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016. *Science of The Total Environment* **766**: 144383.

Marques, R., Otto, S., Di Pane, J., Boersma, M., Meunier, C., Wiltshire, K.H. et al. (2024) Response of the meso-and macro-zooplankton community to long-term environmental changes in the southern North Sea. *ICES Journal of Marine Science* **81**: 526-539.

Messer, L.F., Ostrowski, M., Doblin, M.A., Petrou, K., Baird, M.E., Ingleton, T. et al. (2020) Microbial tropicalization driven by a strengthening western ocean boundary current. *Global Change Biology* **26**: 5613-5629.

Oziel, L., Baudena, A., Ardyna, M., Massicotte, P., Randelhoff, A., Sallée, J.-B. et al. (2020) Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean. *Nature Communications* **11**: 1705.

Peña, M., González-Quirós, R., Munuera-Fernández, I., González, F., Romero-Romero, S., and Nogueira, E. (2019a) Vertical distribution and aggregation patterns of krill (Crustacea:

Euphausiacea) in the Bay of Biscay: interannual and seasonal variability. *Canadian Journal of Zoology* **97**: 619-630.

Peña, M.A., Nemcek, N., and Robert, M. (~~2019~~2019b) Phytoplankton responses to the 2014–2016 warming anomaly in the northeast subarctic Pacific Ocean. *Limnology and Oceanography* **64**: 515-525.

Pitois, S.G., and Fox, C.J. (2006) Long-term changes in zooplankton biomass concentration and mean size over the Northwest European shelf inferred from Continuous Plankton Recorder data. *ICES Journal of Marine Science* **63**: 785-798.

Ratnarajah L, Abu-Alhaija R, Atkinson A, Batten S, Bax NJ, Bernard KS, et al. Monitoring and modelling marine zooplankton in a changing climate. Nature Communications 2023; 14:564. https://doi.org/10.1038/s41467-023-36241-5

Richardson, A.J. (2008) In hot water: zooplankton and climate change. *ICES Journal of Marine Science* **65**: 279-295.

Soviadan, Y.D., Dugenne, M., Drago, L., Biard, T., Trudnowska, E., Lombard, F. et al. (2024) Combining in situ and ex situ plankton image data to reconstruct zooplankton (>1 mm) volume and mass distribution in the global ocean. *Journal of Plankton Research* **46**: 461-474.

Stelmakh, L., Kobrigina, N. and Gorbunova, T. (2023). Phytoplankton seasonal dynamics under conditions of climate change and anthropogenic pollution in the western coastal waters of the Black Sea (Sevastopol Region). Journal of Marine Science and Engineering, 11(3), 569. https://doi.org/10.3390/jmse11030569

Tang, W., Llort, J., Weis, J., Perron, M.M.G., Basart, S., Li, Z. et al. (2021) Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature* **597**: 370-375.

Tarling, G.A., Ward, P., and Thorpe, S.E. (2018) Spatial distributions of Southern Ocean mesozooplankton communities have been resilient to long-term surface warming. *Global ~~change biology~~Change Biology* **24**: 132-142.

Topor, Z., A. Genung, M., and Robinson, K. (2022) Multi-storm analysis reveals distinct zooplankton communities following freshening of the Gulf of Mexico shelf by Hurricane Harvey. *Scientific Reports* **12**: 8721.

Vellend, M. (2010) Conceptual synthesis in community ecology. *The Quarterly review of biology* **85**: 183-206.

Wang, C., Wang, X., Xu, Z., Luo, G., Chen, C., Li, H. et al. (2023) Full-depth vertical distribution of planktonic ciliates (Ciliophora) and a novel bio-index for indicating habitat suitability of tintinnid in the Arctic Ocean. *Marine Environmental Research* **186**: 105924.

Wang, S.W., Budge, S.M., Iken, K., Gradinger, R.R., Springer, A.M., and Wooller, M.J. (2015) Importance of sympagic production to Bering Sea zooplankton as revealed from fatty acid-carbon stable isotope analyses. *Marine Ecology Progress Series* **518**: 31-50.

Xie, N., Hunt, D.E., Johnson, Z.I., He, Y., and Wang, G. (2021) Annual Partitioning Patterns of Labyrinthulomycetes Protists Reveal Their Multifaceted Role in Marine Microbial Food Webs. *Applied and Environmental Microbiology* **87**: e01652-01620.

Chapter 4 Biodiversity

Sub-chapter 4B: Cephalopods

Vecchione, M., G. J. Barord, M. Díaz-Santana-Iturrios, L. Hendrickson, E. Lefkaditou, J. Mather, H. Moustahfid, K. K. Sajikumar, H. Kidokoro, W. H. H. Sauer, and H.-J. Hoving.

1 Keynotes

- As of 2024, there are 87~~7~~61 extant ~~cephalopod~~ species on the planet.
- Most data regarding cephalopod populations and abundance comes from fisheries.
- Squids ~~mostly~~ represent most cephalopod landings.
- The region with the highest species richness is the South Pacific Ocean, with 27 percent of extant cephalopod species.

2 Introduction

This is an update to "Status of pelagic invertebrates: cephalopods", an addendum to World Ocean Assessment II: Volume I. As a result, we concentrate on the variations in knowledge, estimated abundance, distribution, and functional role of cephalopods during the years 2018 to 2024, which straddle WOAII and WOAIII. However, additional information is included here because the addendum was brief and somewhat idiosyncratic.

Cephalopods ~~generally~~ are generally free-swimming (holopelagic or demersal) marine invertebrates with complex nervous systems and behavior. They range in size from small (total length <1 cm) to huge (>14.5 m) and in distribution and abundance from solitary individuals to very large schools. Most have short lives and fast growth, and species are found from the intertidal zones (and estuaries in exceptional cases) to hadal depths, including the water column and benthic environments. In addition to being fishery targets, some species can be important predators and prey within ecosystems and some are model organisms for biomedical and behavioral research.

Other chapters within this assessment and that are relevant to cephalopods include those on fishing, pollution, climate change, marine mammals, and other large predators (e.g., tunas and billfishes) and preys (e.g., plankton and marine benthic invertebrates ~~,~~), as well ~~and~~ chapters on the various marine ecosystems in which cephalopods live. For example, the importance of food-web connections was highlighted recently by a publication (Pérez-

Puig et al., 2024) showing that sperm whales abandoned a traditional hunting area in the Gulf of California~~Sea of Cortez~~, probably because of reduced abundance of Humboldt squid there.

3 The environmental change since WOAII

Despite the lack of data on most of the cephalopod species, it is considered that multiple human activities threaten their populations, including overharvesting through both legal and IUU fishing either as targets or by-catch, and physical disturbance of habitat (Barret et al. 2022). Climatic and environmental shifts also affect habitat, including ~~and~~ spawning grounds, and cause direct physiological effects, e.g., on *Sepia officinalis* (Rosa et al. 2013) and *Octopus rubescens* (Onthank et al. 2020). Notably, even when not catching cephalopods, trawl and dredge fisheries can destroy the eggs of bottom spawners, including myopsids, sepiids, and most octopods (FAO, 2008).

3.1 Changes in the overall status

Table 1 summarizes current knowledge of cephalopod diversity based on the World Registry of Marine Species (WoRMS, 2024). A total of 8~~7~~61 species are currently recognized, categorized across nine Orders in two subclasses. Of these, 33 (4.3%) have been described since 2017 until December, 2024 (averaging >4 n. spp., or about 0.5% of the total per year) (Table I).

As of October 2024, the International Union for Conservation of Nature (IUCN, 2024) Red List assessed 754 cephalopod species, and the cephalopod listing numbers are essentially unchanged from WOA II. The five cirrate octopod species noted previously as “critically endangered”, “endangered”, and “vulnerable” are threatened as bycatch in deep bottom-trawl fisheries. One cuttlefish (*Ascarosepion*~~*Sepia*~~ *apama*), one octopod (*Octopus kaharoa*), and one nautilid (*Nautilus belauensis*) are now “near threatened”. In total, 324 species are of “least concern”, but most species (422) are “data deficient”. The latter include some commercial species, probably due to inadequacies in data collection (Keller at al., 2015). Because cephalopods exhibit different life histories (Ibáñez et al. 2021) and the life

cycle of most species is unknown, their distribution, diversity patterns and abundance ~~of cephalopods~~ are uncertain.

Appendix II of the *Convention on International Trade in Endangered Species of Wild Fauna and Flora* (CITES, 1974) listed only nautilids prior to 2018. Because the listing included the entire family, the newly recognized (since 2017) nautilid species ~~, which had been newly recognized since 2017~~ (Barord et al. 2023) are included in this CITES protection. The primary nautilid problem is overfishing. No other cephalopods have yet been included in CITES listings.

Most information about cephalopod populations and their abundance comes from fisheries, either through fishery-related surveys (for which quantitative data are more rigorous) or, more commonly, landings (Fig. 1A). Cephalopod landings are strongly dominated by the oegopsid squid family Ommastrephidae (Fig. 1B; Arkhipkin et al. 2015). However, landing data for cephalopods in general frequently combines various species into one common name (see Arkhipkin et al. 2015; Sauer et al. 2021~~19~~). Confident determination of diversity patterns and causes of their changes (e.g., poleward shifts in distribution as in *Dosidicus gigas*, see Ramos et al. 2017) require large-scale comparability of abundance data, rather than presence/absence and fisheries landings, the latter being the current state of knowledge about most species. In this regard, assessing populations for conservation or fisheries management proves challenging without precise data collection. For many species, planning for stock sustainability is further complicated due to a lack of joint management plans for transboundary distributions, which could have limited the achievement of target of 14.4 of SDG 14, planned for 2020. Moreover, ~~from the few independent ecological studies of species or populations that have targeted cephalopods,~~ the global patterns of species richness in coastal cephalopods are now known from the few independent ecological studies that have targeted cephalopods (see Rosa et al. 2019). The most diverse region is the South Pacific Ocean with 207 species (Table 2).

Along with decapod crustaceans, cephalopods are the first invertebrates for which ethical treatment in handling and experimentation is being addressed ~~broadly~~ (Fiorito et al., 2015~~Mather, 2022~~). They have had protection in regard to research for ethical reasons in Canada and Australia and broader protection in the European Union (Directive 2010/63/EU) since 2013 (Fiorito et al., 2015) and the UK since 2022. Protection for research in the USA, specifically banning octopods~~us~~ farming, is being considered by the National Institutes of Health under its *Institutional Animal Care and Use Committee* (IACUC) mandate and has been implemented in a couple of states in the US. Few cephalopods are

protected in the wild, but in the US, the Washington Department of Fish and Wildlife has designated eight dive sites in the Seattle region as Octopus Protection Areas.

I~~Similar i~~ssues have been raised concerning the field of cephalopod aquaculture. ~~.~~ Difficulties with artificial diet, ~~lack of a luxury market for farmed cephalopods,~~ potential for environmental pollution and public concern regarding the crowding of solitary octopods, fueled by popular media, argue against octopus farming ~~-~~(Jacquet et al., 2024; Mather, 2022). However, cephalopod aquaculture in the world is still ~~remains largely in the~~ experimental ~~stages for most cases~~, which present~~s~~ing the perfect opportunity to establish rigorous ethical standards for the practice, both for commercial and restorative purposes (Gleadall et al., 2025 ~~in press~~).

4 Region-specific changes

4.1 The Arctic Ocean

Recent studies of the Arctic (Golikov et al. 2013), compared with earlier work by the Soviet Union have shown distinct shifts in cephalopod distributions, consistent with the concept of "Atlantification" of the Arctic, climatic changes leading to boreal cephalopods spreading into the polar basin via its main connection with the North Atlantic. *Teuthowenia megalops* and *Todaropsis eblanae* were found in the Arctic for the first time, 1000 – 2500 km from their historical ranges. These shifts are also related to the fluctuation of *Todarodes* populations in the main part of their North Atlantic range. Meanwhile, the Arctic species *Gonatus fabricii* has expanded its range to areas where warming is particularly noticeable. This may impact species interactions in vulnerable Arctic ecosystems. This pattern of shifting distributions of Arctic and North Atlantic cephalopods in response to climate change has continued and been further demonstrated with additional long-term data by Golikov et al. (2024).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Cephalopod landings are dominated by octopods and cuttlefishes (Pierce at al., 2010), coming mainly from bottom-trawl fisheries and traditional small-scale fisheries, either targeted or as by-catch, ~~targeting cephalopods over many years,~~ particularly in the Mediterranean and along the Iberian Peninsula (Sauer et al., 2021~~19~~). Management of cephalopod stocks in European waters remains limited. Each individual country implements precautionary measures concerning numbers of fishing traps and region-

specific closed seasons in small-scale fisheries targeting *Octopus vulgaris*. Total cephalopod landings from the NE Atlantic have been relatively stable since 1992, but those of cuttlefishes showed high abundance in~~are currently near the low end of the recent range, part of a general downward trend since~~ 2004, which declined in the following years (ICES-WGCEPH, 2023).

The abundance of *Octopus vulgaris* in north-west Africa, particularly off the coast of Morocco, has declined due to fisheries pressure and environmental impacts (FAO, 2020). A catch of 89,000 tons was reported for this region in 2019, accounting for 32% of total demersal catches (FAO, 2020). Octopus holds substantial economic value, particularly in Mauritania, where it is the top fishery resource by value, underscoring the dependence of local economies on this species. The rising global demand for octopus has increased exporting countries, with Japan, Spain, and Italy being the primary importers from Northwest Africa (Sauer et al. 2021~~19~~). In Morocco, *O. vulgaris* is harvested by three main types of fishing fleets: industrial freezer trawlers, artisanal wooden boats employing pots and hand jigs, and coastal ice trawlers utilizing various trawl types. While Morocco has implemented management and conservation measures—such as catch limitations, individual quotas, zoning, and restrictions on immature subadult~~juvenile~~ captures—these efforts must contend with the cumulative effects of overfishing and environmental changes driven by climate factors. Therefore, whereas current regulations aim to promote sustainable fisheries, ongoing monitoring and adaptive management strategies are essential to mitigate the abovementioned risks.

Regarding taxonomic aspects, with the recent resurrection of *Ommastrephes caroli* (Fernández-Álvarez et al. 2020) new studies have been conducted concerning their biology (see Agus et al. 2021; Petrić et al. 2024). This knowledge brings essential information for the species and can be incorporated in future macroevolutionary studies of cephalopods.

4.3 The South Atlantic Ocean and the Wider Caribbean

This region hosts 81 coastal cephalopod species (Rosa et al. 2019). Avendaño et al. (2020) debunked the presence of *Octopus vulgaris* in the western coast and confirmed the distribution of *Octopus americanus* instead. Similarly, the squid species *Ommastrephes cylindraceus* was resurrected by Fernández Álvarez et al. (2020), which will contribute to better delimit its specific distribution range and concomitantly bring the respective implications for conservation and resources management. Another taxon with fishery management implications is *Thysanoteuthis rhombus*, previously considered as the single

species of the family Thysanoteuthidae, with a global distribution range in tropical and subtropical waters, now restricted to the North and South Atlantic Ocean and Mediterranean Sea and with other two congener species (Deville et al. 2024).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Fisheries for cephalopods around the western Indian Ocean are expanding (Fig. 1A), particularly for octopods. Management measures in some countries have increased annual landings. Fluctuations in catch may be an indication of climate-change impacts, natural inter- or intra-annual variability, changes in abundance of stocks or changes in availability due to other environmental drivers or ecosystem shifts.
The Indian Ocean Sea regions, including the Arabian Sea, the Bay of Bengal, and the Southern Indian Ocean, provide a rich and diverse habitat for cephalopods (Aravindakshan and Sakthivel 1973; Sajikumar et al., 2020). A total of 20 species of commercially important cephalopods have been identified from the Indian coast, which includes 8 species of squids (orders Myopsida and Oegopsida) ~~(order Teuthoidea)~~, 6 species of cuttlefishes (order Sepii~~o~~d~~e~~a) and 6 species of octopus (order Octopod~~ide~~a) (Mohamed and Venkatesan, 2017). The dominant species occurring in commercial catches are *Uroteuthis (Photololigo) duvaucelii*, ~~*Sepia*~~ *Acanthosepion pharaonis*, *A~~S~~. aculeata* and *Amphioctopus neglectus* (Mohamed and Venkatesan 2017), with an annual landing of 212517 tonnes (FRAEED, CMFRI, 2024).

Cephalopod conservation measures in the mechanized fisheries sector are mainly related to fisheries regulations. The ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI) has recommended minimum legal size (MLS) and corresponding body weight (BW) for *Uroteuthis duvaucelii* (DML=80 mm and 25 g BW), *Acanthosepion*~~*Sepia*~~ *pharaonis* (DML=115 mm and 150 g BW) and *A. neglectus* (DML=45 mm and 15 g BW) (Mohamed et al., 2014) that is legislated and enforced in Kerala, Karnataka and Maharashtra along the south-west coast of India. Cephalopods are targeted mainly by trawlers. The fisheries closure for all mechanized fishing vessels is applied for 61 days from June 1 to July 31 on the west coast (Arabian Sea) and from April 15 to June 14 on the east coast (Bay of Bengal), as a means to reduce fishing effort and aid conservation of fishery resources, including cephalopods.

The O~~o~~mmastrephidae squid *Sthenoteuthis oualaniensis* occurs in the oceanic waters of all Indian Ocean regions, with high biomass observed in the Arabian Sea (Mohamed et al., 2018). The neon flying squid, *Ommastrephes cylindraceus*, has been studied in the southern Indian ocean (40°11 S to 47°30 S) (Fernández-Álvarez et al., 2020). The diamond-

back squid *Thysanoteuthis rhombus* is also distributed all along the seas around India except the southern Indian ocean (Sajikumar et al., 2020; Deville et al., 2024). Other non-commercial oceanic squids from the region such as *Bathyteuthis bacidifera*, *Histioteuthis miranda*, *Abralia andamanica* and *Nototodarus hawaiiensis*, have been studied (Sajikumar et al. 2017; 2018, 2022 and 2023).

4.5 The North Pacific Ocean

Squid species, *Todarodes pacificus* is among the most abundant cephalopod species in the north-west Pacific Ocean. In recent years, the stock size of *T. pacificus* in the north-west Pacific Ocean and its marginal seas~~the Sea of Japan~~ has declined, and Japan and the Republic of~~South~~ Korea's catches have declined sharply since 2016 (Okamoto et al. 2023). The stock size of *T. pacificus* is projected to increase due to climate change (Ji et al. 2020). However, despite the rapid rise in water temperatures in the north-west Pacific in recent years, the squid stocks have declined. In a marginal sea in the north-west Pacific Ocean~~the Sea of Japan~~, which is one of the main distribution areas, IUU fishing has complicated accurate catch determination since the 2000s (Park et al. 2020). Determining whether the recent drop in stocks of *T. pacificus* is attributed to fisheries impact or shifts in oceanographic conditions is challenging.

Regarding octopods, in the north-east Pacific Ocean, the species richness of coastal benthic octopuses is higher in the warm temperate region (≈12 species, mainly of *Octopus* and *Paroctopus*) compared with the cold temperate region (≈7 species) (González-Gómez et al. 2024).

4.6 The South Pacific Ocean

All nautiluses (*Nautilus* and *Allonautilus*) species inhabit the fore-reef slopes across the S~~s~~outh Pacific and I~~i~~ndo-Pacific regions to depths of 800 meters. Decades of unregulated fishing supporting a worldwide nautilus shell trade (DeAngelis, 2012) led to fishery decline (Dunstan et al., 2010) and significantly lower population abundances (Barord et al., 2014). Though the inclusion of ~~all~~ nautiluses ~~with~~in Appendix II of CITES effectively reduced international trade, it is not clear how this regulation will improve the localized management of ongoing fisheries. While population decline and potential local extinction (Barord et al., 2022) are most closely tied to fishing, little information is available on how larger anthropogenic factors may impact nautiluses and their habitat.

4.7 The Southern Ocean

~~With 15 recognized cephalopod species,~~ ~~T~~the Southern Ocean exhibits high levels of cephalopod endemism (Rosa et al. 2019; Cherel, 2020). Fifty-two cephalopod species are recognized for the Southern Ocean, 15 are coastal species (Xavier et al. 2018; Rosa et al. 2019). Of the squid species, 21 species are endemic (Cherel, 2020).

5 Remaining key knowledge and capacity changes and any new gaps

Little is known about the life history/life cycle, abundance and ecology of most species, other than those fished commercially or used for biomedical research. This problem is even worse for species in deep-sea and polar regions. Future development of deep-sea mining raises many questions, currently unanswerable, about the impacts of these operations at individual, population, and species levels. However, sustainable measurements are being planned for this economic activity (see Chapter 7).

Comprehensive genetic studies of most species are needed to identify sub-species and genetically distinct population structures and connectivity, both for proper management of exploited species and a better understanding of cephalopod roles in their ecosystems, as well as resilience from potential anthropogenic impacts.

Human impacts on cephalopod populations, such as contaminant loads or effects of harvesting prey or predators, are poorly understood and may counteract projected increases in cephalopod abundances (Doubleday et al. 2016). The global proliferation proposed by Doubleday et al. 2016 is based on just a few species. Recent changes in climatic and oceanographic conditions and their likely effects on cephalopod populations (e.g., effects of increasing acidification on statolith malformation, cuttlebone growth, nautilus shell growth or shifts in depth and geographic latitudinal distribution towards warming waters) may also affect future increases.

As with many fields of marine science, discipline-specific capacity (e.g., taxonomic, fisheries management) and research tools vary regionally. Regional differences in understanding cephalopods mirror more significant issues, such as the impacts of climate change. Deliberate educational programmes can alleviate such problems.

6 References

Agus, B., and others. Molecular and Biological Analysis on Ommastrephes caroli Findings in the Central Western Mediterranean Sea (Sardinian Waters) Including First Age Investigation Using Eye Lenses and Beaks. Frontiers in Marine Science, vol. 8, art. 683856, 2021.

Aravindakshan, P.N., and Sakthivel, M. 1973. The location of cephalopod nurseries in the Indian Ocean. Handbook to the international zooplankton collections, vol. 5, pp. 70–75., 1973.

Arkhipkin, A. I., and others Rodhouse, P. G. K., Pierce, G. J., Sauer, W., Sakai, M., Allcock, L., Arguelles, J., Bower, J. R., Castillo, G., Ceriola, L. et al. 2015. World squid fisheries. Reviews in Fisheries Science and Aquaculture, vol. 23, :92–252. 2015.

Avendaño, O., and others Roura, Á., Cedillo-Robles, C.E. et al. 2020. *Octopus americanus*: a cryptic species of the *O. vulgaris* species complex redescribed from the Caribbean. Aquatic Ecology, vol. 54, 909–925. 2020. https://doi.org/10.1007/s10452-020-09778-6

Barord, G. J., and others Dooley, F., Dunstan, A., Ilano, A., Keister, K. N., Neumeister, H., ... & Ward, P. D. (2014). Comparative population assessments of Nautilus sp. in the Philippines, Australia, Fiji, and American Samoa using baited remote underwater video systems. PLoS One, vol. 9, art. (6), e100799. 2017.

Barord, G. J., and others Ilano, A., Veloso, J., & Ward, P. D. (2022). Survey of Nautilus pompilius Linnaeus, 1758 (Cephalopoda) from Siquijor Island and Dalaguete–Alcoy in the Philippines Using Baited Traps and Baited Remote Underwater Video Systems (BRUVS). Thalassas: An International Journal of Marine Sciences, vol. 38, art. (2), 1099-1103. 2022.

Barord, G. J., and others. Combosch, D. J., Giribet, G., Landman, N., Lemer, S., Veloso, J., & Ward, P. D. (2023). Three new species of Nautilus Linnaeus, 1758 (Mollusca, Cephalopoda) from the Coral Sea and South Pacific. ZooKeys, vol. 1143, art. 51, 2023.

Barrett, C.J., and others Bensbai, J., Broadhurst, M. K., Bustamante, P., Clark, R., Cooke, G. M., Di Cosmo, A., Drerup, C., Escolar, O., Fernández-Álvarez, F. A., Ganias, K., Hall, K. C., Hanlon, R. T., Hernández-Urcera, J., Hua, Q. Q. H., Lacoue-Labarthe, T., Lewis, J., Lishchenko, F., Maselli, V., Moustahfid, H., Nakajima, R., O'Brien, C. E., Parkhouse, L., Pengelly, S., Pierce, G. J., Ramírez, J. G., Robin, J-P., Sajikumar, K. K., Sasikumar, G., Smith, C. L., Villanueva, R., Yến, D. T. H. 2022. Cuttlefish conservation: a global review of methods to ameliorate unwanted fishing mortality and other anthropogenic threats to sustainability. ICES Journal of Marine Science, vol. 79, art. (10,): 2579–2596 2022. . https://doi.org/10.1093/icesjms/fsac200

Cherel, Y. A. review of Southern Ocean squids using nets and beaks. Marine Biodiversity, vol. 50, art. 98, 2020.

CITES. 1974. CITES Appendices I, II and III. 1974. https://cites.org/eng/app/index.php, valid from 21.05.2023. Accessed October 2024.

De Angelis, P. 2012. Assessing the impact of international trade on chambered nautilus. Geobios, vol. 45, art. (1), pp. 5–11, 2012.

Deville, D., and others. Mori, S., Kawai, K. et al. (2024) Cryptic biodiversity in the commercial diamondback squid Thysanoteuthis rhombus Troschel 1857. Reviews

in Fish Biology and Fisheries, vol. 34, 293–313. https://doi.org/10.1007/s11160-023-09813-32024.

Doubleday, Z.A., and othersProwse, T. A. A., Arkhipkin, A., Pierce, G. J., Semmens, J., Steer, M., Leporati, S. C., Lourenço, S., Quetglas, A., Sauer, W., Gillanders, B.M. 2016. Global proliferation of cephalopods.,

Current Biology, vol. 26, art. (10,): R406-R4072016.

Dunstan, A., and othersAlanis, O., & Marshall, J. 2010. Nautilus pompilius fishing and population decline in the Philippines: A comparison with an unexploited Australian Nautilus population. Fisheries Research, vol. 106, art. (2), 239-2472010.

FAO. 2008. Report of the FAO workshop on vulnerable ecosystems and destructive fishing in deep-sea fisheries. Rome, 26–29 June 2007. FAO Fisheries Report, No.no 829, 2008.

FAO. 2020. Report of the FAO/CECAF Working Group on the Assessment of Demersal Resources – Subgroup North Nouakchott, Mauritania, 2–10 December 2019 / Rapport du Groupe de travail FAO/COPACE sur l'évaluation des ressources démersales – Sous-groupe Nord Nouakchott, Mauritanie, 2–10 décembre 2019. Rome, CECAF/ECAF 20/83, Rome.2020. https://doi.org/10.4060/cb1539b

Fernández-Álvarez, F. Á., and others. Braid, H. E., Nigmatullin, C. M., Bolstad, K. S. R., Haimovici, M., Sánchez, P., et al. (2020). Global biodiversity of the genus Ommastrephes d'Orbigny, 1834 (Ommastrephidae: Cephalopoda): an allopatric cryptic species complex. Zoological Journal of the Linnean Society, vol. 190, 460–482020. doi: 10.1093/zoolinnean/zlaa014

Fiorito, G., and othersAffuso, A., Basil, J., Cole, A., de Giorlamo, P., D'Angelo, L., & Andrews, P. L. R. 2015. Guidelines for the care and welfare of cephalopods in research—a consensus based on an initiative by CephRes, FELASA and the boyd group. Laboratory Animals, vol. 49, 1–902015.

FRAEED, CMFRI. (2024) Marine Fish Landings in India - 2023. Technical Report. ICAR-Central Marine Fisheries Research Institute, Kochi, 2024.

Tainah B.N. F., and othersreitas [a], Tatiana S. Leite [b], Bruna de Ramos [c], Maíra C. Proietti [a,d]. 2023. Understanding the interactions between cephalopods and marine litter: A research evaluation with identification of gaps and future perspectives. Marine Pollution Bulletin, vol.Volume 190, May art. 2023, 114814, 2023.

Gleadall, I.G., and otherset al. In press. A balanced approach to the potential of octopus aquaculture. Marine Policy., vol. 179, art. 106682, 2025.

González-Gómez, R., and othersAvendaño, O., de los Angeles Barriga-Sosa, I., Bastos, P., Caamal-Monsreal, C., Castillo-Estrada, G., Cedillo-Robles, C., Daw, A., Díaz-Santana-Iturrios, M., Galindo-Cortes, G., Guerrero-Kommritz, J., Haimovici, M., Ibáñez, C.M., Jiménez-Badillo, M. L., Larson, P., Leite, T., Lima, F.D., Markaida, U., Meiners-Mandujano, C., Morillo-Velarde, P.S., Ortiz, N., Pardo-Gandarillas, M. C., Pliego-Cárdenas, R., Ré, M.E., Siegel, B., Urbano, B., Vidal, E. A. G., Gleadall, I.G.. 2024. Biodiversity of octopuses in the Americas. Marine Biology, vol. 171, art. 189, 2024. https://doi.org/10.1007/s00227-024-04489-0

Golikov , A.V., and others. R.M. Sabirov , P.A. Lubin and L.L. Jørgensen (2013): Changes in distribution and range structure of Arctic cephalopods due to climatic changes of the last decades., Biodiversity, vol. 14, art. :1, 28-352013.

Golikov, A.V., and others L.L. Jørgensen, R.M. Sabirov, D.V. Zakharov and H.J. Hoving (2024). Longterm annual trawl data show shifts in cephalopod community in the western Barents sea during 18 years. Frontiers in. Marine. Science,. vol. 11, art. :1392585., 2024. doi: 10.3389/fmars.2024.1392585

Ibáñez, C.M., and others. Macroevolutionary Trade-Offs and Trends in Life History Traits of Cephalopods Through a Comparative Phylogenetic Approach. Frontiers in Marine Science, vol. 8, art. 707825, 2021.

ICES-WGCEPH. 2023. Working Group on Cephalopod Fisheries and Life History (WGCEPH; Outputs from 2022 meeting). ICES Scientific Reports,. vol. 5, art. :01,. 163 pp. 2023.https://doi.org/10.17895/ices.pub.21976718

IUCN. IUCN Red list - Cephalopods. 2024. https://www.iucnredlist.org/fr/search?query=Cephalopods&searchType=species. Accessed October, 2024.

Jacquet, J., and others. et al. 2024. Support US OCTOPUS Act to keep octopuses wild. Science, vol. 385, art. (6710), :721-722. 2024.

Ji, F., and others. Guo, X., Wang, Y. and Yakayama K. (2020) Response of the Japanese flying squid (*Todarodes pacificus*) in the Japan Sea to future climate warming scenarios. Climatic Change, vol. 159, 601–6182020.. https://doi.org/10.1007/s10584-020-02689-3

Keller, S., and others Robin, J. P., Valls, M., Gras, M., Cabanellas-Reboredo, M., & Quetglas, A. (2015). The use of Depletion Methods to assess Mediterranean cephalopod stocks under the current EU Data Collection Framework. Mediterranean Marine Science, vol. 16, art. (3), 513-523.2015. http://dx.doi.org/10.12681/mms.1127

Mather, J. (2022) Why Are Octopuses Going to Be the 'Poster Child' for Invertebrate Welfare?., Journal of Applied Animal Welfare Science, vol. 25, art. :1, 31-40, 2022.DOI: 10.1080/10888705.2020.1829488

Mohamed, K. S., and Venkatesan, V. (2017) Marine molluscan diversity in India – exploitation, conservation. In: Course Manual Summer School on Advanced Methods for Fish Stock Assessment and Fisheries Management. Lecture Note Series No. 2/2017. CMFRI,; Kochi, Kochi, pp. 56-81.2017.

Mohamed, Y., and othersGhobashy, A., Gabr, H., & Tantawy, H. (2014). Maturation, Fecundity and Seasonality of Reproduction of the Squid Uroteuthis duvauceli (Cephalopoda:Loliginidae) in the Suez Canal. Catrina: The International Journal of Environmental Sciences, vol. 9, art. (1), 33-39.2014.

Mohamed, K. S., and others Sajikumar, K. K., Ragesh, N., Ambrose, T. V., Jayasankar, J., Said Koya, K. P., & Sasikumar, G. (2018). Relating abundance of purpleback flying squid Sthenoteuthis oualaniensis (Cephalopoda: Ommastrephidae) to environmental parameters using GIS and GAM in south-eastern Arabian Sea. Journal of Natural History, vol. 52, art. (29–30,), 1869–1882.2018.

Kirt L. Onthank, K.L., and others. L. A. Trueblood, T. Schrock-Duff, and L. G. Kore1 (2022) Impact of Short- and Long-Term Exposure to Elevated Seawater PCO2 on Metabolic

Rate and Hypoxia Tolerance in *Octopus rubescens*. Physiological and Biochemical Zoology, vol. 94, art. (1,):1–11. 2021.2022.

Okamoto, S., and others. Miyahara, H., Matsui, H., Moriyama, T., Kurashima, A., Abo, J., Nishijima, S. and Setou, S. 2023. Stock assessment and evaluation for winter-spawning stock of Japanese flying squid (fiscal year 2022). Marine fisheries stock assessment and evaluation for Japanese waters. Japan Fisheries Agency and Japan Fisheries Research and Education Agency,. Tokyo, 49 p.p. https://abchan.fra.go.jp/wpt/wp-content/uploads/2022/details_2022_18-Surume-W.pdf (in Japanese)., 2023.

Onthank, K.L., and others Trueblood, L.A., Schrock-Duff, T., and Kore, L.G. 2020. Impact of short- and long-term exposure to elevated seawater PCO2 on metabolic rate and hypoxia tolerance in *Octopus rubescens*. Physiological and Biochemical Zoology, vol. 94, art. (1,):1–11.2020.

Park, J., and others. J. Lee, K. Seto, T. Hochberg, B. A. Wong, N. A. Miller, K. Takasaki, H. Kubota, Y. Oozeki, S. Doshi, M. Midzik, Q. Hanich, B. Sullivan, P. Woods and D. A. Kroodsma (2020) Illuminating dark fishing fleets in North Korea. Science Advances, vol. 6, art. eabb1197., 2020. DOI: 10.1126/sciadv.abb1197

Pérez-Puig, H., and others Arias del Razo, A., Gallardo, D.A. and Bolaños, J. 2024. The departure of sperm whales (Physeter macrocephalus) in response to the declining jumbo squid (Dosidicus gigas) population in the central portion of the Gulf of California. PeerJ, vol. 12, art. (1),: e181172024.

Petrić, M., and others. Ommastrephes caroli (Cephalopoda: Ommastrephidae) from the Adriatic Sea: Morphometry, Age, and Genetic Characterization. Journal of Marine Science and Engineering, vol. 12, art. 7, 2024.

Pierce, G. J., Allcock, L., Bruno, I., Bustamante, P., González, Á., Guerra, Á., Jereb, P., Lefkaditou E., Malham S., Moreno A., Pereira J., Piatkowski U., Rasero M., Sánchez P., Santos B. M., Santurtún M., Seixas S., Sobrino I. & R. Villanueva (Editors), 2010. Cephalopod biology and fisheries in Europe. ICES Cooperative Research Report No. 303. 175 pp., 2010.

Pérez-Puig H, Arias Del Razo A, Ahuatzin Gallardo D, Bolaños J. 2024. The departure of sperm whales (*Physeter macrocephalus*) in response to the declining jumbo squid (*Dosidicus gigas*) population in the central portion of the Gulf of California. PeerJ, vol. 12, art. :e18117, 2024.. http://doi.org/10.7717/peerj.18117

Ramos, J. E., and others Ramos-Rodríguez, A., Bazzino-Ferreri, G., Kurczyn, J. A., Rivas, D., Salinas-Zavala, C. A. 2017. Characterization of the northernmost spawning habitat of Dosidicus gigas with implications for its northwards range extension. Marine Ecology Progress Series, vol. 572, :179-1922017.- https://doi.org/10.3354/meps12140

Rosa, R., and others K. Trübenbach, T. Repolho, M. Pimentel, F. Faleiro, J. Boavida-Portugal, M. Baptista, V.M. Lopes, G. Dioni´sio, M.C. Leal, R. Calado, and H.O. Pörtner. 2013. Lower hypoxia thresholds of cuttlefish early life stages living in a warm acidified ocean. Proceedings of the Royal Society B: Biological Sciences, vol. 280,: art. 20131695, 2013.- http://dx.doi.org/10.1098/rspb.2013.1695

Rosa, R., and others Pissarra, V., Borges, F. O., Xavier, J., Gleadall, I. G., Golikov, A., Bello, G., Morais, L., Lishchenko, F., Roura, Á., Judkins, H., Ibáñez, C.M., Piatkowski, U., Vecchione, M. and Villanueva, R. 2019. Global Patterns of Species Richness in Coastal Cephalopods. Frontiers in. Marine. Science, vol. 6, art. :469., 2019. DOI: 10.3389/fmars.2019.00469

Sajikumar, K.K., and others. Arkhipkin AI, Venkatesan V, Jestin Joy KM, Binesh CP, Sasikumar G, Mohamed KS (2017) Range extension of a bathypelagic squid, Bathyteuthis bacidifera (Cephalopoda: Bathyteuthidae), to the south Arabian Sea with special reference to its age and growth pattern. Marine Biodiversity, vol. 48, :1511–1518.2017. https://doi.org/10.1007/s12526-017-0655-x.

Sajikumar, K.K., and othersVenkatesan V, Binesh CP, Mohan G, Sanil NK, Kripa V, Mohamed KS (2018) Presence of the Wondrous jewel squid Histioteuthis miranda (Cephalopoda: Histioteuthidae) in the eastern Arabian Sea and determination of its age from statoliths. Thalassas, vol. 34, :383–390.2018. https://doi.org/10.1007/s41208-018-0076-z.

Sajikumar, K.K., and others Sasikumar, G., Venkatesan, V., Vidya, R., Alloycious, P.S., Jestin Joy, K.M., Karamathullah, P.S., Nataraja, G.D., Mohamed, K.S. 2020. Distribution, age and growth of the diamondback squid, Thysanoteuthis rhombus (Cephalopoda: Thysanoteuthidae) from the tropical Arabian Sea. Fisheries Research, vol. 2024, art. 105478., 2020.

Sajikumar, K. K., and others. Sasikumar, G., Venkatesan, V., Jestin Joy, K M and Mohamed, K S (2022) Age, growth and maturation in the mesopelagic squid Abralia andamanica (Cephalopoda: Enoploteuthidae) from the Arabian Sea. Scientia Marina, vol. 86, art. (3,). pp. 1-7.2022.

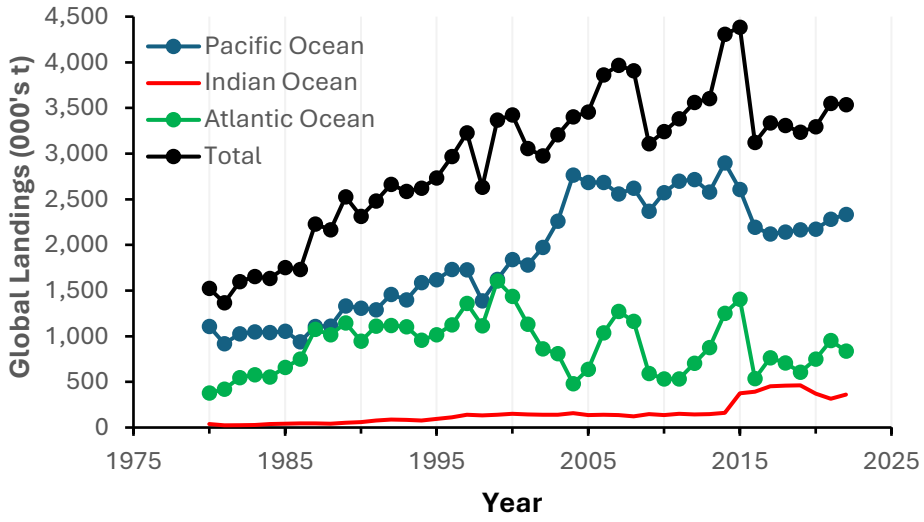
Sajikumar, K.K., and others. Laxmilatha, P., Vargheese, S. et al. (2023). Hawaiian flying squid Nototodarus hawaiiensis (Cephalopoda: Ommastrephidae) in the Arabian Sea: range extension, age, and growth. Marine. Biodiversity, vol. 53, art. 15, 2023. https://doi.org/10.1007/s12526-022-01325-w

Sauer, W. H., and othersGleadall, I. G., Downey-Breedt, N., Doubleday, Z., Gillespie, G., Haimovici, M.,. Ibáñez, C. M, Katugin, O. N., Leporati,S., Lipinski, M.R., Markaida, U., Ramos, J.E., Rosa, R., Villanueva, R., Arguelles, J., Briceño, F.A., Carrasco, S.A., Che, L. J., Chen, C.-S., Cisneros, R., Conners, E., Crespi-Abril, A.C., Kulik, V.V., Drobyazin, E.N., Emery, T., Fernández-Álvarez, F.A., Furuya, H., González, L.W., Gough, C., Krishnan, P. , Kumar, B., Leite, T., Lu, C.-C., Mohamed, K.S., Nabhitabhata, J., Noro, K., Petchkamnerd, J., Putra, D., Rocliffe, S., Sajikumar, K. K., Sakaguchi, H., Samuel, D., Sasikumar, G., Wada, T., Zheng, X., Tian, Y., Pang, Y., Yamrungrueng, A. & Pecl, G. 2019. World octopus fisheries. Reviews in Fisheries Science & Aquaculture, vol. 29, art. (3), 279-429 . 2021.DOI: 10.1080/23308249.2019.1680603

WoRMS (World Registry of Marine Species) 2024. www.marinespecies.org. Accessed October 2024.

Xavier, J.C., and others. A review on the biodiversity, distribution and trophic role of cephalopods in the Arctic and Antarctic marine ecosystems under a changing ocean. Marine Biology, vol. 165, art. 93, 2018.

A



B

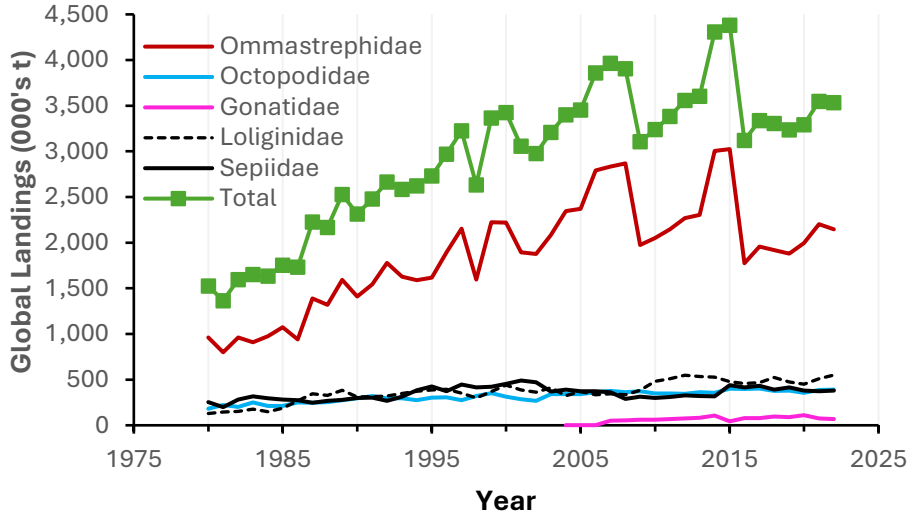


Figure 1. Annual cephalopod landings data compiled by the United Nations Food and Agriculture Organization (FAO). A: Global totals and totals within major ocean basins in terms of landings; B: Global totals and totals for the most heavily fished families.

Table 1. Cephalopod diversity. World Registry of Marine Species (WoRMS, www.marinespecies.org) as of 14 October 2024. Columns are divided into numbers at the ordinal level and at taxonomic levels higher than Order.

	Ff~~f~~amilies		Gg~~g~~enera		Total species	n.spp. described since 2017
	higher/order	higher/order	higher/order			
Class Cephalopoda	47	182	761	33		
Subclass Nautiloidea	1	2	7	3		
Order Nautilida	1	2	7	3		
Subclass Coleoidea	46	180	754	30		
Superorder Decapodiformes	30	119	444	15		
Order Bathyteuthida	2	2	9	3		
Order Idiosepida	1	3	8	1		
Order Myopsida	2	11	39	0		
Order Oegopsida	21	65	177	1		
Order Sepiida*	3	37	210	10		
Order Spirulida	1	1	1	0		
Superorder Octopodiformes	16	61	312	15		
Order Vampyromorpha**	1	1	2	1		
Order Octopoda	15	60	310	14		

* Includes sepiolids and their relatives, considered by many cephalopod systematists/taxonomists to comprise a separate Order.

** Includes a second species of *Vampyroteuthis*, which has not yet been accepted as valid by many cephalopod systematists/taxonomists.

Table 2. Coastal cephalopod species richness by region according to Rosa et al. (2019).

Region	Species Richness
The Arctic Ocean	10
The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea	55
The South Atlantic Ocean and the Wider Caribbean	81
The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf	84
The North Pacific Ocean	125
The South Pacific Ocean	207
The Southern Ocean	15

Section 4

Sub-chapter 4c: Marine benthic invertebrates

Lead: Mehdi Ghodrati Shojaei; Coordinating author: Lis L. Jørgensen

Lis Lindal Jørgensen[1], Anya Dunham[2], Denis Zakharov[3], Hiroko Muraki Gottlieb[4], Kerry Sink[5,6], Paris Stefanoudis[7,8,9], Laurent Guérin[10], Elizabeth Logerwell[11], Leen Vandepitte[12], Lennert Schepers[12], Eva Chatzinikolaou[13], Christina Pavloudi[14], Chris Frid[15], Rachel Przeslawski[16], Elva Escobar[17], Pat Hutchings[18], Bruce C. Glavovic[19], André Pardal[20,21], Lara Atkinson[22,23], Marcel Miranda[24], Daniela Yepes Gaurisas[25], Gordon Watson[26], Amarachi Paschaline Onyena[27], Izwandy Idris[28], Huw J. Griffiths[29], Hongjun Li[30], Sebastian Herrera Kasic[31], Paravanparambil Rajakumar Jayachandran[32], Mehdi Bolouki kourandeh[33]

1. Institute of Marine Research, Tromsø, Norway

2. Fisheries and Oceans Canada, Nanaimo, Canada

3. Zoological institute RAS, Saint-Petersburg, Russia

4. Elisabeth Haub School of Law at Pace University, White Plains, New York; Harvard University, Cambridge, Massachusetts

5. South African National Biodiversity Institute, Cape Town, South Africa

6. Nelson Mandela University Gqeberha, South Africa

7. Oxford University Museum of Natural History, University of Oxford, Oxford, UK

8. Nekton Foundation, Oxford, UK

9. The Biodiversity Consultancy, Cambridge, UK

10. French Biodiversity Agency (OFB), Dinard marine Station, Dinard, France

11. NOAA Fisheries, Alaska Fisheries Science Center, Seattle, WA, USA

12. Flanders Marine Institute (VLIZ), Oostende, Belgium

13. Hellenic Centre for Marine Research (HCMR), Institute of Marine Biology, Biotechnology and Aquaculture (IMBBC), Heraklion, Crete, Greece

14. European Marine Biological Resource Centre (EMBRC-ERIC), Paris, France

15. Griffith University, Queensland, Australia

16. RPS AAP Consulting, Sydney, Australia

17. Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnología, CU Mexico

18. Australian Museum Research Institute (AMRI) Australian Museum, Sydney NSW Australia

19. Massey University, Palmerston North, New Zealand

20. Marine Institute, Federal University of São Paulo (IMar/Unifesp), Santos/SP, Brazil

21. Center for Marine Biology, University of São Paulo (CEBIMar/USP), São Sebastião/SP, Brazil

22. South African Environmental Observation Network, Offshore Node, Cape Town, South Africa

23. Department of Biological Sciences, University of Cape Town, South Africa

24. Department of Biological Oceanography, Oceanographic Institute, University of São Paulo, São Paulo/SP, Brazil

25. Departamento de Oceanografia e Ecologia, Universidade Federal do Espírito Santo, Vitória/ES, Brazil

26. Institute of Marine Sciences, University of Portsmouth, Portsmouth, UK

27. Department of Environmental Management and Pollution, Nigeria Maritime University Okerenkoko, Nigeria

28. South China Sea Repository and Reference Centre, Institute of Oceanography and Environment, Universiti Malaysia Terengganu, Terengganu, Malaysia

29. British Antarctic Survey, Cambridge, UK

30. National Marine Environmental Monitoring Center, China

31. K-ASIC International Consultant (K-ASIC Consultorías)

32. Applied Research Center for Environment and Marine Studies (ARC-EMS), King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia

33. Deputy of Marine Environment and Wetlands, Department of Environment, Tehran, Iran

Acknowledgements: The authors thank Pieter Provoost and Ward Appeltans (IODE - OBIS), Wim Decock (VLIZ - WoRMS), Ken Fong, Karen Dunmall, and John O'Brien (Fisheries and Oceans Canada).

1. Keynotes

- Seafloor hotspots and 7,252 new benthic invertebrates have been described since WOA-II, along with a fivefold increase in critically endangered and doubling of endangered species.
- Marine benthic invertebrates are vital for ocean health but increasingly impacted by human activities.
- There is often limited understanding of the implications of these impacts and inadequate provisions to contain them.
- Research and cooperation are still imbalanced between regions.
- Marine invertebrates are still poorly documented, particularly in the deep ocean, developing States, and island States potentially hosting a high number of endemic taxa.
- Consistent funding for biodiversity monitoring is needed to prevent knowledge gaps from widening.
- Meaningful and ethical use of Indigenous Peoples' knowledge and representation of early career professionals are required.
- Seabed mining raises concerns about negative impacts, calling for coordination and cooperation between the BBNJ COP and ISA.

2. Introduction

Since WOA-II, benthic species and habitats have been impacted by human activities worldwide (Fig. 4C.1).

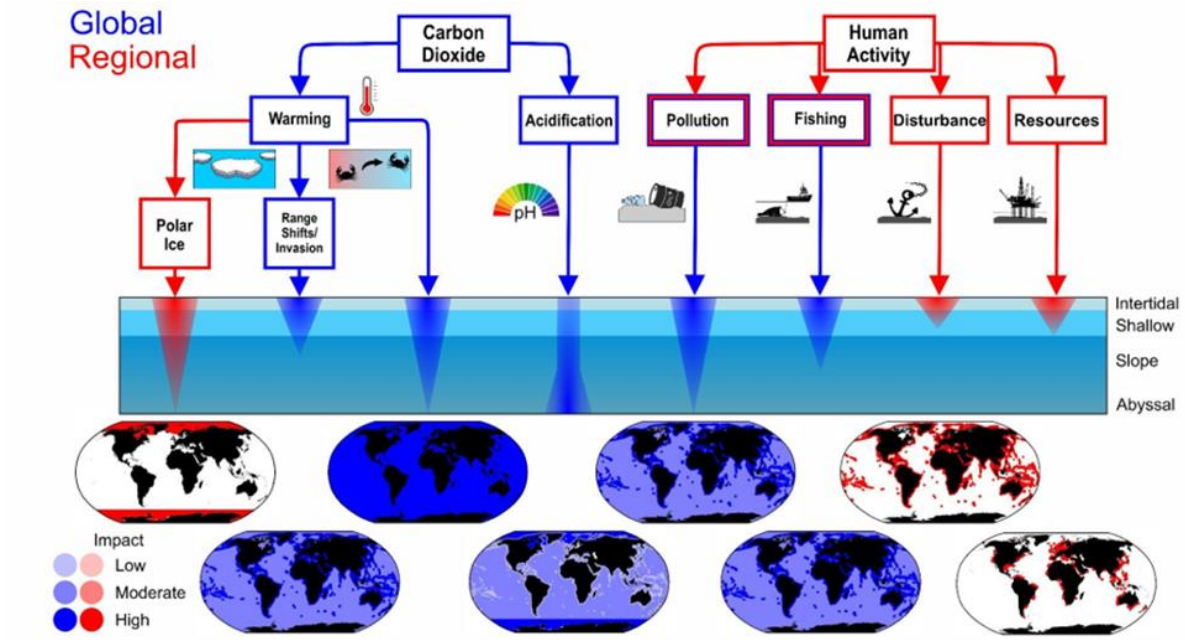


Figure 4C.1. Benthic invertebrates are vital for ocean health and human well-being but are threatened by climate change, human activities (including bottom trawling), and pollution (including microplastics and contaminants). ~~***Their impact on ecosystems and services remains unclear.***~~

3. The environmental change since WOA-II

3.1 Changes in the overall status

Biodiversity

The World Register of Marine Species (WoRMS) currently (2024-08-29) holds 246,517 valid marine species names, including 151,902 marine benthic invertebrates. ~~Fourteen percent of these invertebrates are found in the deep sea (> 500 meters).~~ The annual discovery rate of new marine benthic invertebrates averages 60% of all new marine species. From 2019 to 2023, 10,742 new marine species were described, with 7,252 (67.5%) being benthic invertebrates (Fig. 4C.2).

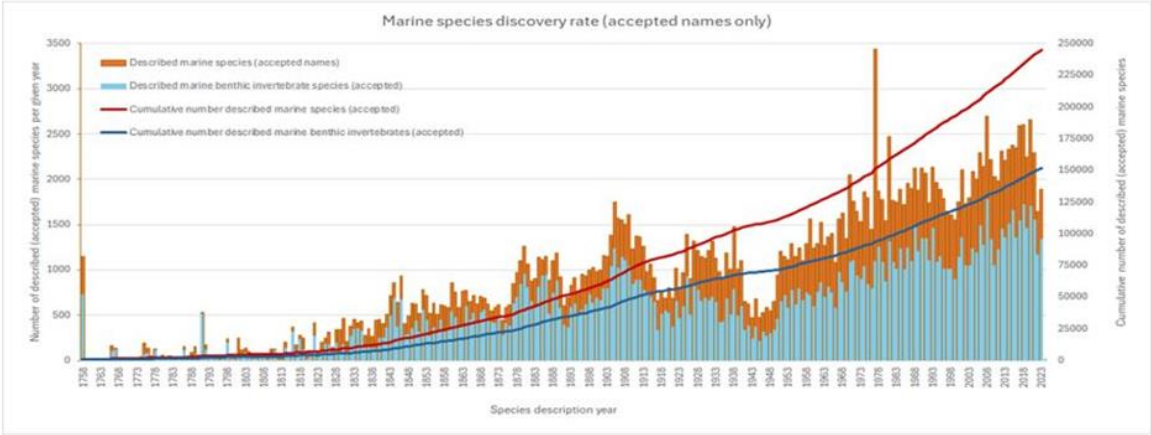


Figure 4C.2. Global marine species discovery rate (accepted species only) since 1758. Absolute (left Y-axis) and cumulative (right Y-axis) numbers.

Of the 32 marine phyla with invertebrate species, 26 phyla include benthic species (Fig. 4C.3). Among these, 21,271 species (14%) live at depths >500 meters.

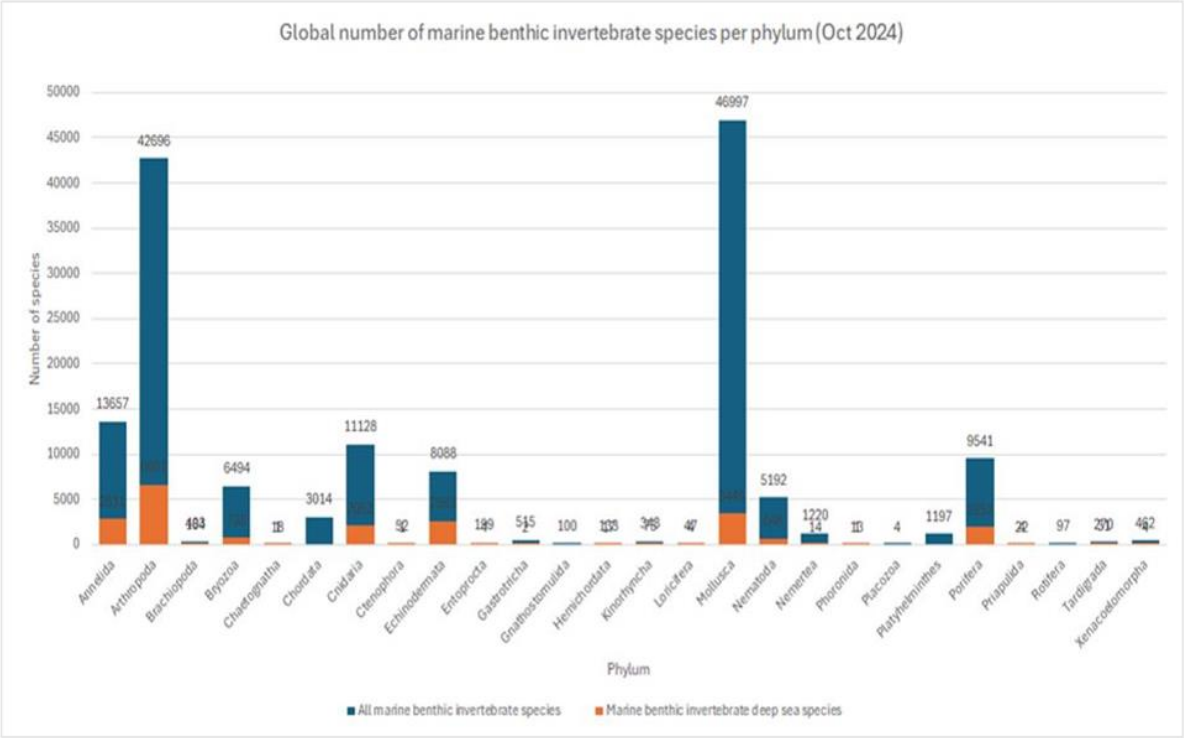


Figure 4C.3. Global number of marine benthic invertebrate species, by group (phylum), showing total species numbers.

Only 1,.7% of marine benthic invertebrate species have been formally assigned to an IUCN Red List of threatened species (Table 4C.1). Most species (98.3%) have not been evaluated due to insufficient information.

Table 4C.1. Number of marine benthic invertebrate species per IUCN Red List of threatened species category.

IUCN Red List category	**Total number of marine invertebrate benthic species**	
	Up to end of 2018	**2018-2023**
Extinct	2	2
Critically endangered	18	91
Endangered	45	88
Vulnerable	237	292
Near threatened	184	239
Conservation dependent	4	4
Least concern	1,104	1,184
Data deficient	624	657

Based on WoRMS, OBIS and Marine Regions (Oct 2024), marine benthic invertebrates are found in all *International Hydrographic Organization* (IHO) areas. However, significant regional variations reflect current knowledge gaps (Fig. 4C.4).

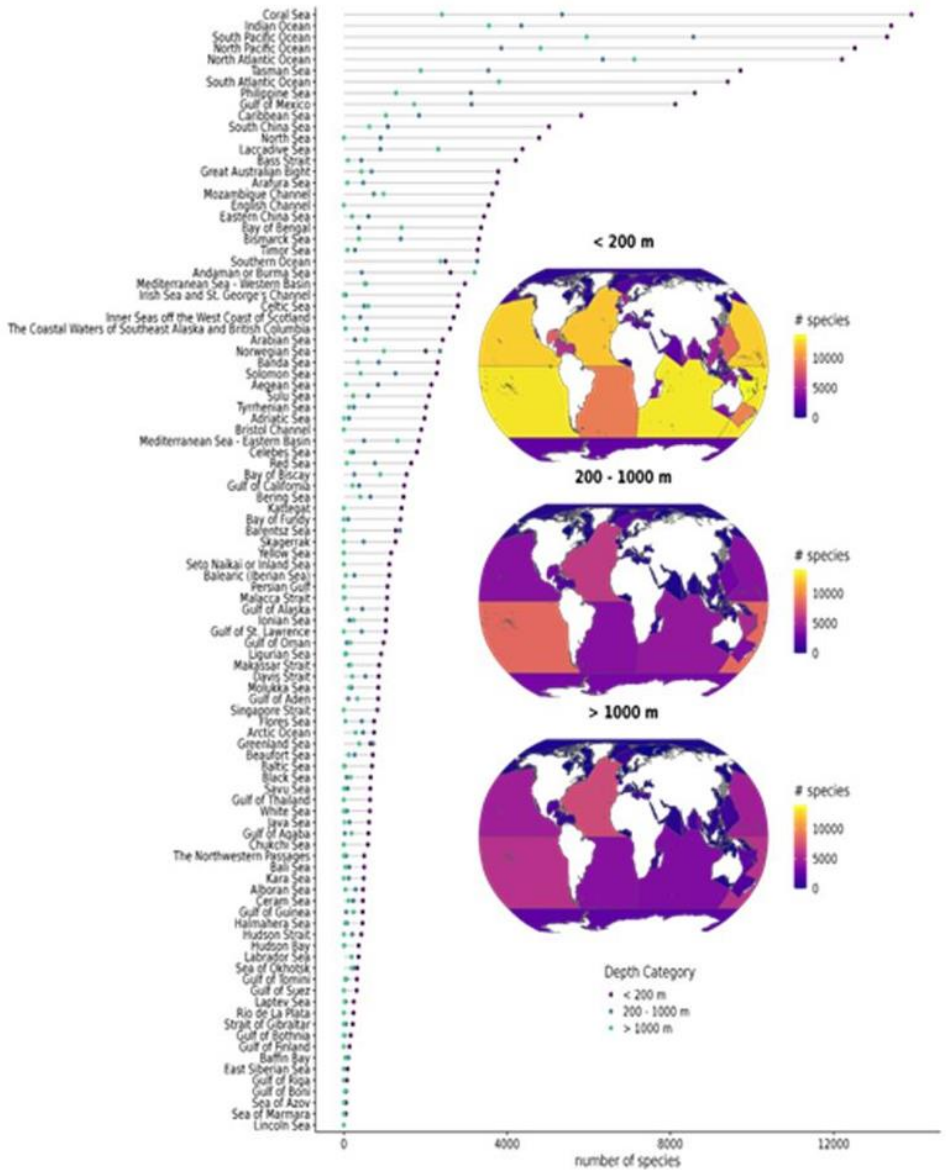


Figure 4C.4. The total number of recorded marine invertebrate benthic species for all IHO Sea Areas for <200m, 200-1000m, >1000m depth. The boundaries of the IHO Sea Areas: follow Claus and others, 2014; IHO Sea Areas version 3 (Flanders Marine Institute, 2024a), available online at http://www.marineregions.org/. https://doi.org/10.14284/323); species occurrences (OBIS, 2024); species group information (WoRMS), bathymetry data (EMODnet, 2016; GEBCO, 2015; Provoost and Bosch, 2018).

Impacts of the change on and interaction with other components of the marine system

Marine benthic ecosystems are crucial for ocean health and human well-being but are under growing pressure from human activities (Sweetman and others, 2017; Halpern and others, 2019; Gissi and others, 2021; Mamede 2024) (Table 4C.2 and Regional sections).

Unprecedented environmental changes are causing range shifts, novel species assemblages, and extirpations. Research and scientific guidance are essential to understand ocean changes, their effects on benthic resources, ecosystem services, and socio-economic impacts, and to develop effective mitigation strategies (Griffiths and others, 2017; Schratzberger and Somerfield 2020; Crespo and Pardal 2022).

Table 4C.2. Anthropogenic stressors and activities impacting benthic marine invertebrates and ecosystems worldwide.

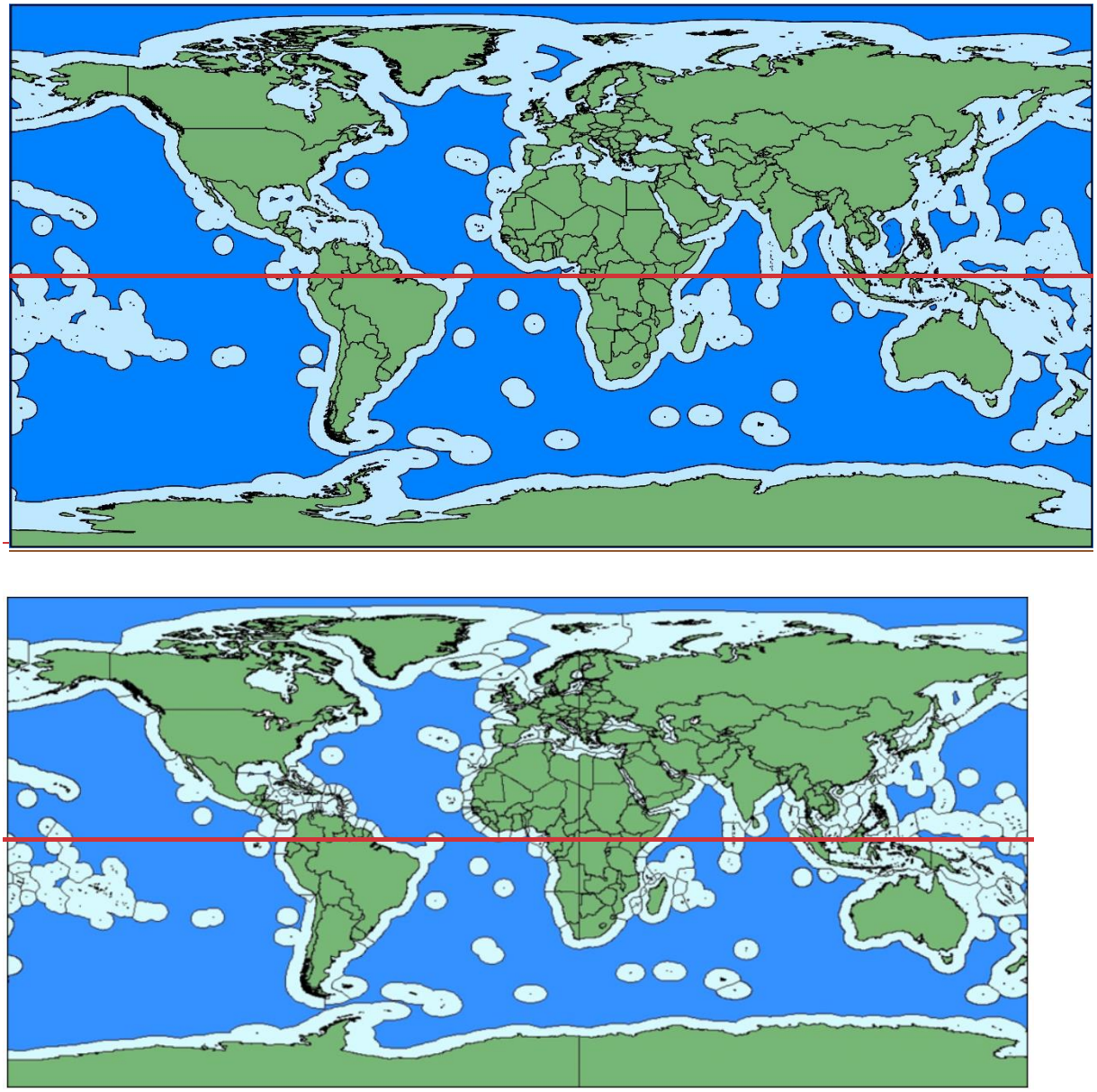
Human stressors and activities	References
Global warming and ocean acidification	Isla and Gerdes, 2019; Pineda-Metz and others, 2020; Venegas and others, 2023
Fishing, especially bottom trawling	Couce and others, 2020
Resource extraction, including mining and hydrocarbon exploitation	Henry and others, 2017
Bioinvasion by non-native species, including invasive, exotic	Zaiko and others, 2024
Marine- and land-based contaminants, including an estimated 3.05 million tonnes of microplastics in deep ocean sediments and perturbations by drifting plastic bags in the deepest ocean	Gao and others, 2022; Harris and others, 2023; Ribó and others, 2023; Shahnawaz and others, 2024; Jamieson and Onda, 2022
Oil spills	Goes and others, 2023
Urbanization	Momota and Hosokawa 2021; Dreujou and others, 2023
Dredging and dumping	Prishchepenko and others, 2023; Neira and others, 2024

Offshore wind farms	Lloret and others, 2022
Anchor scour damage	Davis and others, 2022
Marine invertebrate interactions with Harmful Algal Blooms and implications for One Health	Turner and others, 2021
Coastal defence and offshore structure installations	Wolanski and others, 2020

The seabed accumulates contaminants and microplastics, harming benthic invertebrates and ocean ecosystems (Mason and others, 2022; Ladewig and others, 2023). Widespread damage to benthic habitats and biodiversity affects marine ecosystem services in various ways across the regions, highlighting the need for targeted seabed management (Wang and others, 2021; Lloret and others, 2022; Mamede, 2024).

The governance of the seabed within and beyond national jurisdiction

Deep seabed mining management has drawn significant attention from various stakeholders, including governments, research institutions, intergovernmental organizations, NGOs, and the private sector. Concerns focused on its harm on benthic invertebrates (Amon and others, 2022; Drazen and others, 2020; European Academies' Science Advisory Council, 2023; Rabone and others, 2023; Stenvers and others, 2023; Sweetman and others, 2024) and inadequate management of seabed mining impacts (Picken and others, 2024). There have been calls by some for a moratorium, precautionary pause, or a ban (Deep Sea Conservation Coalition, 2024; WWF, 2024).



~~Figure 4C.5. Ocean Areas Beyond National Jurisdiction, shown in dark blue, cover around 40% of the Earth's surface and have little by wayfew measures of biodiversity conservation in place. Picture and text taken from: Image created using The intersect of the Exclusive Economic Zones and IHO sea areas, version 5 (Flanders Marine Institute, 2024b).~~

For the seabed outside of the national jurisdiction, the BBNJ Agreement, once it comes into force, will provide management measures, including area-based management tools, such as MPAs and environmental impact assessments (Humphries and others, 2025) that could complement the existing management measures of the seabed. To be

effective, such management measures will require strong coordination and cooperation between the BBNJ Conference of the Parties and the ISA and RFMOs to ensure the conservation and sustainable use of ABNJ (Muraki Gottlieb and others, 2025). Further, capacity building and the transfer of marine technology in the BBNJ Agreement that encompasses all of the substantive elements, including the fair and equitable sharing of benefits of marine genetic resources of ABNJ, will help reduce scientific knowledge gaps and support further management measures, which is essential, especially for developing countries. For areas within national jurisdiction, a select regional seabed management aspects are summarized in Table 4C.3.

Table 4C.3. Select examples of regional management of the seabed since 2019.

Regions	Governance of the Seabed
The Arctic Ocean	● Central Arctic Ocean (CAO): ○ The International Agreement to Prevent Unregulated Fishing in the High Seas of the CAO entered into force in June 2021. The Agreement prevents the signatory countries from engaging in commercial fishing ~~for 16 years~~and establishes a Joint Program of Scientific Research and Monitoring~~,~~ to further the understanding of an ecosystem that is emerging below a retreating sea ice cover~~.~~ as part of a long-term strategy to safeguard healthy marine ecosystems and ensure the conservation and sustainable use of fish stocks. ○ The BBNJ Agreement subject to its entry into force may provide an opportunity to address a legal gap wherein no existing legal instrument or body has the legal competence to designate MPAs in the portion of the CAO that lies in ABNJ~~.~~, applicable to the Parties of the BBNJ Agreement. ● Barents Sea: Northward expansion of commercial bottom fish increased the risk of bottom trawling damage to vulnerable benthic species and habitats in pristine,

	previously ice-covered areas in the Northern Barents Sea. In 2019, the Norwegian Government agreed to close 443.000 km2 of seabed to bottom-contact gear (Jørgensen and others, 2020). ● Canadian Arctic: Conservation areas have been established to protect habitat-forming cold-water corals and sponges (DFO, 2024).
The European Baltic Sea, Northeast Atlantic Ocean, Mediterranean Sea and Black Sea	● North Atlantic Ocean: ○ Whilst 18 benthic habitats are already the focus of status assessments in the OSPAR Maritime Area, remote and deep-water habitats remain understudied. Pollution/pressure regulations and the creation of MPAs continue to be enacted across all Regions. Currently, 10.8% of the OSPAR maritime area has been designated an MPA, but challenges remain around generating sufficient ecological coherence (OSPAR, 2023). ○ Green finance (e.g. nutrient, carbon or biodiversity credits) could provide greatly needed investment for effective management and to support restoration at the seascape level (Preston and others, 2025).
The South Atlantic Ocean and the Wider Caribbean	● SW Atlantic: ○ Cumulative impact assessment and conservation planning to strengthen marine protected areas in Brazilian EEZ (Magris and others, 2020). ○ Ongoing marine spatial planning in the Brazilian EEZ. ● Africa (South African and Namibian): ○ In 2019, South Africa increased its marine protected area from 0.4% to 5% through implementation of 20 new Marine Protected Areas (Sink and others, 2023).

	○ Eco-certification of trawl fisheries. Routine benthic monitoring through commercial fishing activity, enhanced mitigation measures for seabed damage by trawl fishing. ○ Ecosystem Based Management was identified as a suitable approach to effectively govern the most impactful human activities in marine systems (Skein and others, 2022).
The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf	● Persian Gulf and the Sea of Oman: ○ Iran, Oman, the UAE, and Qatar, have established MPAs to protect critical habitats. ○ Bottom trawling restrictions, establishment of no-take zones within MPAs, seasonal fishing bans protect spawning seasons. ○ National regulations targets to reduce pollution (oil and chemical spills). ○ *The Regional Organization for the Protection of the Marine Environment* (ROPME) among the Gulf Cooperation Council (GCC) countries, Iraq, and Iran. ● Arabian Sea, Lakshadweep Sea and Bay of Bengal: MPAs (coral, seagrass, sea cucumbers), implementing fishing regulations and pollution control. Marine resource management (supported by initiatives such as BOBP). Enforces pollution control and scientific research. ● Andaman Sea, Strait of Malacca and South China Sea: ○ National Regulations and Conservation Strategies: ASEAN countries with domestic laws and strategies (e.g. artificial reef). MPAs (Marine Park, No Take Zone) is currently increasing in area size. ○ ASEAN countries to protect the marine environment and resources.

	~~The South China Sea Code of Conduct intends to minimize conflict and use resources for the benefit of coastal states.~~ ○ IUU fishing still happens. Overlapping laws and responsibilities between enforcement agencies creates loopholes in enforcement. Issues with maritime borders creates a grey area for enforcement of marine resources. • Bangladesh, India, Myanmar, Pakistan, Sri Lanka: ○ Bangladesh (7.99% coverage), India (0.31%), Myanmar (0.48%), Pakistan (1.23%), and Sri Lanka (0.08%) have established MPA to protect critical habitats such as corals, mangroves and seagrass ○ As members of various regional organizations dedicated to environmental protection (ASEAN, SACEP, BOBLME, and IORA), Bangladesh, India, Myanmar, Pakistan, and Sri Lanka collaborate to address common maritime challenges. These include tackling pollution, combating piracy, and developing joint conservation strategies to protect shared marine ecosystems ○ Implements fishing regulations including seasonal fishing bans.
The North Pacific Ocean	• Various regions in the North Pacific: A number of recent conservation initiatives focused on preserving benthic biodiversity (e.g. Tang.ɢwan – ḥačxwiqak – Tsigis MPA and glass sponge reef marine refuges in Canada; Zhejiang Anji Salamander National Nature Reserve, Lianyungang Ganyu Wetlands, and Dongling Tongzhou Bay Intertidal Zone in China; Muan Tidal Wetland Protected Area in the Republic of Korea).

The South Pacific Ocean	• Southeast Pacific: To achieve sustainable management of the marine resources in the Southeast Pacific, coastal community harvest of benthic marine invertebrates must be included in data and reporting that informs fisheries management. In Chile and Peru, there is no authority to monitor community harvesting of benthic invertebrates, nor associated ecosystem impacts (SUBPESCA, 2024 and IMARPE, 2024). • New marine parks and associated management plans have been established in various parts of the South Pacific, including a large network around Australia, although only ~25% of this is fully protected.
The Southern Ocean	• Antarctica: The Protocol on Environmental Protection to the Antarctic Treaty officially designates Antarctica as a 'natural reserve, devoted to peace and science.' The *Commission for the Conservation of Antarctic Marine Living Resources* is the international body responsible for the conservation of ~~Southern Ocean~~ marine life and ecosystems in waters surrounding Antarctica.

~~4~~3.2 Region-specific changes

The Arctic Ocean

The Arctic is an ecologically and culturally important marine region that remains largely untouched but is facing rapid environmental changes. Recent studies have established quantitative baselines of marine benthic biodiversity in previously under-researched areas (e.g. Azovsky and Kokarev, 2019; Pierrejean and others, 2020; Wei and others, 2020; Zakharov and others, 2020; Dumais and others, 2022; Gianasi and others, 2022; Vedenin and others; 2022, Bilous and others, 2022; Holte and others, 2022; Jacobs and others, 2022; Jørgensen and others, 2022a; Kenchington and others, 2022; Christie and others, 2023; McNicholl and others, 2024; Prozorkevich and others, 2024; Udalov and others, 2024). The Arctic faces major global and local threats such as warming, acidification, fishing, mineral extraction, port development, and increased vessel traffic (Fig. 4C.~~6~~5 and citations therein). Microplastics are also a growing concern (Fang and others, 2018). Recent ecological changes include infaunal and epibenthic invertebrate population declines and species moving northward (e.g. Jørgensen and others, 2022b; Logerwell and others, 2022; Holte and others, 2022; Stewart and others, 2023; Gerland

and others, 2023; Golikov and others, 2024). The status of commercially important crab and shrimp stocks varies from variable to healthy (Niemi and others, 2019; Gonzalez and others, 2024a). As the potential for commercial fisheries expansion, new shipping routes, and oil and gas extraction increases in the region, further mapping and monitoring efforts are necessary.

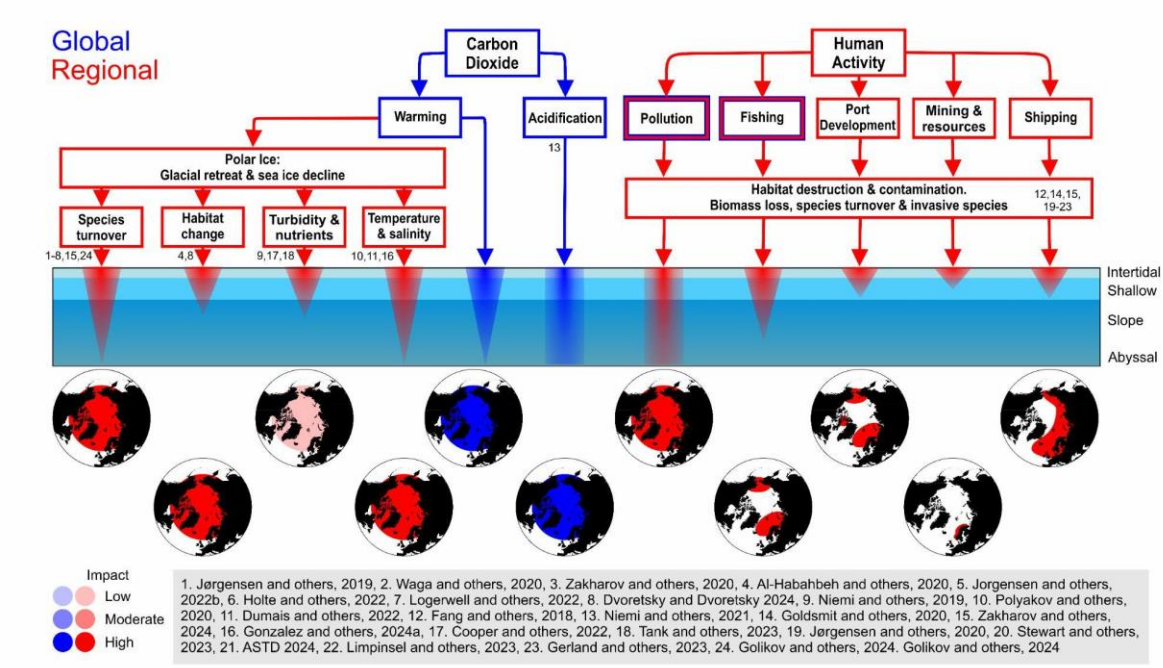


Figure 4C.~~6~~5. The Arctic Ocean. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates.

The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Except for oceanic ridges and hydrothermal vents, benthic habitats across sub-regions remain in poor status (Bevilacqua and others, 2020) with benthic diversity moderate/low for most sub-regions with none showing increases (OSPAR, 2024). Global warming impacts habitats at all depths (MedECC, 2020; Fig. 4C.~~7~~6). Fishing impacts 48% of OSPAR-assessed areas via species extraction and seabed disturbance, agriculture/aquaculture/tourism all drive nutrient enrichment, whilst green technologies increase contaminant inputs (Herbert and others, 2022; OSPAR, 2024). Pressures disrupt

ecosystem functions, exacerbate the effects of other stressors such as epizootic events (e.g., Katsanevakis and others, 2022), and ~~compromise~~ compromise ecosystem services ~~disrupting ecosystem functions~~ (Heckwolf and others, 2021). Benthic biodiversity improvements can benefit coastal communities ~~e.g.~~through processes such as nutrient bioremediation (Watson and others, 2022).

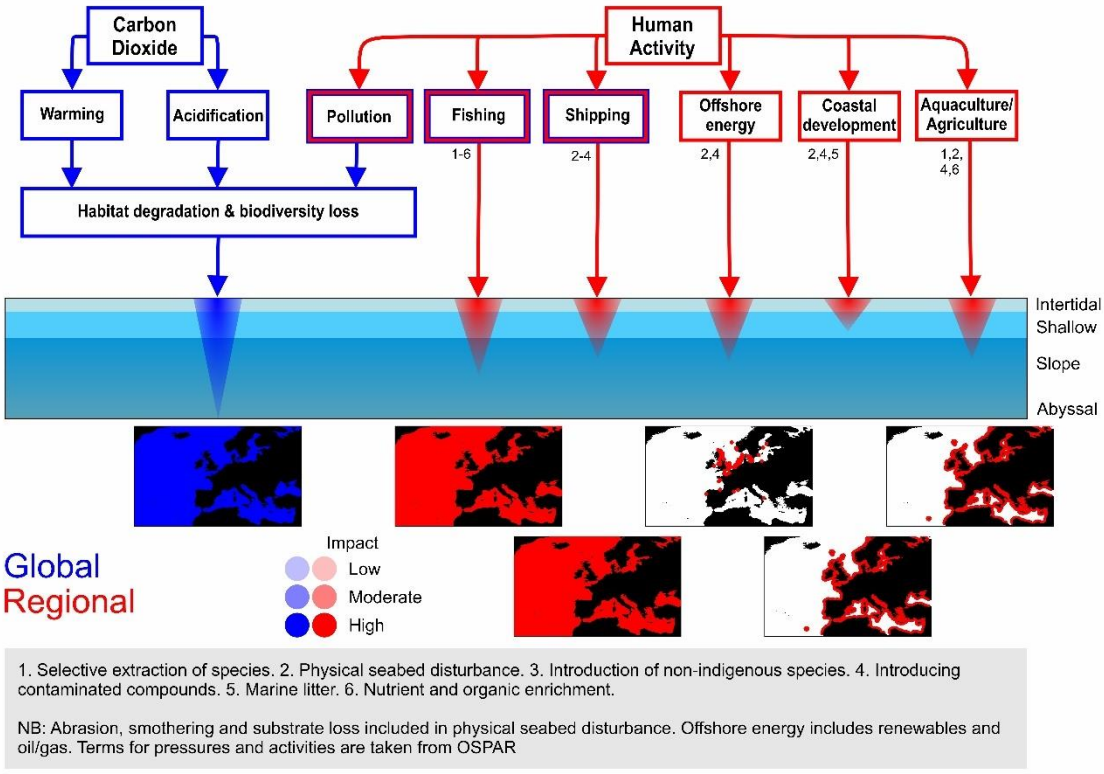


Figure 4C.~~7~~6. The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates.

The South Atlantic Ocean and the Wider Caribbean

Despite limited and fragmented data progress has been made. Research now focuses on deep environments, habitat mapping, identification of foundational species, and ecology (e.g., Sumida and others, 2020; Etnoyer and other, 2022). Changes have been noted in shallow habitats, including coral bleaching and mortality, shifts in benthic communities and commercially valuable invertebrate stocks, and the spread of non-indigenous species

(see Fig. 4C.~~8~~7 and studies cited therein). Climate-driven physical changes increasingly affect benthic ecosystems. Local threats include fishing, coastal development, shipping, mining, and aquaculture causing overexploitation, illegal fishing, pollution, bioinvasions, and habitat damage (Fig. 4C.8). Shifts in fishery stocks also have significant socio-economic impacts (Vögler and others, 2023; Engelhard and others, 2024). Considering the rapid changes underway, along with the potential expansion of the petroleum industry (Rodrigues, 2023), seabed mining (Bridges and others, 2023; Paiva and other, 2023), and the installation of offshore wind farms (Gorayeb and others, 2024), there is a need to expand the monitoring of benthic communities in this region, especially in deep habitats.

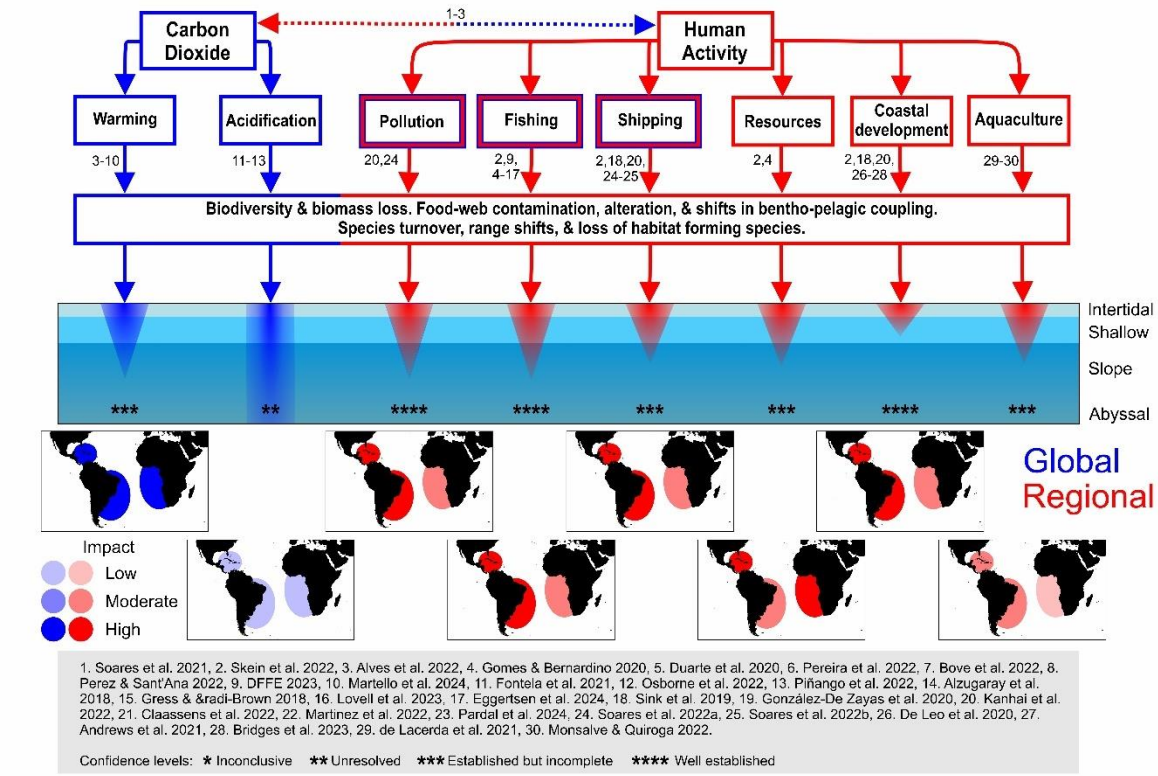


Figure 4C.~~8~~7. The South Atlantic Ocean and the Wider Caribbean. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates. Arrows width identifies relative importance of stressors at/on global and local scales.

The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Multiple global and local stressors impact marine invertebrates in this region (Fig. 4C.~~9~~8). Thermal stress causes coral bleaching and declines in abundance, even at depth (Diaz and others 2023). Overfishing and destructive fishing practices degrade benthic habitats and threaten food security (Obura and others, 2022). Marine debris leads to marine life entanglement (Pattiaratchi and others, 2022), while oil spills and invasive species disrupt native biodiversity (Jayachandran and others, 2019, 2024, Huang, Yi-Cheng and others, 2021). Coastal development and wastewater discharge alter benthic communities (Sink and others, 2019) with prospective offshore mining likely to worsen impacts (Fennessy, 2024). Long-term studies on these pressures are limited (Sink and others, 2019), but new biodiversity surveys (e.g., Amjad and others 2024) and ecological research provide insights into ecosystem resilience (Delfan and others, 2021; Stefanoudis and others, 2023). Functional ecology can help assess biodiversity roles and responses to environmental changes, while biogeography and metacommunity ecology can identify large-scale patterns and habitat connections for conservation planning. Experimental research can inform how marine invertebrates respond to natural variability, climate change, and pollutants. Key ecosystem services at risk include food security through fisheries, coastal protection, and tourism (UNEP-NCW, 2024).

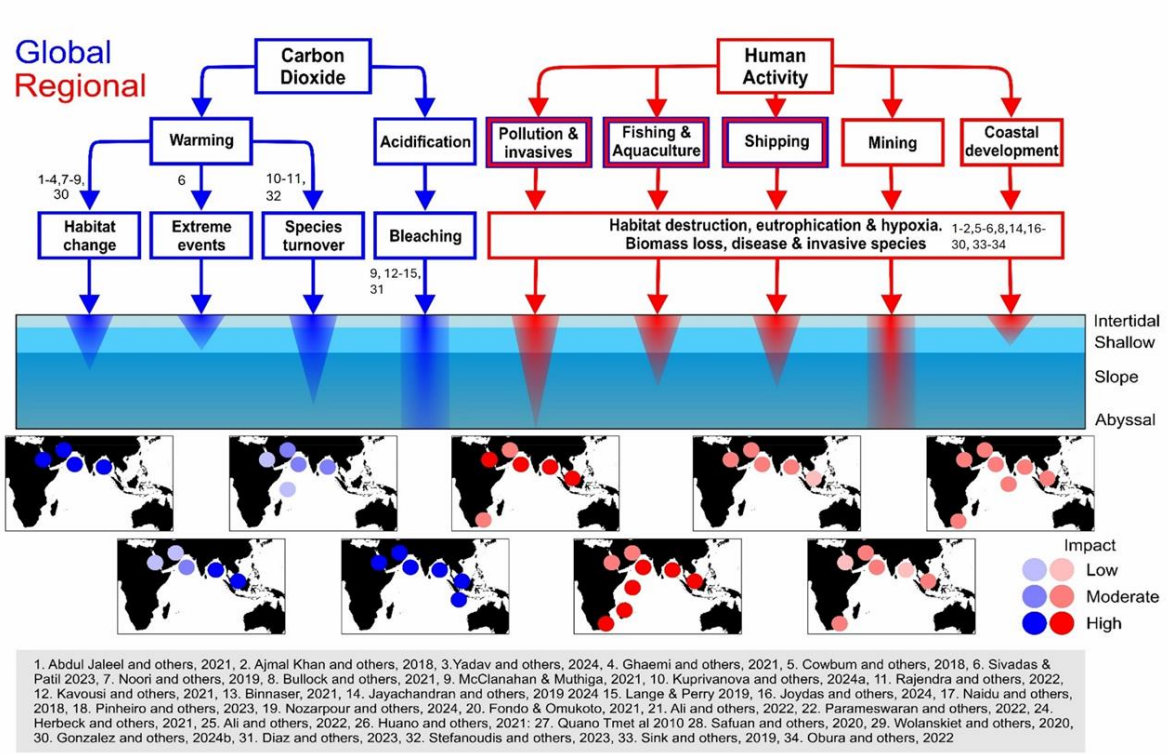


Figure 4C.~~8~~9. The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates. Arrow width identifies relative importance of stressors at global and local scale.

The North Pacific Ocean

Ocean temperatures have increased over the long term (Talloni-Alvarez and others, 2019; Guo and others, 2020; Chen and others, 2020; Boldt and others, 2022, 2023; Alma and others, 2023; Cowan and others, 2023; Han and others, 2023), leading to widespread intertidal die-offs from heatwaves to hypoxia (Raymond and others, 2022; Chen and others, 2020; Wang and others, 2022), species turnover, range shifts and invasive species spread (Buser, 2023; Wang and others, 2019, 2023; Hu and others, 2021; Xu and others, 2020, 2023, 2024; Drinkwin and others, 2019). The Puget Trough and Piip volcano are hotspots of seafloor biodiversity in the North Pacific (Wei and others, 2020; Rybakova and others, 2023) (Fig. 4C.~~10~~9).

Trawl fisheries are a major fishery type in the region (Morgan and Baco, 2021). Many invertebrate stocks including crabs, oysters, Geoduck, Pacific oysters and Northern abalone have declined across the North Pacific, with severe losses such as the Bering Sea snow crab (Szuwalski and others, 2023). Aquaculture faces challenges from ocean acidification, hypoxia, temperature anomalies and invasive species (Alma and others, 2023; Cowan and others, 2023; Qu and others, 2024). In 2021, a sea star outbreak in China's Jiaozhou Bay caused major damage to shellfish farming and fisheries.

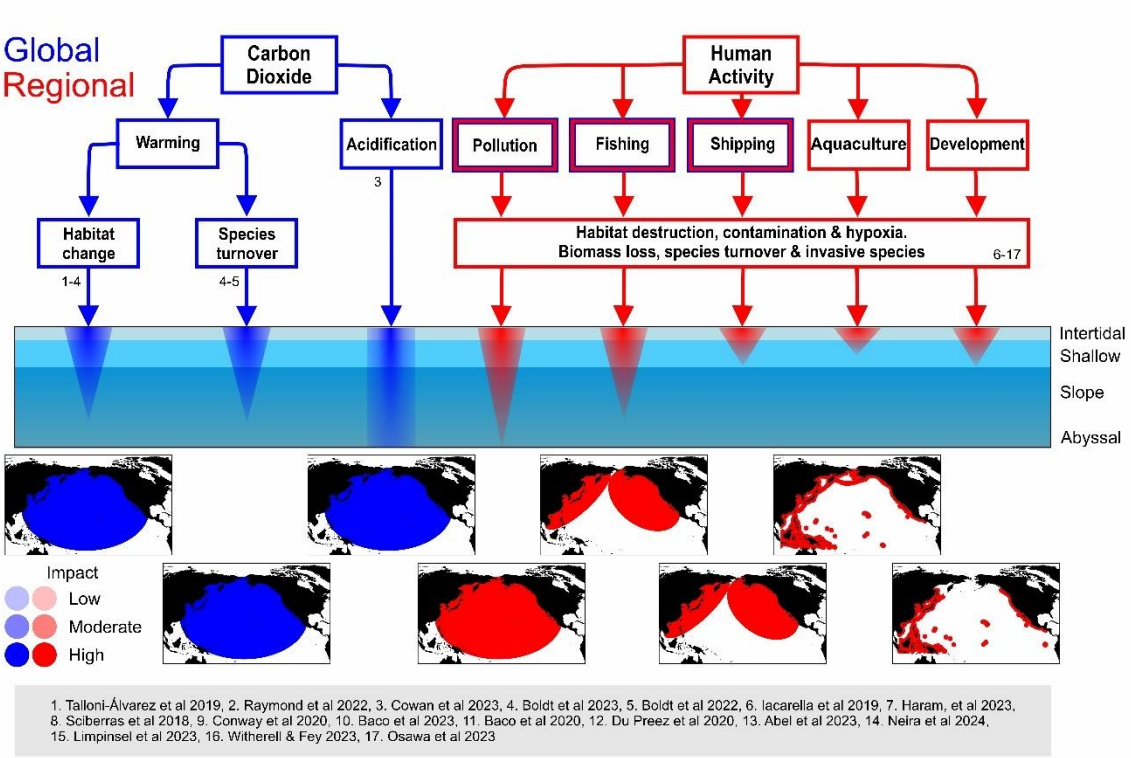


Figure 4C.~~9~~10. The North Pacific Ocean. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates~~.~~.

The South Pacific Ocean

Deep-sea biodiversity of the South Pacific has recently expanded through taxonomic discoveries on the southeastern Australian slope and abyss (Gunton and others, 2021; O'Hara and others, 2020). This includes species inventories (Kupriyanova and others, 2024a), new species (Flaxman and Kupriyanova, 2024; Wu and others, 2021; Blake, 2023; Gunton and others, 2023; Georgieva and others, 2023; Zhang and others, 2020)

and taxonomic revisions (Zhang and others, 2019). Underwater imagery and samples from the Coral Sea provided new data on black corals (Horowitz and others, 2022), carnivorous sponges (Ekins and Hooper, 2023) and mesophotic reefs (Huang and others, 2024).

Warming waters have caused range shifts of benthic invertebrates across the region (Davis and others, 2023; Gervais and others, 2021), leading to ecosystem changes, especially in photic zones such as kelp gardens shifting to urchin barrens in Ling and Keane, 2024; Balemi and Shears, 2023).

Warming waters and marine heatwaves (Fig. 4C.1~~1~~0) have reduced key habitat for marine invertebrates including giant kelp forests (Tait and others, 2021) and coral reefs (Henley and others, 2024), including repeated bleaching events around Lord Howe Island, the world's southernmost coral reef (Moriarty and others, 2023). In Australia, extreme flooding, bushfires, and heatwaves have been associated with freshwater plumes, sedimentation, turbidity, and high temperatures, all of which have been shown to negatively impact certain benthic invertebrates (Larkin and others, 2024; Glasby and others, 2023; Barros and others, 2022).

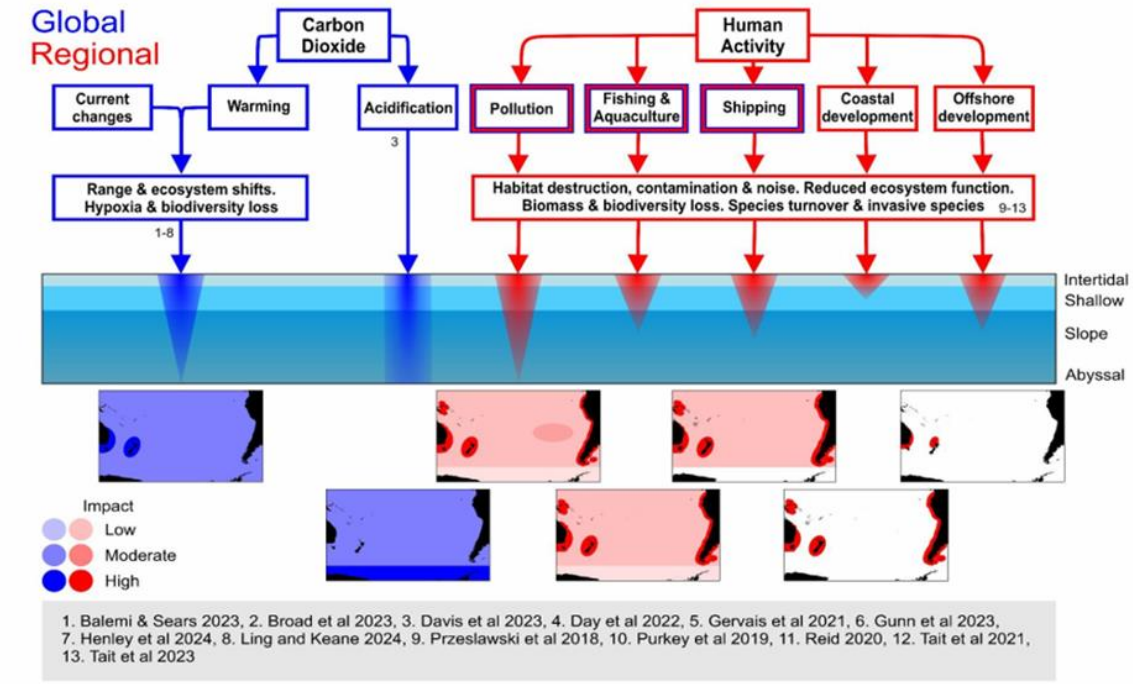


Figure 4C.1~~0~~1. The South Pacific. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates. Arrows width identifies relative importance of stressors at/on global and local scales.

The Southern Ocean

Antarctica's ecosystems host a diverse, highly endemic community shaped by isolation and freezing temperatures. Projected changes (Fig. 4C.112) will likely reach tipping points in physiological limits, primary productivity, ecosystem function and competition by the end of this century (Griffiths and others, 2024). These changes will affect Antarctic benthic ecosystem health, stability, and uniqueness as endemic cold-water species decline and cosmopolitan move south. Benthic changes remain poorly understood, with research mostly focused on a few shallow water taxa, requiring advanced technologies to address geographic, depth, seasonal, and taxonomic gaps (Griffiths and others, 2024).

Cold-adapted species face threats from local and global drivers, including warming, acidification, and changes to the cryosphere. The impacts vary by location, depth and community type, with the most significant changes observed in the shallows of west Antarctic Peninsula (Griffiths and others, 2024). These include the emergence of newly exposed coastline (leading to new habitats), reduced sea ice and increased iceberg scouring and turbidity, leading to higher mortality, lower diversity, and reduced primary production, carbon storage and spatial competition (Griffiths and others, 2024).

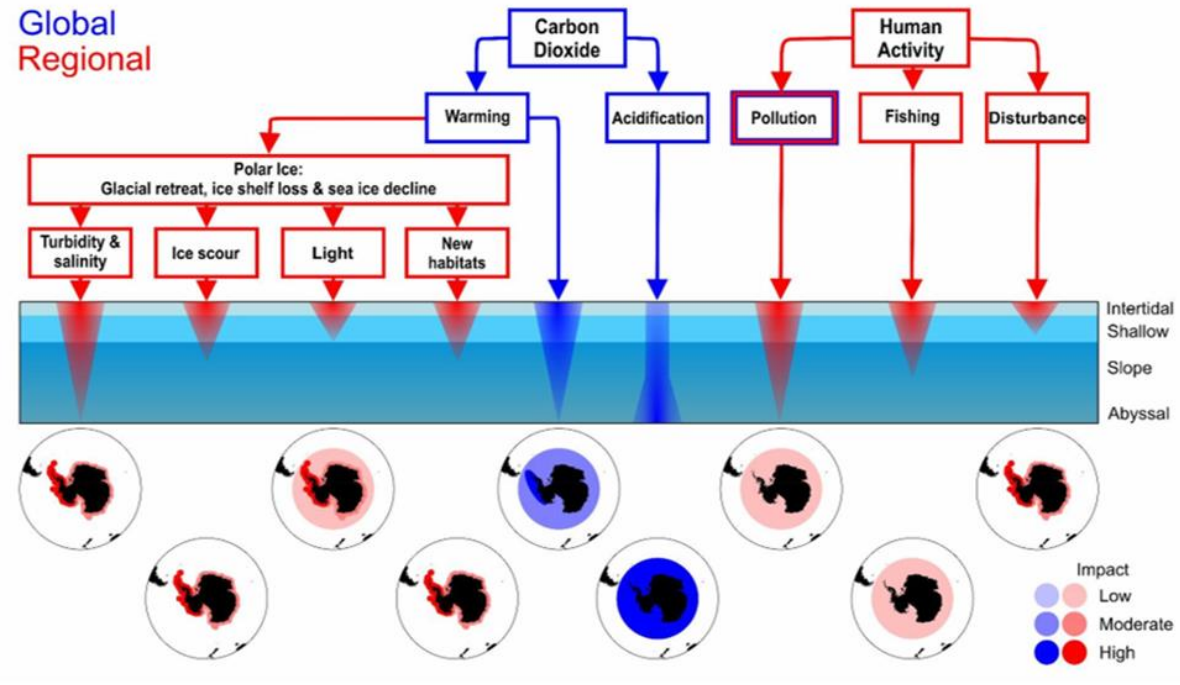


Figure 4C.112. The Southern Ocean. Global and local stressors, associated pressures, and recently documented consequences on marine benthic invertebrates. Arrow width identifies relative importance of stressors at/on global and local scales (adapted from Griffiths et al., 2024 and https://zenodo.org/records/8359585).

4. Implications for achieving the targets of the Sustainable Development Goals of the 2030 Agenda for Sustainable Development

The preservation and sustainable management of marine ecosystems, a key focus of the SDGs, is closely tied to benthic fauna which are crucial for ecosystem health and resilience. This connection is particularly evident in SDG 14, which aims to conserve and sustainably use the ocean´s, seas, and marine resources. The conservation of benthic fauna also supports SDG 13 (Climate Action) SDG 15 (Life on Land), as healthy marine ecosystems help regulate climate and maintain global ecological balance.

The negative biodiversity and ecosystems trends outlined in this chapter hinder progress towards the achieving relevant SDGs. Effective implementation of the BBNJ Agreement to complement existing management measures and strengthened ocean management at regional and national levels (see Section 3.3) are crucial for advancing SDG 14. Increasing conservation-focused ocean management measures at the regional and national levels can support the achievement of SDG 14, contributing to addressing climate change (SDG 13), and reducing biodiversity loss (Kunming-Montreal Global Biodiversity Framework).

5. Remaining key knowledge and capacity changes and any new gaps

- Marine invertebrates are under-documented in the deep ocean, developing States, island States, and taxa with few experts.
- Increased digitization and genomic research are needed to ~~enhance record species records and~~ identify cryptic species, integrate species information, and improve accessibility.~~.~~
- Documenting larval – juvenile settlement in deeper ecosystems remains challenging.

- Research on the biological pump and human impacts is needed.
- Local research and cooperation need improvement:
    - Activate skills/resources to use citizen and community science programmes to fill knowledge gaps.
    - Develop effective succession planning and career development opportunities for early and mid-career marine scientists.
    - Meaningfully and ethically consider Indigenous Peoples/First Nations and local knowledge.
    - Secure consistent funding for long-term biodiversity monitoring.
- The recording of benthic invertebrates during assessments of commercial fisheries using bottom trawl should be used as a supplement to small-scale grab or underwater video methods.
- Develop “Ocean Digital Twins” that compile available data and allow developing future scenarios and predictions.
- Imaging techniques, possibly combined with AI, can be used to monitor infrequently assessed, remote and inaccessible benthic ecosystems.
- Improved seabed management in relation to increasing human activities is needed.
- Networking across regions and disciplines is vital for understanding marine biodiversity, gathering key information, monitoring changes, and conducting research on biodiversity patterns and processes, improving the societal relevance of research (Tolochko and others, 2021).

References

Abel, Serena M., and others. Journey to the deep: Plastic pollution in the hadal of deep-sea trenches. Environmental Pollution, vol. 333, art. 122078, 2023.

Abdul Jaleel, K.U., and others. Response of macrozoobenthic communities to summer monsoon upwelling and related hypoxia in the south eastern Arabian Sea shelf. Marine Environmental Research, vol. 166, art. 105278, 2021.

Ajmal Khan, Syed, and others. Impact of the 2004 tsunami on the macrofauna of the continental slope of the southeast coast of India. Marine Ecology, vol. 39, art. e12527, 2018.

Al-Habahbeh, Amalia K., and others. Arctic coastal benthos long-term responses to perturbations under climate warming. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 378, art. 20190355, 2020.

Ali, M., and others. Issues and challenges in sustainable development of fisheries and aquaculture of the Southeast Asian Region: Fishery management: Management of fishing capacity and combating IUU fishing. The Southeast Asian State of Fisheries and Aquaculture, 2022.

Alma et al (2023) Physiological responses of scallops and mussels to environmental variability: Implications for future shellfish aquaculture. Marine Pollution Bulletin 194(B): 115356

Alves, Catherine, and others. Twenty years of change in benthic communities across the Belizean Barrier Reef. PLoS One, vol. 17, art. e0249155, 2022.

Alzugaray, Romina, and others. The Caribbean spiny lobster (*Panulirus argus*) fishery in Cuba: current status, illegal fishing, and environmental variability. Bulletin of Marine Science vol. 94, No. 2, pp. 393–408, 2018.

Amjad, Farah, and others. An underwater imagery identification guide for shallow, mesophotic and deep-sea benthos in Maldives. Biodiversity Data Journal, vol. 12, art. e120128, 2024.

Amon, Diva J., and others. Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. Marine Policy, vol. 138, art. 105006, 2022.

Andrews, Nathan, and others. Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. Energy Research & Social Science, vol. 75, art. 102009, 2021.

ASTD. Arctic Ship Traffic Database. https://map.astd.is/, 2019, 2024.

Azovsky, Andrey I., and Valentin N. Kokarev. Stable but fragile: long-term dynamics of arctic benthic macrofauna in Baydaratskaya Bay (the Kara Sea). Polar Biology, vol. 42, pp. 1307–1322, 2019.

Baco, Amy R., and others. Bottom-contact fisheries disturbance and signs of recovery of precious corals in the Northwestern Hawaiian Islands and Emperor Seamount Chain. Ecological Indicators, vol. 148, art. 110010, 2023.

Baco, Amy R., and others. Observations of vulnerable marine ecosystems and significant adverse impacts on high seas seamounts of the northwestern Hawaiian Ridge and Emperor Seamount Chain. Marine Policy, vol. 115, art. 103834, 2020.

Balemi, Celia A., and Nick T. Shears NT. Emergence of the subtropical sea urchin *Centrostephanus rodgersii* as a threat to kelp forest ecosystems in northern New Zealand. Frontiers in Marine Science, vol. 10, art. :1224067, 2023.

Barros, Thayanne L., and others. Wildfires cause rapid changes to estuarine benthic habitat. Environmental Pollution, vol. 308, art. 119571, 2022.

Bell, James J., and others. Marine heat waves drive bleaching and necrosis of temperate sponges. Current Biology, vol. 33, No. 1, pp. 158-163, 2023.

Bevilacqua, Stanislao, and others. The status of coastal benthic ecosystems in the Mediterranean Sea: Evidence from ecological indicators. Frontiers in Marine Science, vol. 7, art. 475, 2020.

Bilous, Miranda, and others. Coastal marine biodiversity in the western Canadian Arctic. Arctic Science, vol. 8, No. 4, pp. 1127–1147, 2022.

Binnaser, Yaser S. Global warming, marine invertebrates, and Saudi Arabia Coast on the Red Sea: An updated review. Egyptian Journal of Aquatic Biology & Fisheries, vol. 25, No. 4, pp. 221–240, 2021.

Blake, James A. New species of Scalibregmatidae (Annelida) from slope and abyssal depths off eastern Australia. Records of the Australian Museum, vol. 75, No. 3, pp. 271–298, 2023.

Boldt, Jennifer L., and others, eds. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2022. Canadian Technical Reports of Fisheries and Aquatic Sciences 3542, 2023.

Boldt, Jennifer L., and others, eds. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2021. Canadian Technical Reports of Fisheries and Aquatic Sciences 3482, 2022.

Bove, Colleen. B., and others. A century of warming on Caribbean reefs. PloS Climate, vol. 1, no. 3, art. e0000002, 2022.

Bridges, Amelia E.H., and others. “Review of the central and south Atlantic shelf and deep-sea benthos: science, policy, and management”, in *Oceanography and Marine Biology: An Annual Review Volume 61*, Stephen J. Hawkins and others, eds. (Taylor & Francis, 2023).

Broad, Alison, and others. Anchor scour from shipping and the defaunation of rocky reefs: A quantitative assessment. Science of the Total Environment, vol. 863, art. 160717, 2023.

Bullock, Robert, and others. The conservation status of marine biodiversity of the Western Indian Ocean. Gland, Switzerland: IUCN, 2021.

Buser, Thaddaeus. “Eastern and Northern Bering Sea – Miscellaneous species”, in *Ecosystem Status Report 2023: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report*, Elizabeth Siddon, ed. (North Pacific Fishery Management Council, Anchorage, Alaska, 2023).

Chanrajchakij, Issara. Issues and challenges in sustainable fisheries development of the Southeast Asian Region: Fisheries management: Responsible fishing and practices in Southeast Asia. The Southeast Asian State of Fisheries and Aquaculture 73-74, 2012.

Chen, LinLin, and others. Long-term changes of marine subtidal benthic communities in North East Asia (Yellow and Japan seas) in a global change

context: A review. Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 30, pp. 1451–1475, 2020.

Christie, Laurissa R., and others. (2023) Community-led coastal ecosystem assessments in the Hudson Bay Complex (Igloolik, Kinngait, and Naujaat, NU and Whapmagoostui, QC): Synthesis of 2020-2021 field programs. Canadian Technical Report of Fisheries and Aquatic Sciences, vol. 3540, 2023.

Claassens, Louw, and others. How developed is the South African coast? Baseline extent of South Africa's coastal and estuarine infrastructure. Ocean & Coastal Management, vol. 222, art. 106112, 2022.

Claus, Simon and others. Marine regions: Towards a global standard for georeferenced marine names and boundaries. Marine Geodesy, vol. 37, No.2, pp. 99–125, 2014.

Conway, Kim W., and others. “Sponge reefs on the Northeast Pacific margin: geomorphic and biological variability”, in *Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats (Second Edition)*, Peter T. Harris and Elaine Baker, eds. (Elsevier, 2020).

Cooper, Lee W., and others. Changes in the oxygen isotope composition of the Bering Sea contribution to the Arctic Ocean are an independent measure of increasing freshwater fluxes through the Bering Strait. PLoS One, vol. 17, pp. 1–17, 2022.

Couce, Elena, and others. Reconstructing three decades of total international trawling effort in the North Sea. *Earth System Science Data*, *12*(1), pp.373-386.2020

Couce, Elena, and others. Capturing threshold responses of marine benthos along gradients of natural and anthropogenic change. Journal of Applied Ecology, vol. 57, pp. 1137–1148, 2022.

Cowan, Malcolm W., and others. Role of the Vibrio community, reproductive effort, and environmental parameters in intertidal Pacific oyster summer mortality in British Columbia, Canada. Aquaculture, vol. 565, art. 739094, 2023.

Cowburn, Benjamin, and others. Can luxury and environmental sustainability co-exist? Assessing the environmental impact of resort tourism on coral reefs in the Maldives. Ocean & Coastal Management, vol. 158, pp.120–127, 2018.

Crespo, Daniel, and Miguel A. Pardal. “Ecological and economic importance of benthic communities”, in *Life Below Water, Encyclopedia of the UN Sustainable Development Goals*, W. Leal Filho and others, eds. (Springer Cham, 2022).

Davis, Tom R., and others. Impacts of climate change on densities of the urchin *Centrostephanus rodgersii* vary among marine regions in Eastern Australia. Diversity, vol. 15, No. 3, art. 419, 2023.

Day, Ryan D., and others. The impact of seismic survey exposure on the righting reflex and moult cycle of southern rock lobster (*Jasus edwardsii*) puerulus larvae and juveniles. Environmental Pollution, vol. 309, art. 119699, 2022.

Deep Sea Conservation Coalition. Marine Expert Statement. 2024. https://seabedminingsciencestatement.org/, 2024.

de Lacerda, Luiz D., and others. 20-years cumulative impact from shrimp farming on mangroves of Northeast Brazil. Frontiers in Forests and Global Change, vol. 4, art. 653096, 2021.

De Leo, Fabio C., and others. “Continental Slope and Submarine Canyons: Benthic Biodiversity and Human Impacts”, in Brazilian Deep-Sea Biodiversity, Paulo Y.G. Sumida, and others, eds. (Springer, Cham, 2020).

Delfan, Nastaran, and others. Patterns of structural and functional diversity of macrofaunal communities in a subtropical mangrove ecosystem. Estuarine, Coastal and Shelf Science, vol. 252, art. 107288, 2021.

DFFE. Department of Forestry, Fisheries and the Environment. Status of the South African marine fishery resources 2023. Cape Town: DFFE, 2023.

DFO. Tuvaijuittuq Marine Protected Area. 2024. https://www.dfo-mpo.gc.ca/oceans/mpa-zpm/tuvaijuittuq/index-eng.html, 2024.

Diaz, Clara, and others. Mesophotic coral bleaching associated with changes in thermocline depth. Nature Communications, vol. 14, No. 1, p. 6528, 2023.

Drazen, Jeffrey, and others. Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. Proceedings of the National Academy of Sciences of the United States of America, vol. 117, No. 30, 2020.

Dreujou, Elliot, and others. Multiple human activities in coastal benthic ecosystems: Introducing a metric of cumulative exposure. Elementa: Science of the Anthropocene, vol 11, No. 1, art. 00024, 2023.

Drinkwin, Joan, and others. Salish Sea Transboundary Action Plan for Invasive European Green Crab. Puget Sound Partnership. 2019.

Duarte, Gustavo A., and others. Heat waves are a major threat to turbid coral reefs in Brazil. Frontiers in Marine Science, vol. 7, art. 179, 2020.

Dumais, Philippe-Olivier, and others. Description and spatial modelling of benthic communities distribution in the Canadian Arctic Archipelago. Frontiers in Marine Science, vol. 9, art. 898852, 2022.

Du Preez, Cherisse, and others. 2020. Cold-water corals and other vulnerable biological structures on a North Pacific seamount after half a century of fishing. Frontiers in Marine Science, vol. 7, art. 00017, 2020.

Dvoretsky, Alexander G, and Vladimir G. Dvoretsky. Filling knowledge gaps in Arctic marine biodiversity: Environment, plankton, and benthos of Franz Josef Land, Barents Sea. Ocean & Coastal Management, vol. 249, art. 106987, 2024.

Eggertsen, Linda, and others. Complexities of reef fisheries in Brazil: a retrospective and functional approach. Reviews in Fish Biology and Fisheries, vol. 34, pp. 511–538, 2024.

Ekins, Merrick, and John N.A. Hooper. New carnivorous sponges from the Great Barrier Reef, Queensland, Australia collected by ROV from the RV FALKOR. Zootaxa, vol. 5293, No. 3, pp. 435–471, 2023.

EMODnet Bathymetry Consortium. EMODnet Digital Bathymetry. 2016. https://sextant.ifremer.fr/record/c7b53704-999d-4721-b1a3-04ec60c87238/, 2016.

Engelhard, Georg H., and others. Climate risk assessment of the fisheries in Namibia. Reviews in Fish Biology and Fisheries, vol. 34, pp. 1231–1260, 2024.

Etnoyer, Peter J., and others. Diversity and time-series analyses of Caribbean deep-sea coral and sponge assemblages on the tropical island slope of Isla de Roatán, Honduras. Marine Biodiversity, vol. 52, art. 8, 2022.

European Academies' Science Advisory Council. Deep-Sea Mining: Assessing evidence on future needs and environmental impacts. 2023. https://easac.eu/fileadmin/user_upload/EASAC_Deep_Sea_Mining_Web_publication_.pdf, 2023.

Fang, Chao, and others. Microplastics contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere, vol. 209, pp. 298–306, 2018.

Fennessy, Sean T. Chapter 12: Shelf, deep sea and offshore pelagic, in *Western Indian Ocean Critical Habitats Outlook*, JPM Paula, ed. (Nairobi, Kenya, UNEP and WIOMSA, 2024).

Flanders Marine Institute. IHO Sea Areas, Version 3. 2024a. http:/marineregions.org, 2024.

Flanders Marine Institute. The intersect of the Exclusive Economic Zones and IHO sea areas, Version 5. 2024b. https://www.marineregions.org/

Flaxman, Beth, and Elena K. Kupriyanova. New species of *Laetmonice* (Aphroditidae, Annelida) from bathyal and abyssal depths around Australia. Records of the Australian Museum, vol. 76, No. 4, pp. 195–210, 2024.

Fondo, Esther N., and Johnstone O. Omukoto. Observations of industrial shallow-water prawn trawling in Kenya. Oceanography, vol. 34, No. 4, pp. 44–45, 2022.

Fontela, Marcos, and others. Anthropogenic CO_2 and ocean acidification in Argentine Basin Water Masses over almost five decades of observations. Science of the Total Environment, vol. 779, art. 146570, 2021.

Gao, Haihe, and others. Macro-and/or microplastics as an emerging threat effect crop growth and soil health. Resources, Conservation and Recycling, vol. 186, art. 106549, 2022.

GEBCO. The GEBCO_2014 Grid, version 20150318n.d. IHO-IOC GEBCO Gazetteer of Undersea Feature Names, www.gebco.net, 2015

Georgieva, Magdalena N., and others. (2023) The annelid community of a natural deep-sea whale fall off eastern Australia. Records of the Australian Museum, vol. 75, No. 3, pp. 167–213, 2023.

Gerland, Sebastian, and others. Still Arctic? The changing Barents Sea. Elementa: Science of the Anthropocene, vol. 11, No. 1, art. 00088, 2023.

Gervais, Connor R., and others. Species on the move around the Australian coastline: A continental-scale review of climate-driven species redistribution in marine systems. Global Change Biology, vol. 27, No. 14, pp. 3200–3217, 2021.

Ghaemi, Maryam, and others. Spatial distribution of nutrients and chlorophyll *a* across the Persian Gulf and the Gulf of Oman. Ocean & Coastal Management, vol. 201, art. 105476, 2021.

Gianasi, Bruno L., and others. Biodiversity of coastal epibenthic macrofauna in Eastern Canadian Arctic: Baseline mapping for management and conservation. Frontiers in Marine Science, vol. 9, art. 873608, 2022.

Gissi, Elena, and others. A review of the combined effects of climate change and other local human stressors on the marine environment. Science of the Total Environment, vol. 755, art. 142564, 2021.

Glasby, Tim M., and others. Black summer bushfires caused extensive damage to estuarine wetlands in New South Wales, Australia. Ecological Management and Restoration, vol. 24, No. 1, pp. 27–35, 2023.

Goes, Enatielly R., and others. A seafloor sensitivity index to oil spills in tropical marine protected areas. Continental Shelf Research, vol. 266, art. 105069, 2023.

Goldsmit, Jesica, and others. What and where? Predicting invasion hotspots in the Arctic marine realm. Global Change Biology, vol. 26, pp. 4752–4771, 2020.

Golikov, Alexey V., and others. Long-term annual trawl data show shifts in cephalopod community in the western Barents Sea during 18 years. Frontiers in Marine Science, vol. 11, art. 1392585, 2024.

Gomes, Luiz E.O., and Angelo F. Bernardino. Drought effects on tropical estuarine benthic assemblages in Eastern Brazil. Science of the Total Environment, vol. 703, art. 135490, 2020.

González-De Zayas, Roberto, and others. Stable isotopes used to assess pollution impacts on coastal and marine ecosystems of Cuba and México. Regional Studies in Marine Science, vol. 39, art. 101413, 2020.

Gonzalez, Silvana, and others. Spatiotemporal variability of Pacific Arctic marine ecosystems. In Proceedings of the Alaska Marine Science Symposium, 29 January – 2 February 2024, Anchorage, AK, USA, 2024a.

Gonzalez, Karla, and others. Differential spatio-temporal responses of Red Sea coral reef benthic communitpies to a mass bleaching event. Scientific Reports, vol. 14, art. 74956, 2024b.

Gorayeb, Adryane, and others. Emerging challenges of offshore wind energy in the Global South: Perspectives from Brazil. Energy Research & Social Science, vol. 113, art. 103542, 2024.

Gress, Erika, and Dominic A. Andradi-Brown. Assessing population changes of historically overexploited black corals (Order: Antipatharia) in Cozumel, Mexico. PeerJ, vol. 6, art. e5129, 2018.

Griffiths, Jennifer R., and others. The importance of benthic–pelagic coupling for marine ecosystem functioning in a changing world. Global Change Biology, vol. 23, pp. 2179–2196, 2017.

Griffiths, Huw J., and others. Antarctic benthic ecological change. Nature Reviews Earth & Environment, vol. 5, No. 9, pp.645–664, 2024.

Gunn, K.L., and others. Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin, vol. 13, pp. 537-544, 2023.

Gunton, Laetitia M., and others. Annelids of the eastern Australian abyss collected by the 2017 RV “Investigator” voyage. ZooKeys, vol. 1020, pp. 1–198, 2021.

Gunton, Laetitia M., and others. New species of Melinna (Melinnidae, Annelida) from the Australian abyss with comments on *M. albicincta*, *M. cristata* and *M.*

elisabethae, in *RV Investigator—Abyssal Annelida*, EK Kupriyanova and LM Gunton, eds. Records of the Australian Museum, 2023.

Guo, Jinqiang, and others. Hypoxia, acidification and nutrient accumulation in the Yellow Sea Cold Water of the South Yellow Sea. Science of The Total Environment, vol. 745, art. 141050, 2020.

Halpern, Benjamin S., and others. Recent pace of change in human impact on the world's ocean. Scientific Reports, vol. 9, art. 11609, 2019.

Han, In-Seong, and others. Long-term pattern changes of sea surface temperature during summer and winter due to climate change in the Korea Waters. Fisheries and Aquatic Sciences, vol. 26, pp. 639–648, 2023.

Haram, Linsey E., and others. Extent and reproduction of coastal species on plastic debris in the North Pacific Subtropical Gyre. Nature Ecology & Evolution, vol. 7, pp. 687–697, 2023.

Harris Peter T., and others. A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution. Continental Shelf Research, vol. 255, art. 104947, 2023.

Heckwolf, Melanie J., and others. From ecosystems to socio-economic benefits: A systematic review of coastal ecosystem services in the Baltic Sea. Science of the Total Environment, vol. 755, p. 2, art. 142565, 2021.

Herbeck, Lucia S., and others. Pond aquaculture effluents feed an anthropogenic nitrogen loop in a SE Asian estuary. Science of the Total Environment, vol. 756, art. 144083, 2021.

Herbert-Read, James E., and others. A global horizon scan of issues impacting marine and coastal biodiversity conservation. Nature Ecology & Evolution, vol. 6, No. 9, pp. 1262–1270, 2022.

Henry, Lea-Anne, and others. Historic scale and persistence of drill cuttings impacts on North Sea Benthos. Marine Environmental Research, vol. 129, pp. 219–228, 2017.

Henley, Benjamin J., and others. Highest ocean heat in four centuries places Great Barrier Reef in danger. Nature, vol. 632, pp. 320–326, 2024.

Holte, Børge, and others. Infaunal and epifaunal secondary production in the Barents Sea, with focus on snow crab (*Chionoecetes opilio*) prey resources and consumption. ICES Journal of Marine Science, vol. 79, No. 9, pp. 2524–2539, 2022.

Horowitz, Jeremy, and others. Five new species of black coral (Anthozoa; Antipatharia) from the Great Barrier Reef and Coral Sea, Australia. Zootaxa, vol. 5213, No. 1, 1–35, 2022.

Hu, Li-sha, and others. Northward shift of a biogeographical barrier on China's coast. Diversity and Distributions, vol. 28, pp. 318–330, 2021.

Huang, Yi-Cheng, and others. First record of the invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Bivalvia: Mytilidae) from clam ponds in Taiwan. BioInvasions Record, vol. 10, No. 2, pp. 304–312, 2021.

Huang, Zhi, and others. Marine heatwaves in the Great Barrier Reef and Coral Sea: Their mechanisms and impacts on shallow and mesophotic coral ecosystems. Science of the Total Environment, vol. 908, art. 168063, 2024.

Humphries, Fran, and others. "Bridging divides: The evolution of marine genetic resource governance beyond national jurisdiction", in *Decoding marine genetic resource governance under the BBNJ Agreement*, Fran Humphries, ed. (Springer, 2025).

Iacarella, Josephine C., and others. Biotic exchange from movement of 'static' maritime structures. Biological Invasions, vol. 21, pp. 1131–1141, 2019.

Ibrahim, Nur F., and others. Review of Oweniidae Rioja, 1917 (Annelida, Palaeoannelida) from Malaysia, with a description of two new species and a key to South China Sea species. Zoosystema, vol. 46, No. 20, pp. 513–542, 2024.

IHO Sea Areas. Flanders Marine Institute. IHO Sea Areas, version 3. Available online at https://www.marineregions.org/. https://doi.org/10.14284/323. 2018

IMARPE. Biodiversity and stock assessment research on benthic invertebrates in Peruvian waters. Boletín del Instituto del Mar del Perú. 2024. Retrieved from: https://revistas.imarpe.gob.pe/index.php/boletin/article/download/biodiversidad_marina/410/1014

Isla, Enrique, and Dieter Gerdes. Ongoing ocean warming threatens the rich and diverse macrobenthic communities of the Antarctic continental shelf. Progress in Oceanography, vol. 178, art. 102180, 2019.

Jacobs, Kevin, and others. Biodiversity monitoring stations for benthic macrofauna and meiofauna in the Disko Fan and Hatton Basin Conservation Areas. Canadian Technical Report of Fisheries and Aquatic Sciences, vol. 3487, 2022.

Jamieson, Alan J., and Deo Florence L. Onda. Lebensspuren and müllspuren: Drifting plastic bags alter microtopography of seafloor at full ocean depth (10,000 m, Philippine Trench). Continental Shelf Research, vol. 250, art. 104867, 2022.

Jayachandran, Paravanparambil R., and others. Unveiling the ecological status of the Arabian Gulf's marine ecosystem: Insights from benthic community analysis. Marine Pollution Bulletin, vol. 205, art. 116571, 2024.

Jayachandran, Paravanparambil R., and others. First record of the alien invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Mollusca: Mytilidae) from Indian waters. BioInvasions Records, vol. 8, No. 4, pp. 828–837, 2019.

Jørgensen, Lis L., and others. Impact of multiple stressors on sea bed fauna in a warming Arctic. Marine Ecology Progress Series, vol. 608, pp. 1–12, 2019.

Jørgensen, Lis L., and others. Responding to global warming: New fisheries management measures in the Arctic. Progress in Oceanography, vol. 188, art. 102423, 2020.

Jørgensen, Lis L., and others. International megabenthic long-term monitoring of a changing Arctic ecosystem: Baseline results. Progress in Oceanography, vol. 200, art. 102712, 2022a.

Jørgensen, Lis L., and others. Benthic transition zones in the Atlantic gateway to a changing Arctic Ocean. Progress in Oceanography. Progress in Oceanography, vol. 204, art. 102792, 2022b.

Joydas, Thadickal V., and others. Advancing ecological assessment of the Arabian Gulf through eDNA metabarcoding: opportunities, prospects, and challenges. Frontiers in Marine Science, vol. 11, art. 1276956, 2024.

Kanhai, La Daana K., and others. The status of marine debris/litter and plastic pollution in the Caribbean Large Marine Ecosystem (CLME): 1980–2020. Environmental Pollution, vol. 300, art. 118919, 2022.

Katsanevakis, Stelios, and others. "The fan mussel *Pinna nobilis* on the brink of extinction in the Mediterranean", in *Imperiled: The Encyclopedia of Conservation*, Dominick A DellaSala and Michael I. Goldstein, eds. Oxford, Elsevier, 2022.

Kavousi, Javid, and others. Four consecutive coral bleaching events in the Northern Persian Gulf: 2014–2017. Annals of Marine Science, vol. 5, No. 1, pp. 007–014, 2021.

Kenchington, Ellen, and others. Biodiversity monitoring stations for benthic megafauna in the Disko Fan Conservation Area. Canadian Technical Report of Fisheries and Aquatic Sciences, vol. 3499, 2022.

Kupriyanova, Elena K., and others. Catalogue of the Annelida collected by the IN2021_V04 and IN2022_V08 expeditions to the Australian Christmas Island and Cocos (Keeling) Islands Territories. Museum Victoria Science Reports, vol. 30, pp. 1–71, 2024a.

Kupriyanova, Elena K., and others. Confirming the invasion by tubeworm *Ficopomatus cf. uschakovi* (Pillai, 1960) (Annelida, Serpulidae) in Mexico. BioInvasions Records, vol. 13, No. 4, pp. 979–991, 2024b.

Ladewig, Samantha M., and others. Real-world impacts of microplastic pollution on seafloor ecosystem function. Science of the Total Environment, vol. 858, art. 160114, 2023.

Lange, Ines D., and Chris T. Perry. Bleaching impacts on carbonate production in the Chagos Archipelago: Influence of functional coral groups on carbonate budget trajectories. Coral Reefs, vol. 38, No. 4, pp. 619–624, 2019.

Larkin, Meryl F., and others. La Niña pushes an endangered temperate soft coral species to the brink of localised extinction. Estuaries and Coasts, vol. 47, pp. 448–459, 2024.

Limpinsel, Douglas, and others. Impacts to essential fish habitat from non-fishing activities in Alaska: EFH 5-year review from 2018-2023. National Marine Fisheries Service, Alaska Region, Juneau, Alaska. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/AKR-30, 2023.

Ling, Scott D., and John P. Keane. Climate-driven invasion and incipient warnings of kelp ecosystem collapse. Nature Communications, vol. 15, No. 1, art. 400, 2024.

Lloret, Josep, and others. Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. Science of the Total Environment, vol. 824, art. 153803, 2022.

Logerwell, Elizabrth A., and others. Winners and losers in a warming Arctic: Potential habitat gain and loss for epibenthic invertebrates of the Chukchi and Bering Seas, 2008–2100. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 206, art. 105210, 2022.

Lovell, Tricia A. Understanding the drivers, scale and impact of abandoned, lost and otherwise discarded fishing gear in small-scale fisheries: an Eastern Caribbean perspective. Frontiers in Marine Science, vol. 10, art. 1139259, 2023.

Magris, Rafael A., and others. A blueprint for securing Brazil's marine biodiversity and supporting the achievement of global conservation goals. Diversity and Distributions, vol. 27, No. 2, pp. 195–388, 2020.

Mamede, Renato. Ecology and biogeography of marine benthos. Diversity, vol. 16, art. 502, 2024.

Marine Regions. Flanders Marine Institute. MarineRegions.org. Available online at www.marineregions.org. Consulted on 2024-10-04. 2024.

Martello, Melina F., and others. Projected climate-driven shifts in coral distribution indicate tropicalisation of Southwestern Atlantic reefs. Diversity and Distributions, vol. 30, art. e13851, 2024.

Martinez, Aline S., and others. Reviewing the effects of contamination on the biota of Brazilian coastal ecosystems: scientific challenges for a developing country in a changing world. Science of The Total Environment, vol. 803, art. 150097, 2022.

Mason, Victoria G., and others. Microplastics alter multiple biological processes of marine benthic fauna. Science of the Total Environment, vol. 845, art. 157362, 2022.

McClanahan, Tim R. and Nyawira A. Muthiga. Oceanic patterns of thermal stress and coral community degradation on the island of Mauritius. Coral Reefs, vol. 40, No. 1, pp. 53–74, 2021.

McNicholl, Darcy G., and others. Anguniaqvia Niqiqyuam Marine Protected Area Coastal Monitoring: Synthesis of 2017-2021 Summer and Winter Field Programs. Canadian Technical Report of Fisheries and Aquatic Sciences, vol. 3595, 2024.

MedECC. Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 2020.

Momota, Kyosuke, and Shinya Hosokawa. Potential impacts of marine urbanization on benthic macrofaunal diversity. Scientific Reports, vol. 11, art. 4028, 2021.

Monsalve, Eduardo R., and Eduardo Quiroga. Farmed shrimp aquaculture in coastal wetlands of Latin America - A review of environmental issues. Marine Pollution Bulletin, vol. 183, art. 113956, 2022.

Morgan, Nicole B., and Amy R. Baco. Recent fishing footprint of the high-seas bottom trawl fisheries on the Northwestern Hawaiian Ridge and Emperor Seamount Chain: A finer-scale approach to a large-scale issue. Ecological Indicators, vol. 121, art. 107051, 2021.

Moriarty, Tess, and others. Bleaching, mortality and lengthy recovery on the coral reefs of Lord Howe Island. The 2019 marine heatwave suggests an uncertain

future for high-latitude ecosystems. PLoS Climate, vol. 2, No. 4, art. e0000080, 2023.

Gottlieb, H. Muraki, and others. BBNJ Agreement: A New Infrastructure to Foster Benefit Sharing of Marine Genetic Resources. In Decoding Marine Genetic Resource Governance Under the BBNJ Agreement (pp. 29-54). Chap: Springer Nature Switzerland. 2025

Naidu, S.A., and others. Microplastics in the benthic invertebrates from the coastal waters of Kochi, Southeastern Arabian Sea. Environmental geochemistry and health, vol. 40, pp. 1377–1383, 2018.

Neira, Carlos, and others. Waste barrel contamination and macrobenthic communities in the San Pedro Basin DDT dumpsite. Marine Pollution Bulletin, vol. 203, art. 116463, 2024.

Niemi, Andrea, and others. State of Canada's Arctic Seas. Canadian Technical Report of Fisheries and Aquatic Sciences, vol. 3344, 2019.

Niemi, Andrea, and others. Biological impact of ocean acidification in the Canadian Arctic: Widespread severe pteropod shell dissolution in Amundsen Gulf. Frontiers in Marine Sciences, vol. 8, art. 600184, 2021.

Noori, Roohollah, and others. Recent and future trends in sea surface temperature across the Persian Gulf and Gulf of Oman. PloS One, vol. 14, No. 2, art. e0212790, 2019.

Nozarpour, Rahil, and others. Functional diversity of the macrofauna communities in arid mangroves of the Persian Gulf and Gulf of Oman. Regional Studies in Marine Science, vol. 74, art. 103534, 2024.

OBIS. Ocean Biogeographic Information System. 2019. https://www.obis.org/, 2024.

Obura, David, and others. Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. Nature Sustainability, vol. 5, No. 2, pp.104–113, 2022.

O'Hara, Timothy D., and others. The lower bathyal and abyssal seafloor fauna of eastern Australia. Marine Biodiversity Records, vol. 13, art. 11, 2020.

Osawa, Yumiko, and others. Bathymetric segregation among demersal benthos and its contributions to the differences in the bycatches on bottom fisheries in the Emperor Seamounts area, Northwestern Pacific Ocean. Regional Studies in Marine Science, vol. 68, art. 103261, 2023.

Osborne, Emily, and others. Ocean acidification in the Gulf of Mexico: Drivers, impacts, and unknowns. Progress in Oceanography, vol. 209, art. 102882, 2022.

OSPAR. Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic Assessments. 2024. https://oap.ospar.org/en/, 2024.

OSPAR. Benthic Habitats Thematic Assessment. 2023. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/synthesis-report/key-messages/#benthic-habitats-continue-to-be-damaged, 2023.

Paiva, Sandra V., and others. Marine carbonate mining in the southwestern Atlantic: current status, potential impacts, and conservation actions. Marine Policy, vol. 148, art. 105435, 2023.

Parameswaran, Usha V., and others. Standing stock and composition of macrozoobenthos in the south-eastern Arabian Sea: A revisit after a decade. Journal of Sea Research, vol. 183, art. 102200, 2022.

Pardal, André, and others. Urbanisation on the coastline of the most populous and developed state of Brazil: the extent of coastal hardening and occupations in low-elevation zones. Anthropocene Coasts, vol. 7, art. 15, 2024.

Pattiaratchi, Charitha, and others. Plastics in the Indian Ocean–sources, transport, distribution, and impacts. Ocean Science, vol 18, No. 1, pp.1–28, 2022.

Pereira, Pedro H.C., and others. Unprecedented coral mortality on Southwestern Atlantic coral reefs following major thermal stress. Frontiers in Marine Science, vol. 9, art. 725778, 2022.

Perez, Jose A.A., and Rodrigo Sant'Ana. Tropicalization of demersal megafauna in the western South Atlantic since 2013. Communications Earth & Environment, vol. 3, art. 227, 2022.

Picken, Chris, and others. From what-if to what-now: Status of the deep-sea mining regulations and underlying drivers for outstanding issues. Marine Policy, vol. 169, art. 105967, 2024.

Pineda-Metz, Santiago E.A., and others. 2020. Benthic fauna declined on a whitening Antarctic continental shelf. Nature Communications, vol. 111, art 2226, 2020.

Pierrejean, Marie, and others. Spatial distribution of epifaunal communities in the Hudson Bay system. Elementa: Science of the Anthropocene, vol. 8, No. 1, art. 00044, 2020.

Piñango, Andrés, and others. Ocean acidification and long-term changes in the carbonate system properties of the South Atlantic Ocean. Global Biogeochemical Cycles, vol. 36, art. e2021GB007196, 2022.

Pinheiro, Hudson T., and others. Plastic pollution on the world's coral reefs. Nature, vol. 619, pp. 311–316, 2023.

Polyakov, Igor V., and others. Borealization of the Arctic Ocean in response to anomalous advection from Sub-Arctic Seas. Frontiers in Marine Science, vol. 7, art. 00491, 2020.

Preston, Joanne, and others. Seascape connectivity: Evidence, knowledge gaps and implications for temperate coastal ecosystem restoration practice and policy. Nature Ocean Sustainability (in press), 2025.

Prishchepenko, D.V., and others. Main trends and results of 300-years anthropogenic impact on the geological environment and ecosystem of the Eastern Gulf of Finland. Continental Shelf Research, vol. 265, art. 105058, 2024.

Provoost, Pieter, and Samuel Bosch. Obistools: Tools for data enhancement and quality control. Ocean Biogeographic Information System. Intergovernmental Oceanographic Commission of UNESCO. https://cran.r-project.org/package=obistools, 2018.

Prozorkevich, Dmitry, and others. Survey report (Part 2) from the joint Norwegian/Russian Ecosystem Survey in the Barents Sea and the adjacent waters August-October 2023. IMR-PINRO Report Series, vol. 9, 2024.

Przeslawski, Rachel, and others. Multiple field-based methods to assess the potential impacts of seismic surveys on scallops. Marine Pollution Bulletin, vol. 129, No. 2, pp. 750–761, 2018.

Purkey, Sarah G., and others. Unabated bottom water warming and freshening in the South Pacific Ocean. Journal of Geophysical Research: Oceans, vol. 124, 1778-1794, 2019.

Qu, Liang, and others. Research progress on starfish outbreaks and their prevention and utilization: Lessons from Northern China. Biology, vol. 13, art. 537, 2024.

Quang Tri, Doan, and others. Quantitative assessment of the environmental impacts of dredging and dumping activities at sea. Applied Sciences, vol. 9, No. 8, p. 1703, 2019.

Rabone, Muriel, and others. How many metazoan species live in the world's largest mineral exploration region? Current Biology, vol. 33, No. 12, pp. 2383–2396e5, 2023.

Rajendra, Seepana, and others. "Status and Distribution of Opisthobranchs of Great Nicobar Biosphere Reserve, India", in *Faunal Ecology and Conservation of the Great Nicobar Biosphere Reserve*, Chandrakasan Sivaperuman and others, eds. (Springer, 2022).

Raymond Wendel W., and others. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. Ecology, vol. 103, No. 10, art. e3798, 2022.

Reid, David J. A review of intensified land use effects on the ecosystems of Botany Bay and its rivers, Georges River and Cooks River, in southern Sydney, Australia. Regional Studies in MArine Science, vol. 39, art. 101396, 2020.

Ribó, Marta, and others. Microplastic pollution distribution: Differences between marine reserves and urbanised areas. Continental Shelf Research, vol. 267, art. 105115, 2023.

Rodrigues, Meghie. Oil from the Amazon? Drilling plan for river mouth prompts alarm. Nature, vol. 619, pp. 680–681, 2023.

Rybakova, Elena, and others. Mega- and macrofauna of the hydrothermally active submarine Piip Volcano (the southwestern Bering Sea). Deep Sea Research Part II: Topical Studies in Oceanography, vol. 208, art. 105268, 2023.

Safuan, Che Din Mohd, and others, 2020. First record of tropical storm (Pabuk-January 2019) damage on shallow water reef in Pulau Bidong, south of South China Sea. Regional Studies in Marine Science, vol. 35, art. 101216, 2020.

Samaniego, Joseluis, and others. Current understanding of the potential impact of Carbon Dioxide Removal approaches on the Sustainable Development Goals in selected countries in Latin America and the Caribbean. Summary for policy makers. Carnegie Climate Governance Initiative (C2G)/ Economic Commission for Latin America and the Caribbean (ECLAC), 2021.

Schratzberger, Michaela, and Paul J. Somerfield. Effects of widespread human disturbances in the marine environment suggest a new agenda for meiofauna research is needed. Science of the Total Environment, vol. 728, art. 138435, 2020.

Sciberras, Marija, and others. Response of benthic fauna to experimental bottom fishing: A global meta-analysis. Fish and Fisheries, vol. 19, No. 4, pp. 698–715, 2018.

Shahnawaz, Mohd, and others, eds. Microplastic Pollution. Singapore: Springer, 2024.

Sink, Kerry J., and others. Integrated systematic planning and adaptive stakeholder process support a 10-fold increase in South Africa's Marine Protected Area estate. Conservation Letters, vol. 16, art. e12954, 2023.

Sink, Kerry J., and others. South African National Biodiversity Assessment 2018 Technical Report Volume 4: Marine Realm. South African National Biodiversity Institute, Pretoria. South Africa, 2019.

Sivadas, Sanitha K., and Amit J. Patil. Moving beyond traditional macrofaunal community structure studies in the Indian Ocean continental shelf: A research synthesis based on research weaving. Environmental Science and Pollution Research, vol. 30, pp. 19536–19563, 2023.

Skein, Lisa, and others. Scoping an integrated ecosystem assessment for South Africa. Frontiers in Marine Science, vol. 9, art. 975328, 2022.

Soares, Marcelo O., and others. Impacts of a changing environment on marginal coral reefs in the Tropical Southwestern Atlantic. Ocean & Coastal Management, vol. 210, art. 105692, 2021.

Soares, Marcelo O., and others. The most extensive oil spill registered in tropical oceans (Brazil): the balance sheet of a disaster. Environmental Science and Pollution Research, vol. 29, pp. 19869-19877, 2022a.

Soares, Marcelo O., and others. Alien hotspot: Benthic marine species introduced in the Brazilian semiarid coast. Marine Pollution Bulletin, vol. 174, art. 113250, 2022b.

Stefanoudis, Paris V., and others. Trait-based approaches reveal that deep reef ecosystems in the Western Indian Ocean are functionally distinct. Science of the Total Environment, vol. 872, art. 162111, 2023.

Stenvers, Vanessa I., and others. Experimental mining plumes and ocean warming trigger stress in a deep pelagic jellyfish. Nature Communications, vol. 14, art. 7352, 2023.

Stewart, Joshua D., and others. Boom-bust cycles in gray whales associated with dynamic and changing Arctic conditions. Science, vol. 382, No. 6667, pp. 207–211, 2023.

SUBPESCA. [BUSCAMERB: New app to consult shellfish and crustacean fishing areas data]. We Are Aquaculture. 2024. Retrieved from: https://weareaquaculture.com/news/technology/new-chilean-app-to-consult-shellfish-and-crustacean-fishing-areas-data

Sumida, Paulo Y.G., and others, eds. Brazilian Deep-Sea Biodiversity. Brazilian Marine Biodiversity series. Springer: Springer Cham, 2020.

Sweetman, Andrew K., and others. Evidence of dark oxygen production at the abyssal seafloor. Nature Geoscience, vol. 17, pp. 737–739, 2024.

Sweetman, Andrew K., and others. Major impacts of climate change on deep-sea benthic ecosystems. Elementa: Science of the Anthropocene, vol. 5, art. 4, 2017.

Szuwalski, Cody S., and others. The collapse of Eastern Bering Sea snow crab. Science, vol. 382, No. 6668, pp. 306–310, 2023.

Tait, Leigh W., and others. Loss of Giant Kelp, *Macrocystis pyrifera*, driven by marine heatwaves and exacerbated by poor water clarity in New Zealand. Frontiers in Marine Science, vol. 8, art. 721087, 2021.

Tait, Leigh W., and others. Ecosystem function modified by an invasive species: Density and distance dependent changes in sediment characteristics, fluxes, and benthic communities. Estuarine, Coastal and Shelf Science, vol. 293, art. 108526, 2023.

Talloni-Álvarez, Nicolás E., and others. Climate change impact on Canada's Pacific marine ecosystem: The current state of knowledge. Marine Policy, vol. 104, pp. 163–176, 2019.

Tank, Suzanne E., and others. Recent trends in the chemistry of major northern rivers signal widespread Arctic change. Nature Geoscience, vol. 16, pp. 789–796, 2023.

Tolochko, Petro, and others. Selective world-building: Collaboration and regional specificities in the marine biodiversity field. Environ Sci Policy 126:79–89. https:// doi. org/ 10. 1016/j. envsci. 2021. 09. 003, 2021

Turner, Andrew D., and others. Marine invertebrate interactions with Harmful Algal Blooms – Implications for One Health. Journal of Invertebrate Pathology, vol. 186, art. 107555, 2021.

Udalov, A. A, and others. Differences in megabenthos communities in the Eastern and Western parts of the Kara Sea based on video observations. Oceanology, vol. 64, No. 2, pp. 288–299, 2024.

UNEP-NCW. Nairobi Convention and WIOMSA. Western Indian Ocean Critical Habitats Outlook: Towards achievement of the Global Biodiversity Framework Targets. UNEP and WIOMSA, Nairobi, Kenya, 2024.

Vedenin A.A., and others. Uniform bathymetric zonation of marine benthos on a Pan-Arctic scale. Progress in Oceanography, vol. 202, art. 102764, 2022.

Venegas, Roberto M., and others. Three decades of ocean warming impacts on marine ecosystems: A review and perspective. Deep–Sea Research II, vol. 212, art. 105318, 2023.

Vögler, Rodolfo, and others. Vulnerability assessment of the pink shrimp small-scale fishery to climate change in southwestern Atlantic brackish coastal lagoons (Uruguay). Ocean & Coastal Management, vol. 245, art. 106864, 2023.

Waga, Hisatomo, and others. Recent change in benthic macrofaunal community composition in relation to physical forcing in the Pacific Arctic. Polar Biology, vol. 43, pp. 285–294, 2020.

Wang, Wei, and others. Global warming and artificial shorelines reshape seashore biogeography. Global Ecology and Biogeography, vol. 29, pp. 220–231, 2019.

Wang, Zhi, and others. Recovery of tropical marine benthos after a trawl ban demonstrates linkage between abiotic and biotic changes. Communications Biology, vol. 4, art. 212, 2021.

Wang, Dingqi, and others. Characteristics of marine heatwaves in the Sea of Japan/East Sea. Remote Sensing, vol. 14, art. 936, 2022.

Wang, Fan, and others. The seas around China in a warming climate. Nature Reviews Earth & Environment, vol. 4, pp. 535–551, 2023.

Watson, Stephen C.L., and others. Inclusion of condition in natural capital assessments is critical to the implementation of marine nature-based solutions. Science of the Total Environment, vol. 838, art. 156026, 2022.

Wei, Chih-Lin, and others. Seafloor biodiversity of Canada's three oceans: patterns, hotspots and potential drivers. Diversity and Distributions, vol. 26, No. 2, pp. 226–241, 2020.

Witherell, David, and Michael Fey. Fish bycatch in the North Pacific Halibut, *Hippoglossus stenolepis*, and groundfish fisheries. Marine Fisheries Review, vol 85, No. 1–4, p. 31, 2023.

Wolanski, Eric, and others. Island building and overfishing in the Spratly Islands archipelago are predicted to decrease larval flow and impact the whole system. Estuarine, Coastal and Shelf Science, vol. 233, art. 106545, 2020.

WoRMS Editorial Board. WoRMS - World Register of Marine Species. 2019, 2024. http://www.marinespecies.org/, 2019.

WoRMS Editorial Board. WoRMS - World Register of Marine Species. Available from https://www.marinespecies.org at VLIZ. Accessed 2024-10-04. doi:10.14284/170, 2024.

Wu, Xuwen, and others. *Laetmonice iocasica* sp. nov., a new polychaete species (Annelida: Aphroditidae) from seamounts in the tropical Western Pacific, with remarks on *L. producta* Grube, 1877. Journal of Oceanography and Limnology, vol. 39, pp. 1805–1816, 2021.

WWF. WWF Stop Seabed Mining. 2024. https://www.stopdeepseabedmining.org/endorsers/, 2024.

Xu, Yong, and others. Temporal variation of macrobenthic community zonation over nearly 60 years and the effects of latitude and depth in the southern Yellow Sea and East China Sea. Science of The Total Environment, vol. 739, art. 139760, 2020.

Xu, Yong, and others. Potential impacts of climate change on the distribution of echinoderms in the Yellow Sea and East China Sea. Marine Pollution Bulletin, vol. 194, art. 115246, 2023.

Xu, Yong, and others. Projections of climate-driven biogeographical changes of benthic mollusks in the Yellow Sea and East China Sea. Marine Environmental Research 197, art. 106474, 2024.

Yadav, Anjali R., and others. Effect of climate change on Arabian Sea: A review. Journal of Experimental Zoology India, vol. 27, No. 1, pp. 1445–1453, 2024.

Zaiko, Anastasija, and others. Structural and functional effects of global invasion pressure on benthic marine communities—patterns, challenges and priorities. Diversity and Distributions, vol. 30, No. 7, art. e13838, 2024.

Zakharov, Denis V., and others. Barents Sea megabenthos: Spatial and temporal distribution and production. Marine Biological Journal, Vol. 5, No. 2, pp. 19–37, 2020.

Zakharov, Denis V., and others. Impact of the red king crab and the snow crab on the Barents Sea megabenthic communities. Marine Biological Journal, vol. 9, No. 1, pp. 32–50, 2024.

Zhang, Jinghuai, and others. A revision of the genus *Petta Malmgren*, 1866 (Annelida: Pectinariidae), with two new species from deep waters of southeastern Australia, and comments on phylogeny of the family. Zootaxa, vol. 4614, No. 2, pp. 303–330, 2019.

Zhang, Jinghuai, and others. Two new species of Sabellariidae (Annelida, Polychaeta) from the abyss of eastern Australia. Zootaxa, vol. 4821, No. 3, pp. 487–510, 2020.

Section 4
Sub-chapter 4d: Fishes

Keynote points

- The accelerating impacts of climate change continue~~s~~ to affect fish life histories and populations globally
- Since World Ocean Assessment (WOA) II~~#2~~, 787 new species of fish have been placed in FishBase database, reaching a total of 35,002 species described
- New or improved research techniques such as satellite tagging, video cameras, molecular genetic work are helping us to understand fish diversity, behaviour and biology

1: Introduction

This subchapter provides an update on taxonomy, biology, distribution, habitat and conservation status of bony (Osteichthyes) and non-bony (Chondrichthyes and Agnatha) fish. It focusses on the years 2018 to 2023, what changes have occurred globally and regionally in terms of production and diversity, and any new information that has become available since World Ocean Assessment 2 (WOA II~~#2~~). This chapter will also discuss remaining key knowledge gaps, our capacity changes to better understand fish and if any new gaps have come to light.

Other overlapping or complementary information relevant to fishes, including changes to fish biomass, is provided in chapters such as: large and small scale fisheries (Section 5, chapter 1, sub-chapters 1a, 1b); recreational fishing (Section 5, chapter 2); climate change (Section 4, chapter 1); specific fish habitats (Section 4, chapter 5, various chapters); physical conditions and cumulative pressures (Section 4, chapters 3, 6); and socio-economic importance of fish and how they fit into One Health (Section 5, subsections A,B, various chapters).

2: Description of environmental change since the second World Ocean Assessment

Fish biomass is strongly affected by environmental, anthropogenic, global and regional pressures. Climate change and the resulting impacts on the marine environment (see Section 4, chapters 1 and 3) are having a significant effect on fish populations globally, from positive expansion and growth in new areas (e.g. polar, high latitude) to significant declines in other areas (Nagelkerken and others, 2023; Blanchard and Novaglio, 2024). These pressures also affect fish biology and growth, behaviour, the timing of spawning/migration and natural mortality (Nagelkerken and others, 2023). Many regions are affected by the removal of fish by poorly managed fishing and fisheries (Section 5, chapters 1a, 1b, and 2), including habitat damage from fishing gears and illegal unreported and unregulated (IUU) fishing as well as from the arrival/introduction of alien species.

The latest Intergovernmental Panel on Climate Change (IPCC) and Food and Agriculture Organisation (FAO) reports have projected range shifts among marine fish, suggesting latitudinal changes in fish biomass and decreasing biodiversity (Cooley and others, 2022). Most areas in lower latitudes are projected to have decreasing fish biomass into the future due to unfavorably warm ocean temperatures, while high latitude areas are expected to have increased fish biomass as a result of more favorable warm temperatures (Blanchard and Novaglio, 2024).

Climate change is also increasing spatio-temporal life history mismatches, such as larval access to food sources (Nagelkerken and others, 2023). Non-climate, anthropogenic factors amplify the impacts of climate change (Gissi and others, 2021).

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) ~~agreement~~ will support habitat protection and ~~regulate~~ management of fishing in high seas areas not already under international agreements, which will in turn support fish populations and biodiversity (Wang 2025; Santos and others, 2022).

Continuous research and documentation of the spatial biodiversity and International Union for the Conservation of Nature (IUCN) status of fish has advanced in recent years (Tables 1, 2). A total of 787 new species have been described in Fishbase (Table 1) and 6,062 have been assessed by IUCN (Table 2) since 2019.

Table 1. Number of described marine species of fishes in different habitats across taxonomic class, includinge newly identified since 2019.

Habitat	Class								
	Teleostei		Elasmobranchii		Holocephali		Coelacanthi		
	Described since 2019	All Species (2024)	Described since 2019	All Species (2024)	Described since 2019	All Species (2024)	Described since 2019	All Species (2024)	Total species identified by habitat (Percentage of all identified fish)
Bathydemersal	38	1900	9	327	2	52	–	–	**2,279 (6.5)**
Bathypelagic	14	1399	1	36	–	–	–	2	**1,437 (4.1)**
Benthopelagic	234	11546	5	169	–	–	–	–	**11,715 (33.5)**

Demersal	225	11448	19	480	–	3	–	–	**11,931 (34.1)**
Pelagic	48	1196	–	1	–	–			**1,197 (3.4)**
Pelagic-neritic	48	917	1	36	–	–	–	–	**953 (2.7)**
Pelagic-oceanic	9	406	3	86	–	–	–	–	**492 (1.4)**
Reef associated	130	4890	1	108	–	–	–	–	**4,998 (14.3)**
Total (percentage of all identified species)	**746 -**	**33702 (96.3)**	**39 -**	**1243 (3.6)**	**2 -**	**55 (0.2)**	**0 -**	**2 (<0.1)**	**35,002**

Source: Fishbase (Froese and Pauly 2024).

Table 2. Number of marine fish species in each IUCN category across taxonomic classes, including the number newly assessed since WOA II (2019).

	CLASS								
	Teleostei		Elasmobranchii		Holocephali		Coelacanthi		All
IUCN Category	Assessed Since Last WOA (2019)	Total (2024)	Assessed Since Last WOA (2019)	Total (2024)	Assessed Since Last WOA (2019)	Total (2024)	Assessed Since Last WOA (2019)	Total (2024)	Total fish species by IUCN Category (percentage of all IUCN assessed species)
Least Concern	3685	9262	345	503	20	35	-	-	9,800 (74.2)
Near Threatened	37	113	102	119	4	4	-	-	236 (1.8)
Vulnerable	63	235	160	171	4	4	-	1	411 (3.1)
Endangered	43	95	114	124	-	-	-	-	219 (1.7)
Critically Endangered	10	21	88	92	-	-	-	1	114 (0.9)
Extinct in the Wild or Extinct	-	1	1	1	-	-	-	-	2 (< 0.1)
Data Deficient	1311	2281	66	137	9	10	-	-	2418 (18.4)
Total	**5149**	**12008**	**876**	**1147**	**37**	**53**	**0**	**2**	**13210 (100)**

Sources: The IUCN Red List (IUCN 2024) and Fishbase (Froese and Pauly 2024).

3: Region-specific changes

The Arctic Ocean

Arctic fish populations are experiencing significant shifts in spatial distribution, population dynamics and community composition due to climate change, overfishing, and environmental changes. The warming Arctic Ocean is driving the poleward migration of sub-Arctic species such as Atlantic cod (*Gadus morhua*), altering the composition of marine ecosystems (Gordó-Vilaseca and others, 2024). Concurrently, the retreat of sea ice is enabling increased fishing pressure in previously inaccessible areas, ~~leading to~~raising concerns ~~over the impact on~~for vulnerable species ~~such as~~like polar cod (*Boreogadus saida*) (Bryndum-Buchholz and others, 2019; Steiner and others, 2021). Invasive species and the expansion of commercial fisheries are compounding the pressures on endemic Arctic fish populations (Ogorelec and others, 2022). The cumulative effects of these changes threaten the sustainability of key species and the broader Arctic marine food web necessitating adaptive management strategies (Bluemel and others, 2022; Nilsen and others, 2022). Recent studies emphasize the importance of implementing spatial fisheries management and establishing marine protected areas to mitigate these impacts (Phillips and others, 2025), including meaningful partnerships and collaborations with local and Indigenous Arctic ~~communities~~Peoples. These measures are crucial for preserving Arctic biodiversity and ensuring the long-term viability of commercial fish stocks in the region (Gordó-Vilaseca and others, 2024).

The North Atlantic Ocean, the Baltic Sea and the North Sea

Climate change is expected to increasingly affect fish populations in the northern oceanic waters. Atlantic water temperatures are projected increase, reducing sea ice extent and boosting primary productivity, influencing distribution, growth rates, spawning locations and early-stage mortality of fish species (Gordó-Vilaseca and others, 2024). There has been a shift in the ranges of North Atlantic species moving eastward and warmer-water species migrating north leading to an enrichment of the Arctic and sub-Arctic marine fauna (Gordó-Vilaseca and others, 2023). These waters face decreasing biomass and biodiversity of traditionally high latitude sedentary species (Gordó-Vilaseca and others, 2024). In more southern areas (e.g. Canary Islands region) there is a tropicalization of fish populations, where many new species from tropical origin are being increasingly reported (Bañón and others, 2024; Falcón and others, 2023), and northwards expansion of common species off NW Africa (such as *Scomber colias* and *Sardinella aurita*) have been reported (Amenzoui and Baali 2018, Blanchet and others, 2019; ICES, 2021). The patterns of change are highly variable from location to location depending on the rapidity of change, for example fast warming locations develop more fast-growing fish and slow changing areas have more slow-growing species (Receveur and others, 2024).

The Mediterranean and the Black Sea (199/200 words)

The Mediterranean Sea is a hotspot of climate change cumulative impacts and is subject to increasing heat waves, extreme events, seasonal warming, changes in currents and degree of stratification (Hidalgo and others 2018). These changes are causing changes to fish ranges, spawning seasons (Moltó and others, 2024), population structures, dispersal patterns, structure of food webs, and changes in the composition of communities, including increasing presence of non-endemic species (Zenetos and Galanidi, 2020; Yapici, 2021).

There is strong biogeographical structuring of populations with many examples in northern areas showing northward displacements (e.g. Sbragaglia and others, 2020) but also fish populations are responding unexpectedly to change in more intermediate latitudes with southward distributional shifts of demersal species (Sanz-Martín and others, 2024; Sbragaglia and others, 2020). There is an east-west

gradient in warming and increasing Red Sea-Indian Ocean immigrants, making the Eastern Mediterranean a hotspot of invasive species (Öztürk, 2021).

Anthropogenic disasters, such as the explosion of the Kakhovka Dam in 2023, are expected to significantly worsen the ecological state of the Black Sea (Minicheva and others, 2023; Vyshnevskyi and others, 2023), although some large pelagic species (bluefin tuna and swordfish) are slowly returning to the Black Sea for uncertain reasons (Di Natale and others, 2019; Di Natale, 2021).

The South Atlantic Ocean and the Wider Caribbean

The South Atlantic Ocean and Caribbean Sea have undergone significant changes since 2018, with warming trends and salinity alterations (Chidichimo and others, 2023; Craig and others, 2021) as well as increased extreme events (Gramcianinov and others, 2023). These changes are having significant effects on marine ecosystems, including shifts in species distributions (e.g. tropical species, tuna) and impacts on biodiversity (Perez and Sant'Ana, 2022; Townhill and others, 2021; Craig and others, 2021). Coral reefs in some areas have been dying from disease and bleaching resulting in loss of reef fish habitat and changes in fish communities (Swaminathan and others, 2024; Reimer and others, 2024).

The Indian Ocean

The Indian Ocean region is known for its exceptional biodiversity driven by a unique monsoon system that drives upwelling, nutrient-rich currents, and high primary productivity (Marscac and others, 2024). Estimates of fish diversity report over 3,600 species of coastal fishes in the western Indian Ocean (WIO) (Bullock and others, 2021). The region is also increasingly experiencing rapid sea surface warming, leading to deoxygenation in some coastal areas of the Arabian Sea and Bay of Bengal (Dalpadado and others, 2023) contributing to biodiversity loss. Large fish biomass reductions (over 50%) have been projected with tunas being particularly impacted (Wilson and others, 2021), though bluefin tuna have expanded their distribution range (Di Natale and others, 2022). Hotspots of threatened species have been identified in the southern Red Sea and the southern coast of India, with more than 90% being impacted by targeted fisheries and bycatch, as well as illegal, unreported, and unregulated fishing activities, particularly the valuable species including sharks and tunas (Bullock and others, 2021, Worm and others, 2024).

The North Pacific Ocean

The North Pacific features the highest fish species and genetic diversity globally, owing to its diversity in marine habitats and ocean currents, including arctic to tropical waters, part of the Coral Triangle and numerous oceanic islands and archipelagos (Manel and others, 2020; Miller and others, 2018; Tittensor and others, 2010). Mesophotic zones around tropical coral reefs harbor high fish diversity (Pinheiro and others, 2019).

Climate change is increasing poleward shifts in teleost and elasmobranch distributions and fish invasions and extinctions, particularly in oceanic islands (Cruz and others, 2024; Hastings and others, 2020; Tanaka and others, 2021). Increasingly frequent and intense marine heatwaves are likely to drive marine fish extinctions in Pacific islands, potentially impacting future food security (Asch and others, 2018; Jacox and others, 2020; Smale and others, 2019; Oliver and others, 2021). The effects of climate change, El Niño and La Niña are expected to redistribute tuna species (Lehodey and Senina, 2018).

The South Pacific Ocean

The South Pacific fish diversity, including tropical, subtropical and temperate regions, faces increasing threats from climate change, pollution and over-exploitation (Clarke and others, 2020; Dulvy and others,

2021; O'Hara and others, 2021). Warming oceans are shifting distributions poleward and are predicted to alter patterns of migration, invasion, and potentially cause extinctions (Rodriguez-Burgos and others, 2022; Clarke and others, 2020). El Niño Southern Oscillation (ENSO) affects fish diversity and distribution and is forecast to increase in frequency and intensity (Oliver and others, 2021). Marine heatwaves in 2023/24 triggered the fourth global coral bleaching event, spreading across the Australian Great Barrier Reef and South Pacific islands but the impacts on fish biodiversity are still unclear (Mellin and others, 2024). Microplastic ingestion in marine fish, including commercial species in South Pacific coastal regions and oceanic islands, is rising but population-level impacts have not been assessed (Muñoz-Pérez and others, 2023; Savoca and others, 2021; Wootton and others, 2021).

The Southern Ocean

Antarctic fish populations are increasingly impacted by climate change, marine heatwaves, ~~overfishing~~fishing pressures, and environmental shifts. Warming waters in regions like the Antarctic Peninsula are disrupting reproductive cycles of species such as black rockcod, (*Notothenia coriiceps*), and causing habitat loss for ice-dependent species like emerald rockcod (*Trematomus bernacchii*) and Yellowfin icefish (*Chaenocephalus aceratus*) (Novillo and others, 2024). ~~The reduction in~~Reduced sea ice is severely affecting Antarctic silverfish (*Pleuragramma antarcticum~~a~~*), a key prey species, especially along the Western Antarctic Peninsula (Caccavo and others, 2021). Fishing pressures in areas like the Ross Sea exacerbates these challenges, particularly for top predators like ~~the~~ Antarctic toothfish (*Dissostichus mawsoni*), which plays a critical role in the ecosystem (Caccavo and others, 2021). Recent studies highlight the vulnerability of Antarctic lanternfish (*Electrona antarctica*), as changes in prey availability and oceanographic conditions alter their feeding strategies (Duan and others, 2024). Adaptive management strategies, such as those implemented through~~advocated by~~ the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), are crucial to mitigating these impacts and preserving Antarctic marine ecosystems (Corso and others, 2024). Conservation efforts are critical as ~~the effects of~~ climate change effects intensify, emphasizing the need for continued research and monitoring (Greco, 2022).

4: Remaining key knowledge and capacity changes and any new gaps

Key gaps in our current understanding of marine fish and steps to reduce the gaps are listed in Tables 3 and 4.

Table 3. Key gaps from WOA II~~2~~ and recent effort to reduce those gaps.

Knowledge and capacity gaps	Recent steps taken to address the gaps
Taxonomic and biosystematics infrastructure and capacity	FAO ~~(UN)~~Ecosystem Approach to Fisheries (EAF)-Nansen Program is providing a ship and research support staff to train students and scientists in coastal developing countries.
Mobilization of existing data into open, global repositories	Creation of Global Biodiversity Information Facility (GBIF 2024) To obtain data from samples not examined (e.g. from scientific surveys)
Understanding of mesopelagic and deep-sea fish diversity	European Marine Strategies include implementation of monitoring programs of deep-sea habitats

Cumulative stressors on fish	Convention on Migratory Species Resolution 7.2 (Rev.COP14)~~None identified~~ identifies cumulative stressors on migratory species, including fish, and the need for action on this.

Table 4. New gaps identified since WOA II~~2~~.

New knowledge and capacity gaps	Steps taken to address the gaps
IUU detection	Improved satellite monitoring of vessels (e.g. Global Fishing Watch)
Satellite surveillance	Satellite monitoring has improved for tracking illegal fishing, pollution, and maritime traffic, providing real-time data (Matley and others, 2024; Paolo and others, 2024). Electronic devices (e.g. satellite tags) have improved understanding of life cycles and migratory movements (Renshaw and others, 2023).
Spatial dimension of stock assessments	Improved assessment and management of transboundary/migratory stocks (e.g. FAO 2020; Hidalgo and others, 2024; etc.). Increased application of best practice spatial stock assessment (Goethel and others, 2023, Berger and others, 2024). This implies certain improvement in data collection, data management, and data sharing between jurisdictions (Cope et al. 2024)
Understanding of life history traits at regional scales	Harmonization of life history research and better understanding of phenotypic and phenological plasticity and spatial variation (Zarco-Perello and others, 2022; Carbonara and others, 2019; Follesa and others, 2019; Vitale and others, 2019).
Fish populations	Baited Remote Underwater Video Systems (BRUVS), hydro-acoustics (Kang and others, 2024) and genomics have improved the understanding of spatial dynamics of global fish communities, biodiversity and habitat associations (Leonetti and others, 2024; Mateos-Molina and others, 2024; Moore and others, 2020; Orozco-Ruiz and others, 2023; Vaux and others, 2021). ~~New global approaches to identify essential habitats for elasmobranchs to guide spatial management (Notarbartolo di Sciara, 2021). In Brazil, especially in Rio de Janeiro, pioneering studies on shark migration and behaviour - evaluating the influence of environmental and climatic variables on their behaviour -support conservation measures in the South Atlantic (Andrzejaczek and others, 2022; Queiroz and others, 2019, 2021a, 2021b).~~ More accessible, improved data and modelling are increasingly informing our understanding of spatial and temporal trends in fish biomass (e.g. FisGlob innitiative; Maureaud and others, 2021, Receveur, 2024; Blanchard and Novaglio, 2024; Fredston and others, 2023; Payne 2023, Fuchs and others, 2024).
Threatened species protection	There area based conservation measures being applied globally for threatened fish species, especially elasmobranch.

	Important shark and ray areas are being identified through IUCN. Since WOA I, the identification of Important Shark and Ray Areas (ISRAs) by the IUCN has advanced significantly. ISRAs are defined as spatially discrete habitats critical for the survival of sharks and rays, based on science-driven criteria aligned with global conservation frameworks. As of 2025, ISRAs have been identified in regions such as the Mediterranean, Western Indian Ocean, South Atlantic and South Pacific, with ongoing efforts elsewhere. The ISRA process informs spatial planning, MPA design, and other conservation measures to protect elasmobranch biodiversity amid environmental change..(https://sharkrayareas.org/about-isras/). New global approaches to identify essential habitats for elasmobranchs to guide spatial management (Notarbartolo di Sciara, 2021). In Brazil, especially in Rio de Janeiro, pioneering studies on shark migration and behaviour to support conservation measures in the South Atlantic (Andrzejaczek and others, 2022; Queiroz and others, 2019, 2021a, 2021b). Globally,action plans are being developed throughth Convention on the Conservation of Marine Species (CMS) to support elasmobranch populations (e.g. Mediterranean Angelshark; Cancino 2024). CMS also providing advice (CMS Resolution 14.5) on preventing vessel strikes on marine mega fauna (e.g. whale sharks)(Womersley and others, 2024)
Fish behaviour/communication	Developing understanding of intraspecific communication in fish (Looby and others, 2022; Valastro and others, 2024).
Microplastic pollution	There is increasing evidence for the ingestion of microplastics and nanoplastics by fish in this region, but the impacts on biomass and diversity remain unknown (Wootton and others, 2021; Jonathan and others, 2021, Savoca and others, 2021, Tekman and others, 2022)
Deep scattering layers	Deep scattering layers provide an important link between shallow and deepwater areas (Peña, 2024)
Understanding of biotic perturbations of water column	High-spatial resolution acoustic and hydrological data (Fernández-Castro and others, 2022)

Acknowledgements:
Artificial intelligence (AI) was used through search engines to assist with finding reference material and through word processors to assist with some text/grammar correction. All text was written without the use of AI.

REFERENCES

Amenzoui, Khadija, and Baali Ayoub. Biological parameters of *Sardinella aurita* (Valenciennes, 1847) exploited in the Dakhla zone (South Atlantic Morocco). International Journal of Scientific and Engineering Research, vol. 9, No. 8, pp. 85-90, 2018.

Andrzejaczek, Samantha, and others. Diving into the vertical dimension of elasmobranch movement ecology. Science Advances (AAAS), vol. 8, No. 33, eabo1754, 2022.

Asch, Rebecca G., and others. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Marine Policy, vol. 88, pp. 285–294, 2018

Bañón, Rafael, and others. Tropicalization of fish fauna of Galician coastal waters, in the NW Iberian upwelling system. Regional Studies in Marine Science, vol. 70, art. 103369, 2024.

Berger, Aaron, M., and others. Synthesizing the spatial functionality of contemporary stock assessment software to identify future needs for next generation assessment platforms. Fisheries Research, vol. 275, art. 107008, 2024.

Blanchet, Marie-Anne, and others. How vulnerable is the European seafood production to climate warming? Fisheries Research, vol. 209, pp. 251-258, 2019.

Bluemel, Joanna, and others. Decline in Atlantic wolffish *Anarhichas lupus* in the North Sea: Impacts of fishing pressure and climate change. Journal of Fish Biology, vol. 100, No. 1, pp. 253-267, 2022

Blanchard, Julia, L., and Novaglio, Camilla, eds. Climate change risks to marine ecosystems and fisheries – Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project. FAO Fisheries and Aquaculture Technical Paper, No. 707, Rome FAO, 2024.

Bryndum-Buchholz, Andrea, and others. Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. Global Change Biology, vol. 25, No. 2, pp. 459-472, 2019.

Bullock, Robert and others. The conservation status of marine biodiversity of the Western Indian Ocean. International Union for the Conservation of Nature, Gland, IUCN, 2021.

Caccavo, Jilda Alicia, and others. Productivity and change in fish and squid in the Southern Ocean. Frontiers in Ecology and Evolution, vol. 9, 2021.

Cancino, X, CMS Single Species Action Plan for Angelshark (Squatina squatina) in the Mediterranean Sea, Convention on the Conservation of Migratory Species of Wild Animals. Germany, 2024. COI: 20.500.12592/6t1g6td.

Carbonara, Pierluigi, and Follesa, Maria Cristina, eds. Handbook on fish age determination: a Mediterranean experience. Studies and Reviews. General Fisheries Commission for the Mediterranean, FAO, Rome, No. 98, pp. 1-192, 2019.

Chidichimo, María Paz, P., and others. Energetic overturning flows, dynamic interocean exchanges, and ocean warming observed in the South Atlantic. Communications Earth and Environment, vol. 4, No. 10, 2023.

Clarke, Tayler M., and others. Climate change impacts on living marine resources in the Eastern Tropical Pacific. Diversity and Distributions, vol. 27, pp. 65–81, 2020.

Cope, Jason M. "The good practices of practicable alchemy in the stock assessment continuum: Fundamentals and principles of analytical methods to support science-based fisheries management under data and resource limitations." Fisheries Research 270: 106859, 2024.

Cooley, Sarah, and others. Oceans and coastal ecosystems and their services. In: Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change, [H.-O. Pörtner, Hans-0tto, and others , eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550, 2022.

Corso, Andrew D., and others. Thermal tolerance of larval Antarctic cryonotothenioid fishes. Polar Biology, vol. 47, No.8, pp. 731-740, 2024.

Craig,, Kevin J., and others. Ecosystem Status Report for the U.S. South Atlantic Region. NOAA Technical Memorandum, NMFS-SEFSC-753, pp. 1-145, 2021.

Cruz, Leonardo, and others. Fisheries track the future redistribution of marine species. Nature Climate Change, vol. 14, No. 10, pp. 1093–1100, 2024.

Dalpadado, Palmini, and others. 2023. Rapid climate change alters the environment and biological production of the Indian Ocean. Science of The Total Environment, vol. 906, art. 167342, 2023.

Di Natale, Antonio, and others.. Is the bluefin tuna slowly returning to the Black Sea? An updating of our knowledge on bluefin tuna in the eastern Mediterranean Sea. Collected volumes of scientific papers, International commission for the conservation of Atlantic tunas, ICCAT, Madrid, vol. 75, No. 6, pp. 1261-1277, 2019.

Di Natale, Antonio. Is the swordfish slowly returning into the Black Sea? Recent evidences. SCRS/2020/092, Collected volumes of scientific papers, International commission for the conservation of Atlantic tunas, ICCAT, Madrid, vol. 78, No. 7, pp. 142-152, 2021.

Di Natale, Antonio, and others. Unusual presence of bluefin tuna in the Gulf of Aden and in the Indian Ocean. 8th working party on temperate tunas (WPTMT), 13-15 April 2022, Indian Ocean tuna commission, IOTC, Mahe (Seychelles), IOTC-2022-WPTmT08DP-19, pp. 1-8, 2022.

Duan, Mi, and others. The feeding strategies of the antarctic lanternfish *electrona antarctica* (pisces: myctophidae) in the amundsen and cosmonaut seas (southern ocean), assessed with a classification tree analysis. Polar Biology, vol. 47, No. 5, pp. 515-532, 2024.

Dulvy, Nicholas K. and others. Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Current Biology, vol. 31, No. 21,pp. 1-15, 2021.

Falcón, Jesús M., and others. Peces marinos tropicales exóticos de Canarias. RedPromar. Ed. Consejería de Transición Ecológica, Lucha contra el Cambio Climático y Planificación Territorial del Gobierno de Canaria, pp. 1-249, 2023.

FAO https://www.fao.org/in-action/eaf-nansen/news-events/detail/fr/c/1269478/, 2020.

FAO The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO, 2022.

Fernández-Castro and others, Intense upper ocean mixing due to large aggregations of spawning fish. Nat. Geosci. 15, 287–292, 2022.

Froese, Rainier, and Daniel Pauly, Editors. FishBase 2000: concepts, design and data sources. ICLARM, Los Baños, Laguna, Philippines. pp. 344, 2000.

Galanidi, Marika, and others. Validated inventories of non-indigenous species (NIS) for the Mediterranean Sea as tools for regional policy and patterns of NIS spread. Diversity, vol. 15, pp. 962., 2023.

GBIF 2024. Global Biodiversity Information Facility www.gbif.org

Gerringer, Mackenzie. E., and others. *Pseudoliparis swirei* sp. nov.: A newly-discovered hadal snailfish (Scorpaeniformes: Liparidae) from the Mariana Trench. Zootaxa, vol. 4358, No. 1, pp. 161–177, 2017.

GFCM FAO. Sub-regional group on stock assessment for the Black Sea (SGSABS). Black Sea Explore data, 2024.

Gissi, E., and others. A review of the combined effects of climate change and other local human stressors on the marine environment. Science of Total Environment, vol. 755, art. 142564, 2021.

Goethel, Daniel R., and others. Spatial awareness: good practices and pragmatic recommendations for developing spatially structured stock assessments. Fisheries Research, vol. 264, art. 106703, 2023.

Gordó-Vilaseca, Cesc, and others. Three decades of increasing fish biodiversity across the northeast Atlantic and the Arctic Ocean. Proceedings of the National Academy of Sciences. vol. 120, No 4, art. e2120869120, 2023.

Gordó-Vilaseca, Cesc, and others. Future trends of marine fish biomass distributions from the North Sea to the Barents Sea. Nature communications, vol. 15(1), No. 14, art. 5637, 2024.

Gramcianinov, Carolina B., and others. Recent changes in extreme wave events in the south-western South Atlantic. in: 7th edition of the Copernicus Ocean State Report (OSR7), edited by: von Schuckmann, K., and others. Copernicus Publications, State Planet, 1-osr7, 12, 2023.

Greco, S., Gaetano, A.S. (eds.). Gene expression profiling of *Trematomus bernacchii* in response to thermal and stabling stress. Fishes, vol. 7, No. 6, art. 20, 2022.

Hastings, Reuben A, and others. Climate change drives poleward increases and equatorward declines in marine species. Current Biology, vol. 30; No. 8, pp. 1572-1577, 2020.

Hidalgo, Manuel, and others, eds. Transboundary population structure of sardine, European hake and blackspot seabream in the Alboran Sea and adjacent waters – A multidisciplinary approach. Studies and Reviews, No. 104 (General Fisheries Commission for the Mediterranean). Rome, FAO, 2024.

Hidalgo, Manuel, and others. Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries. Impacts of climate change on fisheries and aquaculture, 139, 2018.

Howell, Daniel, and others. Report series: IMR-PINRO 2024-7 Published: 21.06.2024 Updated: 14.08. 2024

ICES. Second workshop on Atlantic chub mackerel (*Scomber colias*) (WKCOLIAS2). ICES Scientific Reports. vol. 3, No. 18, pp. 1-231, 2021.

ICES 2022. Greater North Sea ecoregion – fisheries overview. ICES Advice: Fisheries Overviews. Report.

ICES. Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK). ICES Scientific Reports. vol. 6, No. 38, pp. 1249, 2024.

IUCN (International Union for Conservation of Nature). All species IUCN categories. The IUCN red list of threatened species 2024. https://www.iucnredlist.org. Accessed on 26 August 2024.

Jacox, Michael G., and others. Thermal displacement by marine heatwaves. Nature, vol. 584, pp. 82–86, 2020.

Kang, Myounghee, and others. Acoustic characterization of fish and macroplankton communities in the Seychelles-Chagos thermocline ridge of the southwest Indian ocean. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 213, art. 105356, 2024.

Kleiber, D., and others. Gender and small-scale fisheries: a case for counting women and beyond. Fish and Fisheries. vol. 16, No. 4, pp. 547-562, 2015

Lehodey, Patrick, and Senina Inna. Pacific tuna & climate: Trends and forecasts. Infofish International, vol. 3, pp. 44-47, 2018.

Leonetti, Francesco L., and others. Studying chondrichthyans using baited remote underwater video systems: A review. Animals, vol. 14, No. 13, art. 1875, 2024.

Marsac, Francis, and others. Indian Ocean primary productivity and fisheries variability. In the Indian Ocean and its role in the global climate system. Elsevier, pp. 245-264, 2024.

Lian, Peng, Gao, Le. Impacts of central-Pacific El Niño and physical drivers on eastern Pacific bigeye tuna. Journal of Oceanology and Limnology. vol. 42, pp. 972–987,2024.

Looby A., and others. A quantitative inventory of global soniferous fish diversity. Reviews in Fish Biology and Fisheries, vol. 32, pp. 581–595, 2022.

Manel, S., Guerin, PE., Mouillot, D. and others, Global determinants of freshwater and marine fish genetic diversity. Nature Communications, vol. 11, art. 692, 2020.

Mateos-Molina, D. and others. Coastal lagoons in the United Arab Emirates serve as critical habitats for globally threatened marine megafauna. Marine Pollution Bulletin, vol. 200, art. 116117, 2024.

Matley, J., and others.Long-term effects of tagging fishes with electronic tracking devices. Fish and Fisheries, vol. 25, pp. 1009–1025, 2024.

Miller E.C., and others. Explaining the ocean's richest biodiversity hotspot and global patterns of fish diversity. Proceedings of The Royal Society B, vol. 285, art. 20181314, 2018.

Minicheva, G., and others. Reaction of the marine ecosystem to the consequences of destruction of the Kakhovka Reservoir dam. Marine Ecological Journal. No. 1-2, pp. 52-68, 2023.

Moore, B. R., and others, Defining the stock structures of commercial tunas in the Pacific Ocean II: sampling considerations and future directions. Fisheres Research. vol. 230, art. 105524, 2020.

Moltó, Vicenç, and others (2024). Predicting fish spawning phenology for adaptive management: Integrating thermal drivers and fishery constraints. Marine Environmental Research, vol. 202, art. 106713.

Muñoz-Pérez, JP, and others. Galápagos and the plastic problem. Frontiers in Sustainability, Vol. 4, art. 1091516, 2023.

Nagelkerken, Ivan, and others. The effects of climate change on the ecology of fishes. PLOS Climate, vol. 2, No. 8, art. e0000258, 2023.

Nilsen, Ina, and others. Exploring the role of Northeast Atlantic cod in the Barents Sea food web using a multi-model approach. Fish and Fisheries, vol. 23, No. 5, pp. 1083-1098, 2022.

Notarbartolo, di Sciara G. Towards an "Important Shark and Ray Area" (ISRA) process: implementation strategy. Report to IUN Species Survival Commission Shark Specialist Group, pp. 42, 2021.

Novillo, Manuel, and others. First insights into the influence of temperature on reproduction in Antarctic fish: The case of *Notothenia coriiceps*. Estuarine Coastal and Shelf Science, vol. 297, pp. 12, 2024.

Oliver, Eric, and others. Marine Heatwaves. Annual Review of Marine Science. vol. 13, pp. 313-342, 2021.

Ogorelec, Ziga, and others. Can young-of-the-year invasive fish keep up with young-of-the-year native fish? A comparison of feeding rates between invasive sticklebacks and whitefish. Ecology and Evolution, vol. 12, No. 1, 2022.

O'Hara, Casey C., and others. At-risk marine biodiversity faces extensive, expanding, and intensifying human impacts. Science, vol. 372, No. 6537, pp. 84-87, 2021.

Orozco-Ruiz, A. M., and others. Genetic analyses reveal a non-panmictic genetic structure in the sablefish *Anoplopoma fimbria* in the northern Pacific. ICES Journal of Marine Science, vol. 80, No. 5, pp. 1319–1328, 2023.

Öztürk, Bayram. Non-indigenous species in the Mediterranean and the Black Sea. Studies and Reviews, General Fisheries Commission for the Mediterranean. Rome, FAO, No. 87, 2021.

Paolo, Fernado S., and others. Satellite mapping reveals extensive industrial activity at sea. Nature, vol. 625, pp. 85–91, 2024.

Peña, M. Atlantic versus Mediterranean deep scattering layers around the Iberian península. Progress in Oceanography, 221:103211, 2024

Perez, Jose Aangel Alvarez, and Sant'Ana, Rodrigo. Tropicalization of demersal megafauna in the western South Atlantic since 2013. Communications Earth and Environment, vol. 3, art. 227, 2022.

Pinheiro, H.T., Shepherd, B., Castillo, C. and others, Deep reef fishes in the world's epicenter of marine biodiversity. Coral Reefs, vol. 38, pp. 985–995, 2019.

Phillips, Genevieve, A. C., Ogier, Eily, and others, The ambiguous role of partially protected marine protected areas in Australia: Results from a systematic literature review. PLOS one. Vol. 20, No. 1, art. e0307324, 2025.

Pita, P., and others.Mind the gender gap in marine recreational fisheries. Sustainability. vol. 15, No. 14, art. 11292, 2023.

Racault, M,F, Rost, B, and Skern-Mauritzen, M. 2022: Oceans and Coastal Ecosystems and Their Services. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550, 2023.

Queiroz, N., and others. Reply to: Caution over use of ecological big-data for conservation. Nature, vol. 595, pp. E20-E28, 2021a.

Queiroz, N., and others. Reply to: Shark mortality cannot be assessed by fishery overlap alone. Nature, vol. 595, pp. E8-E16, 2021b.

Queiroz, N., and others. Global spatial risk assessment of sharks under the footprint of fisheries. Nature, vol. 572, pp. 461-466, 2019.

Receveur, A., and others. Long-term changes in taxonomic and functional composition of European marine fish communities. Ecography, vol. 2024, No. 9, art. e07234, 2024.

Rice, E.D., and others. The future of gender research in small-scale fisheries: Priorities and pathways for advancing gender equity. Fish and Fisheries, vol. 25, No. 3, pp. 401-408, 2024.

Reimer, J.D., and others.The Fourth Global Coral Bleaching Event: Where do we go from here?. Coral Reefs, vol. 43, pp. 1121–1125, 2024.

Renshaw, S, and others. Global tracking of shark movements, behaviour and ecology: A review of the renaissance years of satellite tagging studies, 2010–2020, Journal of Experimental Marine Biology and Ecology, vol. 560, art. 151841, 2023.

Rodriguez-Burgos AM, and others. The impact of climate change on the distribution of *Sphyrna lewini* in the tropical eastern Pacific. Marine Environmental Research, Vol. 180, art.105696, 2022.

Santos BS, and others.. The diverse benefits of biodiversity conservation in global ocean areas beyond national jurisdiction. Front. Marine Science, vol. 9, art. 1001240, 2022.

Savoca MS, and others. Plastic ingestion by marine fish is widespread and increasing. Global Change Biology, vol. 27, No. 10, pp. 2188-2199, 2021.

Sbragaglia, Valerio, and others. Local ecological knowledge of recreational fishers reveals different meridionalization dynamics of two Mediterranean subregions. Marine Ecology Progress Series, vol. 634, pp. 147-157, 2020.

Scientific, Technical and Economic Committee for Fisheries (STECF) – Stock assessments in the Black Sea (STECF-17-14). Luxemburg: Publications Office of the European Union. – pp. 498, 2017.

Smale, D.A., and others, Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, vol. 9, pp. 306–312, 2019.

Steiner, N. S., and others. Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa-Science of the Anthropocene, vol. 9(1), No. 55, art. 1, 2021.

Swaminathan, S,D, and others . Stony coral tissue loss disease indirectly alters reef communities. Science Advances, vol. 10, No. 18, 2024.

Tanaka, K.R., and others. North Pacific warming shifts the juvenile range of a marine apex predator. Scientific Reports, vol. 11, art. 3373, 2021.

Tekman, M. B., and others. Impacts of plastic pollution in the oceans on marine species, biodiversity and ecosystems, pp. 1–221, WWF Germany, Berlin, 2022.

Tittensor, D., and others. Global patterns and predictors of marine biodiversity across taxa. Nature, vol. 466, pp. 1098–1101, 2010).

Vitale, F., L. Worsøe Clausen and G. Ní Chonchúir (Eds.). Handbook of fish age estimation protocols and validation methods. ICES Cooperative Research Report, No. 346, pp. 59-102, 2019.

Townhill, B. L., and others. Climate change impacts on Atlantic oceanic island tuna. Fisheries Frontiers in Marine Science, vol. 8, art. 634280, 2021.

Valastro M., and others. The swordfish CPUE poses several questions and enigmas. A discussion paper. Collect. Vol. Sci. Pap. ICCAT, SCRS/2024/045, vol. 81, No. 3, pp. 1-5, 2024.

Vaux F, and others. Adaptive markers distinguish North and South Pacific Albacore amid low population differentiation. Evolutionary Applications, vol. 14, No. 5, pp. 1343-1364, 2021.

Wilson, R.J., and others. Large projected reductions in marine fish biomass for Kenya and Tanzania in the absence of climate mitigation. Ocean & coastal management, vol. 215, art.105921, 2021.

Vyshnevskyi V., and others. The destruction of the Kakhovka dam and its consequences, Water International, vol. 48, No. 5, pp. 631–647, 2023.

Yapıcı, S. A Risk Screening of Potential Invasiveness of Alien and Neonative Marine Fishes in the Mediterranean Sea: Implications for Sustainable Management. Sustainability, vol. 13, art. su132413765, 2021.

Wang, J. The BBNJ Agreement: Achievements and Prospects. Chinese Journal of Environmental Law, 9(1), 88-106, 2025

Womersley, F. C., and others Identifying priority sites for whale shark ship collision management globally. The Science of the Total Environment, 934, 2024.

Wootton, N., and others. Microplastic in fish – A global synthesis. Reviews in Fish Biology and Fisheries, vol. 31, pp. 753–771, 2021.

Worm, B., and others. Global shark fishing mortality still rising despite widespread regulatory change. Science, vol. 383, No. 6679, pp. 225-230, 2024.

Zarco-Perello, S., and others. Maximization of fitness by phenological and phenotypic plasticity in range expanding rabbitfishes (Siganidae). Journal of Animal Ecology, vol. 91, No. 8, pp. 1666-1678, 2022.

Zenetos, A., Galanidi, M. Mediterranean non indigenous species at the start of the 2020s: recent changes. Marine Biodiversity Records, vol. 13, No. 10, 2020.

UNEP/CMS/Resolution 7.2 (Rev.COP14)

Section 4

Sub-chapter 4e: Marine mammals

Ellen Hines, André Silva Barreto, Daniel P. Costa, Luciano Dalla Rosa, Caterina Fortuna, Frances Gulland, Kit M. Kovacs, Songhai Li, Helene Marsh, Shambhu Paudel

Keynotes

- Major threats to marine mammals include bycatch, chemical pollution, vessel strikes, and climate change.
- Anthropogenic noise, plastics, and other emerging threats require investigation
- Quantitative research on cumulative effects of threats is limited.

Introduction

Marine mammals are top predators and good indicators of environmental change. They face direct, indirect, and cumulative anthropogenic threats. Data on their distribution, abundance and trends are incomplete and should be considered top priorities for management and conservation.

Changes in taxonomy since 2018 are related to the definition of subspecies although some new species have been identified: https://marinemammalscience.org/science-and-publications/list-marine-mammal-species-subspecies/

Few threats have been alleviated since WOA II, despite some advancements in ~~monitoring techniques~~threat abatement in a very small number of regional populations. Global climate change poses a significant threat, though its effects are clearest in Polar Regions (Gulland et al. 2022; Meredith et al. 2019~~22~~). Though climate change and overfishing are serious ecosystem-level threats, species are challenged by bycatch, pollution, emerging diseases, ~~and~~ vessel ~~-~~ strikes, and disturbances to animal culture and communities~~.~~

Environmental changes since WOAII

1.0 Changes in overall status: Updates by taxon

1.1Pinnipeds (36 species, 2 extinct)

Pinnipeds are susceptible to climate change-induced shifts and fisheries interactions (mortality and prey availability). Mid-latitude species are affected by marine heat waves (Garcia-Aguilar et al. 2018; Backe et al. 2021; Jog et al 2022). IUCN has updated some pinnipeds since WOA II: ice-dependent species assessed are in decline. Intensive conservation efforts have improved status for Mediterranean monk seals (Karamanlidis et al. 2023) also through national legislation and marine protection frameworks **(Monk Seal Alliance, 2024)** ~~(Karamanlidis et al. 2025in press2023)~~, Hawaiian monk seals (Baker et al. 2025), and Saima seals (Auttila and Alakoski 2025).

1.2 Cetaceans

1.2.a Mysticetes (15 species)

Changing oceanographic processes in the Northwest Atlantic due to climate change have altered the range and foraging behavior of critically endangered North Atlantic right whales, reducing calving rates and increasing vessel strike risks and fishing gear entanglement (Meyer-Gutbrod et al., 2022). Since 2011, the population has declined to fewer than 400 individuals (Frasier et al., 2024).

Rice's whale (Rosel and Wilcox 2014; Rosel et al 2021), in the northeastern Gulf of Mexico numbers circa 33 individuals, are listed as Endangered under the US ESA and Critically Endangered (CR) on the IUCN Red List.

1.2.b Odontocetes (79 species, 1 possibly extinct)

Coastal and estuarine dolphins and porpoises

Bycatch continues to be the primary threat (Brownell et al., 2019) with habitat loss and degradation from coastal development and pollution negatively affecting feeding and breeding grounds (Bartalini et al., 2022; Lailson-Britto Jr., et al., 2022). The Critically Endangered Atlantic

humpback dolphin (Braulik et al., 2023), found along West Africa, faces threats from artisanal fisheries and rapid coastal development (Genov et al 2024). To assist with their conservation, CMS adopted Resolution 14.10 the Species Specific Action Plan for the Atlantic humpback dolphin (*Sousa teuszii*) (UNEP/CMS, 2024). In 2023, gillnet blocking devices created a sanctuary for vaquitas in Baja California. Rojas-Bracho et al. (2024) recommend further development of vaquita-safe fishing gear to allow artisanal fishing. The IWC (International Whaling Commission) issued its first ever extinction alert for the vaquita (IWC 2023).

Pelagic toothed whales, dolphins and porpoises

Beaked whales (n=24) lack population structure and abundance data (Feyrer et al. 2024). Threats to these deep-diving species include military sonar, climate change, entanglement, plastic pollution, vessel strikes, and oil spills.

Freshwater dolphins

Anthropogenic threats endanger freshwater dolphins in Asia and South America due to their limited ranges (Campbell et al. 2022). In 2023, unprecedented droughts in the Amazon Basin lead to extreme water heating and increased dolphin mortality (Grossman 2024; Fleischmann et al. in press). Irrawaddy dolphins ~~*(Orcaella brevirostris)*~~ in the Mekong River are likely extirpated due to population fragmentation from dams, high fishing mortality, vessel -strikes, pollutants, genetic outbreeding depression, and low recruitment (Krutzen et al. 2018; Dove 2022).

1.3 Sirenians (5 species, 1 extinct)

Dugong populations are mostly declining outside Australia (Panyawai & Prathep 2022; Marsh et al. 2025), and are listed as Vulnerable globally (Marsh and Sobztick 2019). Three sub-populations have recently been listed by IUCN: New Caledonia (Endangered~~N~~, Hamel et al. 2022); Japan (Endangered~~N~~, Brownell et al. 2019) and coastal Eastern African (Critically Endangered~~R~~; ,Trotzuk et al. 2022). Research on the three manatee species has progressed in the Amazon (Amaral et al 2023), Caribbean (Galves et al 2023), Africa (Keith-Diagne et al 2021; Factheu et al 2023) and Florida (Brady et al. 2022).

1.4 Other Carnivores

1.4.a Polar Bears (1 species)

Trend assessments for all polar bear populations indicate that: five are stable, three increasing, and two declining (Laidre et al. 2022; PBSG 2023). Improved harvest management and transient improvement in habitat conditions, have resulted in improved status for some populations (Dyck et al. 2020; Laidre et al. 2023), while longer ice-free seasons and reductions in ice-seal prey have reduced body condition, productivity, and survivorship in others (Dyck et al. 2022; Bromaghin et al. 2015; Atkinson et al. 2022). Given the rate of climate change (Molnár 2020, Stroeve et al. 2024), few polar bear populations are expected to exist beyond 2100.

1.4.b Mustelids (3 species)

Southern sea otters in western North America have not recovered from hunting, though protection began in 1911 (International Fur Seal Treaty Act). The population is estimated at 3,000 (Hatfield et al. 2019). Reintroductions of otters to parts of their historical range are under consideration (Hughes et al 2019; Rudebusch et al, 2020). There is little information on the marine otter or chungungo along South America's west coast; it is considered endangered on the IUCN Red List.

3.0 Area-based protection

Since 2018, 234 Important Marine Mammal Areas (IMMAs) for 110 species have been identified by IUCN. IMMAs can inform the implementation of area-based management measures, e.g., the NW Mediterranean IMO Particularly Sensitive Sea Areas (PSSA). See: https://www.marinemammalhabitat.org/immas/immas-searchable-database/

4.0 Changes in overall status

Overall, 26.9% of all marine mammal species (including freshwater species) are under threat (Table 1A). One-third of the 30 species not assessed in WOA II are still "data deficient". Only two changed status (Tables 1B & C): the Mediterranean monk seal now classified as vulnerable, and the North Atlantic right whale now CR.

Table 1A. Marine mammal species in each IUCN Red List category in 2024. Regional, subspecies or sub-population assessments are excluded.

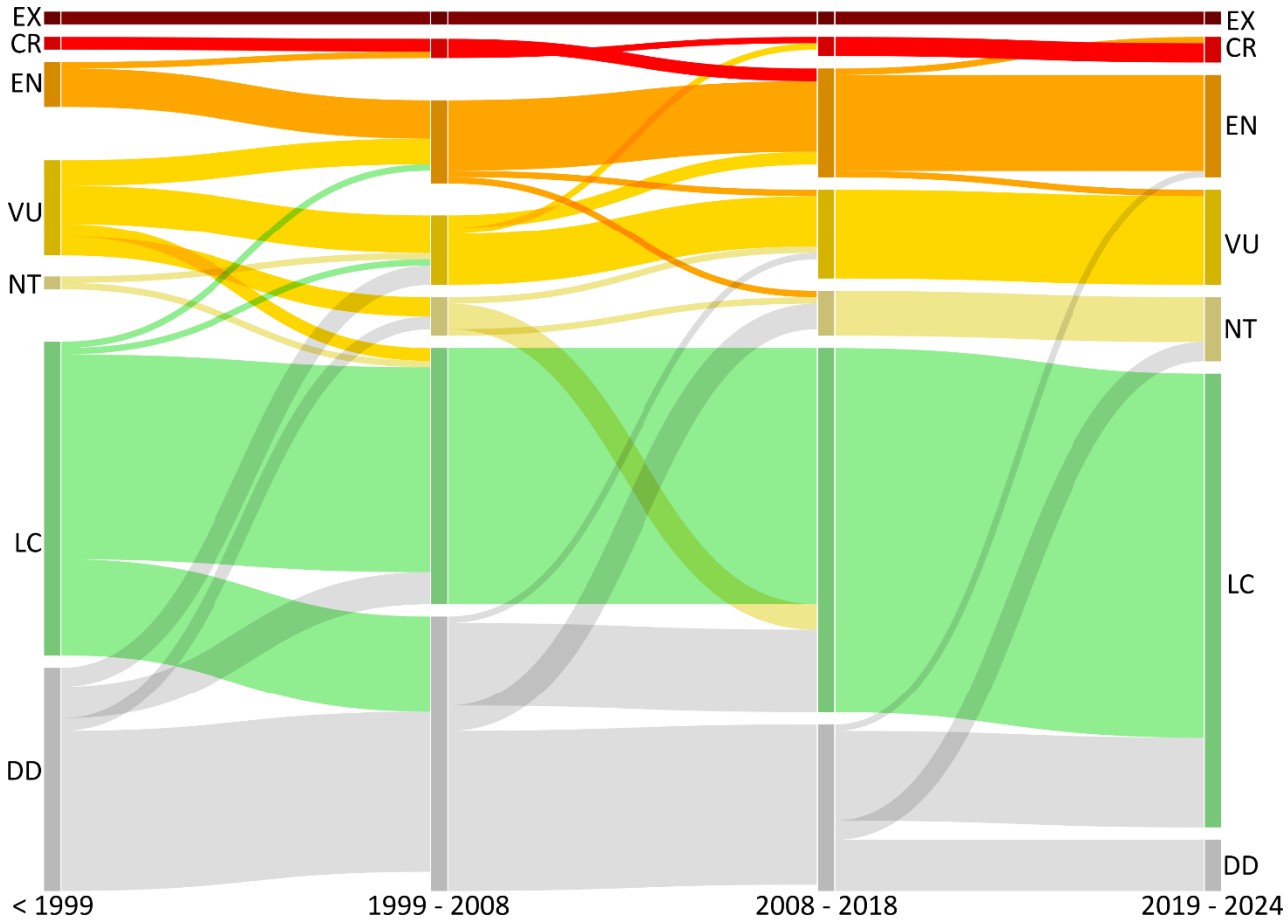
Group	EX	CR	EN	VU	NT	LC	DD	Total
Freshwater dolphins		1	4					5

Mysticetes		2	3	1	1	7	1	15
Odontocetes		2	5	6	9	42	9	73
Pinnipeds	2		6	4	1	23		36
Polar bear				1				1
Sea otters			2					2
Sirenia				4				~~3~~4
Total	**2**	**5**	**20**	**~~15~~16**	**11**	**72**	**10**	**~~135~~136**

Table 1B. Changes in the IUCN Red List status of marine mammals since WOA II . “New”: species evaluated after WOAII or previously DD; “Uplisted”: worsened conservation status; “Downlisted”: improved conservation status.

Group	New	Uplisted	Unchanged	Downlisted	Data deficient	Total
Freshwater dolphins	1		4			5
Mysticetes		1	13		1	15
Odontocetes	20		44		9	73
Pinnipeds			35	1		36
Polar bear			1			1
Sea otters			2			2
Sirenia			4			4
Total	**21**	**1**	**~~102~~103**	**1**	**10**	**~~135~~136**

Table 1C. Status changes over time.



5.0 Region-specific changes

5.1 The Arctic Ocean

Since WOA II, Arctic marine ecosystems have changed dramatically due to global warming, with temperature increases 4x the global average (Meredith et al. 2019; Rantanen et al. 2022). Arctic

sea ice has drastically declined in extent and thickness. An ice-free Arctic is predicted for mid-century (Kim et al. 2023~~), representing~~), representing virtually total habitat loss for 11 endemic Arctic marine mammal species. Transformed food webs, altered predator-prey relationships, changing distribution/migration patterns, local overharvesting, increasing disease risks and human encroachment are threats (Heide-Jørgensen et al. 2020; Kovacs et al. 2021; Kuletz et al. 2024).

5.2 North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

Regional downlisting of Mediterranean monk seals, common bottlenose dolphins, and striped dolphins, and the establishment of the NW Mediterranean PSSA are examples of positive developments. For example, Greece has designated new marine protected areas and management actions. However, mass strandings of beaked whales and bycatch still raise serious concerns. The critically endangered Baltic harbour porpoise (Celemin et al. 2023) and endangered Black Sea endemic harbour porpoise are threatened by bycatch in gillnets (ICES 2024) and in turbot gillnets (Popov et al. 2023), respectively.

5.3 The South Atlantic Ocean and the Wider Caribbean

Entanglement in fishing gear remains the main threat to coastal marine mammals regionally (Domit et al., 2021; Secchi et al., 2021; da Silva et al., 2023). Although legally protected in most countries, direct take and consumption occur in some countries (Ingram et al., 2022; Nuno et al., 2022)[15]. Environmental degradation is considered the leading cause of some population declines (Lailson-Brito Jr et al., 2022; Oliveira-Ferreira et al., 2024). In 2023-2024 the H5N1 avian influenza severely affected South American pinnipeds (Plaza et al., 2024; Uhart et al., 2024).

5.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Since WOAII, freshwater and oceanic mammals in the Bay of Bengal and its tributaries have been increasingly exposed to human-induced threats including fisheries, habitat degradation, and pollution (Paudel et al., 2020a and 2020b; Campbell et al., 2022). A lack of monitoring and research in some countries limits information availability for 23 cetacean species and the dugong.

[15] Recent initiatives like the CMS resolution 14.15 action plan to address aquatic wild meat harvest in west Africa

5.5 The North Pacific Ocean

Knowledge of cetaceans in ~~China~~ the East and South China Seas has increased since WOA II, with at least 25 confirmed cetacean species in the South China Sea (Liu et al. 2023; Liu et al. 2024a,b; Li et al. 2024). Dugongs may ~~be functionally~~be functionally extinct in China (Lin et al. 2022a). Several populations of Indo-Pacific humpback dolphin have rapidly declined in recent decades, with at least one group facing extirpation (Lin et al. 2022b, 2024a,b). As of 2022 the Yangtze finless porpoise is increasing after implementation of a ten-year fishing ban (Hao et al. 2024).

5.6 The South Pacific Ocean

In Chile, South American sea lions are depredating fish catches, resulting in fishermen illegally killing them (approximately 3 per boat per month)(Sepulveda et al., 2018). In the Southwest Pacific, data on strandings around New Caledonia could be used to determine species distributions and provide samples for genetic, ageing, diet, and pollutant analysis (Garrigue et al. 2024).

5.7 The Southern Ocean

In the Southern Ocean, habitats are shifting poleward, increasing habitat for sub-Antarctic species and reducing habitat for ice-dependent species (Hindell et al. 2020; Melbourne-Thomas 2020). Antarctic krill distribution has drifted south ~~abundance and recruitment have declined~~ with declining sea ice (Kawaguchi et al. 2024) raising concerns because they are primary prey for blue, fin, humpback, ~~and~~ Antarctic minke whales, and crabeater seals. There is concern about increased vessel traffic associated with ecotourism (Pallin et al. 2022).

6.0 Changes in key threatening processes since WOA II

6.1 Fisheries bycatch

Research on bycatch has increased in some countries since WOA II because of export regulations (e.g. NOAA OIAT&C 2023).

Good governance and involvement of local communities are key to addressing artisanal gillnet fisheries threats to small cetaceans globally (Brownell et al. 2019). The Bycatch Risk Assessment Toolkit is available to address data-poor cases (Hines et al. 2020). In many areas, animals are increasingly relying on fishing activities as a foraging strategy (e.g. Papageorgiou et al. 2024).

6.2 Vessel -strikes

A global analysis of the risk of vessel strikes to four large whale species from global shipping found less than 10% of populations had protective measures (Nisi et al. 2024). The IWC leads global efforts on risk assessment and identification of mitigation options, advising countries and intergovernmental organisations, such as the ~~IMO~~International Maritime Organization. The IWC holds a global vessel strike database (Winkler et al. ~~2022~~2020). Reducing the risks of vessel strikes for marine megafauna has been addressed by CMS.[16]

6.3 Climate change

Climate change impacts are recognized as a global threat to marine biodiversity, creating both direct and indirect negative effects on marine mammals (Marsh et al. 2022; D'Amen et al. 2024). Since WOA II, this threat has escalated. Oceans have become warmer, fresher, increasingly stratified, and less oxygenated (IPCC 2022). Sea levels have risen, storm activity has intensified, and sea ice has declined. These changes impact marine mammals directly through physical habitat changes and indirectly via altered ecosystems. Other climate related concerns for marine ~~mammals include~~mammals include increased harmful algal blooms and infectious disease exposure (Kebke et al. 2022; Barratclough et al. 2023) and the impacts of warmer water on sound propagation and exposure to contaminants (Affatati et al. 2022; Borgå et al. 2022).

6.4 Contaminants

~~*Pollutants*~~

Legacy compounds identified in WOA II have declined in many species, but continue to accumulate in tissues in some regions despite being banned under the Stockholm Convention on Persistent Organic Pollutants (2004). Novel contaminants now add to threats, especially perfluoralkyl compounds and microplastics (Schaap et al. 2023).

6.5 Diseases

[16] CMS Resolution 14.5 (UNEP/CMS Secretariat 2024).

Harmful algal blooms

Since WOA II, climate change has increased the spatiotemporal distribution of harmful algal blooms (HAB) globally (Hallegraef et al. 2021), which can cause marine mammal death and disease. Saxitoxin has been detected north of the Bering Straits for the first time (Lefebvre et al. 2022~~3~~). HABs have been responsible for deaths of sirenians, dolphins and baleen whales (Haussermann et al. 2017; Starr et al. 2017; Broadwater et al. 2018).

Infectious diseases

Multiple viral epizootics have caused severe die-offs of marine mammals since WOA II. Morbilliviruses have killed thousands of cetaceans and pinnipeds (Duignan et al. 2014; Van Bressem et al. 2014; Groch et al., 2018). Die-offs of pinnipeds in South America in 2022 and 2023 were caused by avian influenza virus, H5N1 (Ulloa et al. 2023; Uhart et al. 2024).

The spread of terrestrial pathogens to marine mammals has been facilitated by coastal development and increases in coastal run-off. Toxoplasmosis causes mortality globally, killing critically endangered Maui dolphins in New Zealand, monk seals in Hawaii, and sea otters in the U.S.A. (Barbieri et al. 2016; Miller et al. 2018).

6.6 Offshore wind energy production

Worldwide production of offshore wind energy has expanded rapidly. Both exploration and implementation pose risks to marine mammals (Macrander et al. 2022). Passive acoustic monitoring can be used to define critical habitats and reduce risk of vessel strikes, for example in studies in New England (Van Parijs et al. 2023).

6.7 ~~Warfare~~ Armed Conflict

~~War~~ Armed conflict precludes research and conservation management in many countries (Marsh et al. 2025). The geopolitical situation in Eastern Europe has caused an increase in cetacean strandings in the Black Sea, with possibly thousands of dead animals (UNEP, 2022; Węgrzyn et al., 2023; Popov & Meshkova 2024). Preliminary accounts reveal severe environmental impacts, including habitat destruction, extreme chemical pollution due to toxic flooding and shelling, underwater noise, unexploded sea mines, and oil spills (Hryhorczuk et al. 2024).

~~The Ukraine-Russia war has caused an increase in cetacean strandings, with possibly thousands of dead animals (UNEP, 2022; Węgrzyn et al., 2023; Popov & Meshkova 2024). Preliminary accounts reveal severe environmental impacts, including habitat~~

~~destruction, extreme chemical pollution due to toxic flooding and shelling, underwater noise, unexploded sea mines, and oil spills (Hryhorczuk et al. 2024).~~

6.8 Tourism

Wildlife-tourism is growing in scale, numbers and revenue (O'Connor et al. 2009). Recent research enables quantification of ~~disturbance of~~disturbance of unmanaged tourism at population-levels ~~-~~(Bejder et al 2022). Possible physiological and behavioral consequences can lead to decreased health and survival (Booth 2022). CMS have developed International Guidelines for Sustainable Marine Wildlife Interactions: Boat-Based and In-Water Activities - Technical Series No. 49 (CMS, 2025).

7.0 Remaining key knowledge gaps and capacity-building gaps

Knowledge & capacity gaps	**Steps to address gaps since WOA II**
Global distribution, abundance and population structure	Advances in satellite imagery and AI (Cubaynes et al. 2023) Regional/international large-scale surveys (e.g., Gilles et al. 2023; Panigada et al. 2023) Marine acoustics (Ferguson et al. 2023; Cominelli et al. 2024) Advances in genetics (McGowen et al. 2024; Morin et al 2024)
Species-specific distribution modeling	Habitat use

	(Bedrinana-Romano et al. 2022; Cañadas et al. 2023; Fiedler et al 2023; Frantz et al 2024)
Spatiotemporal identification of climatic refugia for marine mammals	Climate refugia (Gulland et al. 2022; Garcia-Reyes et al. 2023; Zelli et al 2025)
Plastics/microplastics	Marine mammals and microplastics (Zantis et al. 2021)

8.0 References

Affatati, A., Scaini, C. & Salon, S. 2022. Ocean Sound Propagation in a Changing Climate: Global Sound Speed Changes and Identification of Acoustic Hotspots. Earths Future 10(3): e2021EF002099. Doi.org.10.1029/2021EF002099.

Amaral, R., Marmontel, M. et al 2023. Advances in the knowledge of the biology and conservation of the Amazonian manatee (*Trichechus inunguis*). Latin American Journal of Aquatic Mammals https://doi.org/10.5597/lajam00296

Atkinson, S.N., Boulanger, J., Campbell, M., Trim, V. Ware, J., and Roberto-Charron, A. 2022. 2021 Aerial survey of the Western Hudson Bay polar bear subpopulation. Final report to the Government of Nunavut, 16 November 2022.

Auttila, M. & Alakoski, R. 2025. Pusa hispida ssp. saimensis, Saimaa Ringed Seal. IUCN Red List of Threatened Species, in press.

Backe, K, Hines, E., Nielsen, K., George, D., Twohy, E., and M. Lowry. 2021. Effects of sea-level rise and storm enhanced flooding on Pacific harbor seal habitat: a comparison of haul-out changes at the Russian and Eel River Estuaries. *Aquatic Conservation https://doi.org/10.1002/aqc.3574*

Baker, J., Robinson, S., Harting, A., Barbieri, M. & Littnan, C. 2025. *Neomonachus schauinslandi* Hawaiian Monk Seal. IUCN Red List of Threatened Species, in press.

Barbieri MM, et al. 2016. Protozoal-related mortalities in endangered Hawaiian monk seals *Neomonachus schauinslandi. Dis Aquat Organ* 121:85-95

Barratclough, A., Ferguson, S.H., Lydersen, C., Thomas, P.O. & Kovacs, K.M. 2023. A review of circumpolar Arctic marine mammal heath – a call to action in a time of rapid environmental change. Pathogens 12: 937. doi.org/10.3390/pathogens12070937

Bartalini, A., Muñoz-Arnanz, J., García-Álvarez, N., Fernández, A., Jiménez, B., 2022. Global PBDE contamination in cetaceans. A critical review. **Environmental Pollution** 308, 119670. https://doi.org/10.1016/j.envpol.2022.119670

Bejder, L., Higham, JES, and D. Lusseau. 2022. Tourism and research impacts on marine mammals: A bold future informed by research and technology. In Marine Mammals: the Evolving Human Factor, Eds: Notarbartolo di Sciara, G, and B Wursig. Springer Nature, Switzerland: 255-276.

Bedrinana-Romano, L., Zarate, PM, et al 2022. Abundance and distribution patterns of cetaceans and their overlap with vessel traffic in the Humboldt Current Ecosystem, Chile. Scientific Reports https://doi.org/10.1038/s41598-022-14465-7

Booth, H., Mourato, S. and EJ. Milner-Gulland. 2022. Investigating acceptance of marine tourism levies, to cover the opportunity costs of conservation for coastal communities. Ecological Economics https://doi.org/10.1016/j.ecolecon.2022.107578

Borgå, K., McKinney, M.A., Routti, H., Fernie, K.J., Giebichenstein, J., Hallanger, I. & Muir, D.C.G. 2022. The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. Environmental Science – Processes Impacts 24: 1544-1576. Doi.org.10.1038/D1EM00469G.

Brady, B., Moore, J., and K. Love. 2022. Behavior related vocalizations of the Florida manatee (*Trichechus manatus latirostris*). Marine Mammal Science https://doi.org/10.1111/mms.12904

Braulik, GT., Taylor, BL., et al 2023. Red-list status and extinction risk of the world's whales, dolphins and porpoises. Conservation Biology https://doi.org/10.1111/cobi.14090

Broadwater, M.H., Van Dolah, F.M., Fire, S.E., 2018. Vulnerabilities of marine mammals to harmful algal blooms. In: Shumway, S.E., Burkholder, J.M., Morton, S.L. (Eds.), Harmful Algal Blooms. John Wiley & Sons, Ltd, Chichester, UK, pp. 191–222.

Bromaghin, J.F., Mcdonald, T.L., Stirling, I., Derocher, A.E., Richardson, E.S., Regehr, E.V., Douglas, Durner, G.M., Atwood, T. & Amstrup, S.C. 2015. Polar bear population dynamics in the southern Beaufort Sea during a period of sea ice decline. Ecological Applications 25: 634-651.

Brownell Jr, R.L., Reeves, R.R., et al. 2019. Bycatch in gillnet fisheries threatens Critically Endangered small cetaceans and other aquatic megafauna. **Endangered Species Research** 40, 285–296. https://doi.org/10.3354/esr00994

Campbell, E., Alfaro-Shigueto, J., Aliaga-Rossel, E., Beasley, I., Briceño, Y., Caballero, S., da Silva, V.M., Gilleman, C., Gravena, W., Hines, E. Khan, MS et al., 2022. Challenges and priorities for river cetacean conservation. Endangered Species Research, 49, pp.13-42. https://doi.org/10.3354/esr01201

Cañadas A., Pierantonio N., Araújo H., David L., Di-Méglio N., Ghislain D., et al. (2023). Distribution patterns of marine megafauna density in the Mediterranean Sea assessed through the ACCOBAMS Survey Initiative. *Front. Mar. Sci. Sec. Mar. Megafauna* 10. doi: 10.3389/fmars.2023.1270917

Celemin, E., Autenrieth, M., et al 2023. Evolutionary history and seascape genomics of Harbour porpoise (*Phocoena phocoena*) across environmental gradients in the North Atlantic and adjacent waters. Molecular Ecology Resources https://doi.org/10.1111/1755-0998.13860

Cubaynes, HC, Clarke, PJ, Goetz, KT, Aldrich, T, et al 2023. Annotating very high-resolution satellite imagery: A whale case study. MethodsX. https://doi.org/10.1016/j.mex.2023.102040

Cominelli, S., Bellin, N. et al 2024. Acoustic features as a tool to visualize and explore soundscapes: Applications illustrated using marine mammal passive acoustic monitoring datasets. Ecology and Evolution https://doi.org/10.1002/ece3.10951

D'Amen, M., Fortuna, CM. et al 2024. Climate change and cetacean habitat suitability in the Mediterranean Sea: a challenge for Marine Strategy Framework Directive D1C4, D1C5 criteria. Animal Conservation. https://doi.org/10.1111/acv.13002

da Silva, A.Z., Bornatowski, H., Domit, C., 2023. Small-scale fisheries and their interactions with marine megafauna: implications for the conservation of threatened species. Desenvolv. E Meio Ambiente 61, 213–241. https://doi.org/10.5380/dma.v61i0.80221

Domit, C., Caballero, S., Miranda, A., Fruet, P.F., Torres-Florez, J.P., Cunha, H.A., Farro, A.P.C., Azevedo, A.F., Bisi, T.L., Briceño, Y., Cremer, M.J., Tardin, R.H., Barreto, A.S., Bertozzi, C.P., Brito, J.L., Barrios-Garrido, H., Belleghem, T.V., May-Collado, L.J., Di Tullio, J.C., Bracarense, A.P.F.R., Cantor, M., Andriolo, A., 2021. Report of the Sotalia guianensis Pre-Assessment Workshop (São Paulo, Brazil, 26-28 November 2019). J Cetacean Res Manage 22, 335–378. https://doi.org/10.47536/jcrm.v22i1.1007

Dove, V. 2022. The impact of health and environmental factors on a population of Mekong River Irrawaddy dolphins (*Orcaella brevirostris*) in Cambodia. Doctoral dissertation, Murdoch University, Australia.

Duignan P.J., Van Bressem M., Baker J.D et al. 2014. Phocine distemper virus: Current knowledge and future directions. Viruses 6: 5093-5134.

Dyck, M., Lukacs, P. & Ware, J.V. 2020. Re-estimating the abundance of a recovering polar bear subpopulation by genetic mark-recapture in M'Clintock Channel, Nunavut, Canada. Final Report, Government of Nunavut, Department of Environment, Iglulik. 29 July 2020.

Dyck, M., Dunham, K.D., Ware, J.V., Koons, D.N., Regehr, E.V., Hosmer, D.W., Derocher, A.E., Dale, A., Pisapio, J., and Szor, G. 2022. Re-estimating the abundance of the Davis Strait polar bear subpopulation by genetic mark-recapture. Final Report, Government of Nunavut, Department of Environment, Iglulik.

Factheu, C., Rycyk, AM, et al 2023. Acoustic methods improve the detection of the endangered African manatee. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2022.1032464

Ferguson, EL., Clayton, HM., and Sakai, T. 2023. Acoustic indices respond to specific marine mammal vocalizations and sources of anthropogenic noise. Frontiers in Marine Science https://doi.org/10.3389/fmars.2023.1025464

Feyrer, LJ., Stanistreet, JE, and HB. Moors-Murphy. 2024. Navigating the unknown: assessing anthropogenic threats to beaked whales, family Ziphiidae. Royal Society Open Science https://doi.org/10.1098/rsos.240058

Fiedler, PC., Becker, EA., Forney, KA., Barlow, J., and JE. Moore. 2023. Species distribution modeling of deep diving cetaceans. Marine Mammal Science https://doi.org/10.1111/mms.13057

Fleischmann, A., Papa, F. et al. In Press. Extreme warming of Amazon waters in a changing climate. EarthArXiv. https://eartharxiv.org/repository/view/7437/

Frantz, BH, Sepulveda, M., Garcia-Reyes, M., Vega, R., Palacios, D., Bedrinana-Romano, L., Huckstadt, L., Santos-Carvallo, M. and E. Hines. 2024. Combining potential and realized distribution modeling for a bycatch risk assessment using telemetry data. *Ecology and Evolution:* https://doi.org/10.1002/ece3.11541

Frasier, TR, Hamilton, PK., and RM Pace III. 2024. How compromised is reproductive performance in the endangered North Atlantic right whale? Endangered Species Research. https://doi.org/10.3354/esr01378

Galves, J., Galves, CG, Gomez, NA, et al 2022. Analysis of a long-term dataset of Antillean manatee strandings in Belize: implications for conservation. Oryx https://doi.org/10.1017/S0030605321000983

Garcia-Aguilar, M., Turrent, C., Elorriaga-Verplanken, F.R., Arias-Del-Razo, A. & Schramm, Y. 2018. Climate change and the northern elephant seal (*Mirounga angustirostris*) population in Baja California, Mexico. PLoS One 13(2): e0193211. Doi.org.10.1371/journal.pone.0193211.

Garcia-Reyes, M, Sydeman, W., Koval, G., Palacios, D., Bedriñana-Romano, L., Sepulveda, M., DeForest, K., and E. Hines. 2023. Most eastern boundary upwelling regions represent thermal refugia in the age of climate change. *Frontiers in Marine Science:* https://doi.org/10.3389/fmars.2023.1158472

Garrigue, C., Derville, S., et al. 2024. Marine mammal strandings recorded in New Caledonia, South West Pacific Ocean, 1877-2022. Pacific Conservation Biology https://doi.org/10.1071/PC23016

Genov, T., Malapert, A. et al. 2024. Atlantic humpback dolphin (*Sousa teuszii*) in Guinea, West Africa. IWC SC69B/SM/15 https://www.sousateuszii.org/wp-content/uploads/2020/11/SC_69B_SM_15_Genov-et-al-Guinea-report.pdf

Gilles, A, Authier, M, Ramirez-Martinez, NC, Araújo, H, Blanchard, A, Carlström, J, Eira, C, Dorémus, G, Fernández-Maldonado, C, Geelhoed, SCV, Kyhn, L, Laran, S, Nachtsheim, D, Panigada, S, Pigeault, R, Sequeira, M, Sveegaard, S, Taylor, NL, Owen, K, Saavedra, C, Vázquez-Bonales, JA, Unger, B, Hammond, PS (2023). Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS-IV aerial and shipboard surveys. Final report published 29 September 2023. 64 pp. https://tinyurl.com/3ynt6swa

Groch, K.R., Santos-Neto, E.B., Díaz-Delgado, J., Ikeda, J.M.P., Carvalho, R.R., Oliveira, R.B., Guari, E.B., Bisi, T.L., Azevedo, A.F., Lailson-Brito, J., Catão-Dias, J.L., 2018. Guiana Dolphin Unusual Mortality Event and Link to Cetacean Morbillivirus, Brazil. Emerging Infectious Diseases journal – CDC 24(7): 1349-1354. DOI: 10.3201/eid2407.180139

Grossman, D. 2024. A river in flux. Science Vol 383, Issue 6684: 692-697

Gulland, FMD, Baker, JD, Howe, M, et al 2022. A review of climate change effects on marine mammals in United States waters: Past predictions, observed impacts, current research and conservation imperatives. Climate Change Ecology https://doi.org/10.1016/j.ecochg.2022.100054

Hallegraeff, G.M.A.Zingone, Enevoldsen, H. (Eds.), 2021. Global Harmful Algal Bloom Status Reporting. HARALG. 100.

Hamel, M.A., Marsh, H., Cleguer, C., Garrigue, C. & Oremus, M. 2022. *Dugong dugon* (New Caledonia subpopulation). The IUCN Red List of Threatened Species 2022: e.T218582754A218589361. https://dx.doi.org/10.2305/IUCN.UK.2022-2.RLTS.T218582754A218589361.en

Hao, Y., Bin Tang, Zhigang Mei, Jinsong Zheng, Kexiong Wang, Ding Wang. (2024) Further suggestions on conservation of the Yangtze finless porpoise based on retrospective analysis of the current progress. *Acta Hydrobiologica Sinica*, 2024, 48(6): 1065-1072. DOI: 10.7541/2024.2024.0020.

Hatfield, B.B., Yee, J.L., Kenner, M.C., and Tomoleoni, J.A., 2019, California sea otter (*Enhydra lutris nereis*) census results, spring 2019: U.S. Geological Survey Data Series 1118, 12 p., https://doi.org/10.3133/ds1118

Haussermann et al. (2017), Largest baleen whale mass mortality during strong El Niño event is likely related to harmful toxic algal bloom. PeerJ 5:e3123; DOI 10.7717/peerj.3123

Heide-Jørgensen, M-P., Garde, E., Hansen, R.G., Tervo, O.M., Sinding, M.H.S., Witting, L., Marcoux, M., Watt, C., Reeves, R.R. & Kovacs, K.M. 2020. Narwhals require targeted conservation. Science 370: 416. Doi.10.1126/science.abe7105.

Hindell, M. A., R. R. Reisinger, Y. et al. 2020. Tracking of marine predators to protect Southern Ocean ecosystems. Nature 580:87-92.

Hines, EM, Johnson, A., Ponnampalam, L., Peter, C., Junchompoo, C., Vu, L., Thien, H., Caillat, M., and Verutes, G. (2020) Getting to the Bottom of Bycatch: A GIS-based toolbox to assess the risk of marine mammal bycatch. *Endangered Species Research:* https://doi.org/10.3354/esr01037

Hryhorczuk, D., Levy, B.S., Prodanchuk, M. *et al.* 2024. The environmental health impacts of Russia's war on Ukraine. Journal of Occupational Medicine and Toxicology https://doi.org/10.1186/s12995-023-00398-y

Hughes, B. B., Wasson, K., Tinker, T. M., Williams, S. L., Carswell, L. P., et al including Hines, E. and Rudebusch, ~~J.~~J. ~~(2020~~2019~~)~~ Sea otters in estuaries: opportunities for recovery and restoration: Recovering sea otters reveal their true fundamental niche. *PeerJ:* http://dx.doi.org/10.7717/peerj.8100

ICES. 2024. Workshop on Supporting the EU Action Plan to restore marine ecosystems (WKSUP). ICES Scientific Reports. 6:102. 57 pp. https://doi.org/10.17895/ices.pub.27918315

Ingram, D.J., Prideaux, M., Hodgins, N.K., Frisch-Nwakanma, H., Avila, I.C., Collins, T., Cosentino, M., Keith-Diagne, L.W., Marsh, H., Shirley, M.H., Van Waerebeek, K., Djondo, M.K., Fukuda, Y., Glaus, K.B.J., Jabado, R.W., Lang, J.W., Lüber, S., Manolis, C., Webb, G.J.W., Porter, L., 2022. Widespread Use of Migratory Megafauna for Aquatic Wild Meat in the Tropics and Subtropics. Front. Mar. Sci. 9.

IPCC 2022. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

International Whaling Commission (IWC) 2023. First ever extinction alert from the IWC: the vaquita porpoise. https://iwc.int/resources/media-resources/news/first-ever-extinction-alert-from-the-iwc

Jog, K., Sutaria, D., Diedrich, A. & Grech, A. 2022. Marine mammal interactions with fisheries: review of research and management trends across commercial and small-scale fisheries. Frontiers in Marine Science 9: 758013. Doi.org.10.3389/fmars.2022.758013

Karamanlidis, A.A., Dendrinos, P., Fernandez de Larrinoa, P., Kıraç, C.O., Nicolaou, H. & Pires, R. 2023. Monachus monachus. The IUCN Red List of Threatened Species 2023: e.T13653A238637039. https://dx.doi.org/10.2305/IUCN.UK.2023-1.RLTS.T13653A238637039.en. ~~Karamanlidis, A.A., Dendrinos, P., Kıraç, K.O., Fernandez de Larrinoa, P., Nicolaou, H. & Pires, R. Monachus monachus, Mediterranean Monk Seal. IUCN Red List of Threatened Species, in press.~~

Kawaguchi, S., A. Atkinson, D. Bahlburg, K. S. Bernard, E. L. Cavan, M. J. Cox, S. L. Hill, B. Meyer, and D. Veytia. 2024. Climate change impacts on Antarctic krill behaviour and population dynamics. Nature Reviews Earth & Environment 5:43-58.

Kebke, A., Samarra, F. & Derous, D. 2022. Climate change and cetacean health: impacts and future directions. Philosophical Transactions of the Royal Society of London, B Biological Sciences. 4: 377(1854): 20210249. Doi.org 10.1098/rstb.2021.0249

Keith-Diagne, LW., Fernandez de Larrinoa, P., Diagne, T., and LM Gonzalez. 2021. First satellite tracking of the African manatee (*Trichechus senegalensis*) and movement patterns in the Senegal River. Aquatic Mammals. DOI 10.1578/AM.47.1.2021.21

Kim, Y-H., Min, S-K., Gillett, N.P., Notz, D. & Malinina, E. 2023. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. Nature Communications

Kovacs, K.M., Belikov, S., Boveng, P., Desportes, G., Ferguson, S., Hansen, R., Laidre, K., Stenson, G., Thomas, P., Ugarte, F. & Vongraven, D. (2021). 2021 State of the Arctic Marine Biodiversity Report (SAMBR) - Update for Marine Mammals. Technical Report. Conservation of Arctic Flora and Fauna International Secretariat: Akureyri, Iceland.

Krutzen, M., Beasley, I., et al 2018. Demographic collapse and low genetic diversity of the Irrrawaddy dolphin population inhabiting the Mekong River. PLOSOne https://doi.org/10.1371/journal.pone.0189200

Kuletz, K.J., Ferguson, S.H., Frederiksen, M., Gallagher, C.P., Hauser, D.W., Hop, H., Kovacs, K.M., Lydersen, C., Mosbech, A. & Seitz, A.C. 2024. A review of climate change impacts on migration patterns of marine vertebrates in Arctic and Subarctic ecosystems. Frontiers in Environmental Science 12:1434549. Doi. 10.3389/fenvs.2024.1434549.

Laidre, K.L., Regehr, E.V., Wiig, Ø., Ugarte, F., Aars, J., Dietz, R., Sonne, C., Hegelund, P., Isaksen, C., Aske, G.B., Cohen, B., Stern, H.L., Moon, T., Vollmers, C., Corbett-Detig, R., Paetkau, D. & Shaprio, B. 2022. Glacial ice supports a distinct and undocumented polar bear subpopulation persisting in late 21st-century sea-ice conditions. Science 376(6599): 13331338. Doi.10.1126/science.abk2793

Laidre KL, Arnold TW, Regehr EV, Atkinson SN and others (2023) Demographic response of a high-Arctic polar bear (*Ursus maritimus*) subpopulation to changes in sea ice and subsistence harvest. Endang Species Res 51:73-87. https://doi.org/10.3354/esr01239

Lailson-Brito Jr, J., Oliveira-Ferreira, N., Manhães, B.M.R., Bisi, T.L., Santos-Neto, E., 2022. Chapter 11 - Chemical pollution and franciscana—a review, in: Simões-Lopes, P.C., Cremer, M.J. (Eds.), The Franciscana Dolphin. Academic Press, pp. 235–264. https://doi.org/10.1016/B978-0-323-90974-7.00017-3

Lefebvre, Kathi A., Evangeline Fachon, Emily K. Bowers, David G. Kimmel, Jonathan A. Snyder, Raphaela Stimmelmayr, Jacqueline M. Grebmeier et al. "Paralytic shellfish toxins in Alaskan Arctic food webs during the anomalously warm ocean conditions of 2019 and estimated toxin doses to Pacific walruses and bowhead whales." *Harmful Algae* 114 (2022): 102205.

Li, S., Mingming Liu, Wenzhi Lin, Lijun Dong, Mingli Lin, Hui Kang, Inge Seim. (2024) Identification of the enigmatic Deraniyagala's beaked whale. *iScience*. 27, 111465. https://doi.org/10.1016/j.isci.2024.111465

Lin, M., Samuel T. Turvey, Chouting Han, Xiaoyu Huang, Antonios D. Mazaris, Mingming Liu, Heidi Ma, Zixin Yang, Xiaoming Tang, and Songhai Li. (2022a) Functional extinction of dugongs in China. *Royal Society Open Science*. 9: 211994. https://doi.org/10.1098/rsos.211994.

Lin, W., Ruiqiang Zheng, Binshuai Liu, Shenglan Chen, Mingli Lin, Mingming Liu, Wenhua Liu, and Songhai Li. (2022b) Low survival and rapid demographic decline of a threatened estuarine delphinid. *Frontiers in Marine Science*. 9: 782680. doi: 10.3389/fmars.2022.782680.

Lin, W., Ruiqiang Zheng, Shiyao Xu, Songhai Li. (2024a) Indo-Pacific humpback dolphins face extirpation in Shantou waters. *Regional Studies in Marine Science*. 77: 103641. https://doi.org/10.1016/j.rsma.2024.103641.

Lin, W., Shenglan Chen, Binshuai Liu, Ruiqiang Zheng, Agathe Serres, Mingli Lin, Mingming Liu, Songhai Li. (2024b) Survival and population size of the Indo-Pacific humpback dolphins off the eastern Leizhou Peninsula. *Marine Mammal Science*. e13156. https://doi.org/10.1111/mms.13156.

Liu, M., Mingli Lin, and Songhai Li. (2023) Sperm whales (*Physeter macrocephalus*) in the waters off China: A glimpse of the past and present. *Water Biology and Security*. 2: 100133. doi.org/10.1016/j.watbs.2022.100133.

Liu, M., Wenzhi Lin, Mingli Lin, Lijun Dong, Binshuai Liu, Shenglan Chen, Mingyue Ouyang, Peijun Zhang, Zixin Yang, Hui Kang, and Songhai Li. (2024a) Species diversity and critical habitats of offshore and deep-diving cetaceans in the South China Sea. *Biological Conservation*. 299, 110808. https://doi.org/10.1016/j.biocon.2024.110808.

Liu, M., Wenzhi Lin, Mingli Lin, Lijun Dong, Songhai Li. (2024b) Short-finned pilot whales in the South China Sea: Insights into regional distribution, movement pattern, and habitat characteristics. *Marine Mammal Science*. 40, 89–107. https://doi.org/10.1111/mms.13052.

Macrander, AM, Brzyzy, L, et al. 2021. Convergence of emerging technologies: Development of a risk-based paradigm for marine mammal monitoring for offshore wind energy operations. Integrated Environmental Assessment and Management https://doi.org/10.1002/ieam.4532

Marsh, H. and Sobtzick, S. (2019) *Dugong dugon* (amended version of 2015 assessment). The IUCN Red List of Threatened Species 2019: e.T6909A160756767. https://doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A160756767.en.

Marsh, H., Albouy, C., et al. 2022. How might climate change affect the ethology and behavioral ecology of dugongs and manatees? In Ethology and Behavioral Ecology of Sirenia. Ed. Helene Marsh. Springer Nature, Switzerland. 351-406.

Marsh, H, Loates, PJ & Schramm, L (eds.). [2025]. A global assessment of dugong status and conservation needs. Bonn: United Nations Environment Program.

McGowen, Michael, et al. 2024. Rangewide phylogeographic structure of the endangered Irrawaddy dolphin (*Orcaella brevirostris*) using expanded sampling from contemporary and historical specimens. Marine Mammal Science. DOI: 10.1111/mms.13159

Melbourne-Thomas, J. 2020. Climate shifts for krill predators. Nature Climate Change. https://doi.org/10.1038/s41558-020-0756-6

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C., Ottersen, G., Pritchard, H. & Schuur, E.A.G. 2019. Polar Regions. In Pörtner, H-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. & Weyer, N.M. (eds.). 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. IPCC,Gland Switzerland. Pp 203-320.

Meyer-Gutbrod, EL., Davies, TA. et al. 2022. Redefining North Atlantic right whale habitat-use patterns under climate change. Limnology and Oceanography https://doi.org/10.1002/lno.12242

Miller M, et al. 2018. Protozoan parasites of marine mammals. In *CRC Handbook of Marine Mammal Medicine*. Gulland F, Dierauf L, Whitman K (eds) CRC Press, Boca Raton 414-45.

Molnár, P.K., Bitz, C.M., Holland, M.M., Kay, J.E., Penk, S.R & Amstrup, S.C. 2020. Fasting season length sets temporal limits for global polar bear persistence. Nature Climate Change https://doi.org/10.1038/s41558-020-0818-9

Monk Seal Alliance (2024) *Greece's Ministerial Decree paves the way for stronger conservation efforts*, 9 September. Available at: https://www.monksealalliance.org (Accessed: 5 August 2025)

Morin, PA., McCarthy, ML. 2024. Revised taxonomy of eastern North Pacific killer (*Orcinus orca*): Bigg's and resident ecotypes deserve species status. Royal Society Open Science. https://doi.org/10.1098/rsos.231368

National Oceanic and Atmospheric Administration, Office of International Affairs and Commerce. 2023. Modification of deadlines under the fish and fish product import provisions of the Marine Mammal Protection Act. https://www.federalregister.gov/documents/2023/11/17/2023-25399/modification-of-deadlines-under-the-fish-and-fish-product-import-provisions-of-the-marine-mammal

Nisi, AC, Welch, H, et al. 2024. Ship collision risk threatens whales across the world's oceans. Science https://doi.org/10.1126/science.adp1950

Nuno, A., Fernandes, C., Guedes, M., Loloum, B., Matos, L., Nazaré, L., Carvalho, I., 2022. Aquatic wild meat consumption of cetaceans in São Tomé and Príncipe (Gulf of Guinea). Anim. Biodivers. Conserv. 25–33. https://doi.org/10.32800/abc.2023.46.0025

O'Connor, S., Campbell, R., Cortez, H., & Knowles, T., 2009, Whale Watching Worldwide: tourism numbers, expenditures and expanding economic benefits, a special report from the International Fund for Animal Welfare, Yarmouth MA, USA, prepared by Economists at Large.

Oliveira-Ferreira, N., Manhães, B.M.R., Santos-Neto, E., Carvalho, R.R., Cunha, H.A., Azevedo, A.F., bisi, T.L., Lailson-Brito, J., 2024. Organohalogen compounds in a hotspot for chemical pollution: Assessment in free-ranging Atlantic spotted dolphins (*Stenella frontalis*). Sci. Total Environ. 926, 171912. https://doi.org/10.1016/j.scitotenv.2024.171912

Pallin, L.J., Botero-Acosta, N., Steel, D. *et al.* Variation in blubber cortisol levels in a recovering humpback whale population inhabiting a rapidly changing environment. *Sci Rep* 12, 20250 (2022). https://doi.org/10.1038/s41598-022-24704-6

Panigada S., Pierantonio N., Araújo H., David L., Di Meglio N., Dorémus G., et al. (2023). The ACCOBAMS Survey Initiative: the first synoptic assessment of cetacean abundance in the Mediterranean Sea through aerial surveys. *Front. Mar. Sci.Sec. Mar. Megafauna* 10. doi: 10.3389/fmars.2023.1270513

Panyawai, J., & Prathep, A. (2022). A Systematic Review of the Status, Knowledge, and Research Gaps of Dugong in Southeast Asia. Aquatic Mammals, 48(3), 203–222. https://doi.org/10.1578/AM.48.3.2022.203

Papageorgiou, M., Hadjieftychiou, S-I., Chistodoulou, C., Petrou, A., and Mouttopoulos, D.K. 2024. Describing dolphin interactions with Cypriot fisheries using fishers' knowledge. Journal of Marine Science and Engineering, 12(12). https://doi.org/10.3390/jmse12122240

Paudel, S., Koprowski, J.L. and Cove, M.V., 2020a. Seasonal flow dynamics exacerbate overlap between artisanal fisheries and imperiled Ganges River dolphins. Scientific Reports, 10(1), p.18798.

Paudel, S. and Koprowski, J.L., 2020b. Factors affecting the persistence of endangered Ganges River dolphins (*Platanista gangetica gangetic*a). Ecology and Evolution, 10(6), pp.3138-3148.

PBSG (Polar Bear Specialist Group – IUCN). 2023. Polar bear – global – population statushttps://www.iucn-pbsg.org/2024/12/05/pbsg-status-table-updated-2/

Plaza, P.I., Gamarra-Toledo, V., Rodríguez Euguí, J., Rosciano, N., Lambertucci, S.A., 2024. Pacific and Atlantic sea lion mortality caused by highly pathogenic Avian Influenza A(H5N1) in South America. Travel Med. Infect. Dis. 59, 102712. https://doi.org/10.1016/j.tmaid.2024.102712

Popov D, Meshkova G, Vishnyakova K, Ivanchikova J, Paiu M, Timofte C, Amaha Öztürk A, Tonay AM, Dede A, Panayotova M, Düzgünes¸ E and Gol'din P (2023) Assessment of the bycatch level for the Black Sea harbour porpoise in the light of new data on population abundance. Front. Mar. Sci. 10:1119983. https://doi.org/10.3389/fmars.2023.1119983

Popov, D.; Meshkova, G. Cetacean Strandings along the Bulgarian Coast of the Black Sea in 2010–2022. Oceans 2024, 5, 429–441. https://doi.org/10.3390/oceans5030025

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T. & Laaksonen, A. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3:168. Doi.org/10.1038/s43247-022-00498-3.

Rojas-Bracho, L., Taylor, BL, et al 2024. Mexico must save the vaquita from gill nets. Science Vol 285, Issue 6708: 504.

Rosel PE, Wilcox LA (2014) Genetic evidence reveals a unique lineage of Bryde's whales in the northern Gulf of Mexico. Endang Species Res 25:19-34. https://doi.org/10.3354/esr00606

Rosel, PE., Wilcox, LA, Yamada, TK., and KD. Mullin. 2021. A new species of baleen whale (*Balaenoptera*) from the Gulf of Mexico, with a review of its geographic distribution. Marine Mammal Science https://doi.org/10.1111/mms.12776

Rudebusch J, Hughes BB, Boyer KE, Hines E. 2020. Assessing anthropogenic risk to sea otters (*Enhydra lutris nereis*) for reintroduction into San Francisco Bay. *PeerJ* 8:e10241 https://doi.org/10.7717/peerj.10241

Schaap I., Buedenbender, L, Johann, S. Hollert,H., Dogruer G. 2023. Impact of chemical pollution on threatened marine mammals: A systematic review. Journal of Hazardous Materials,459 doi.org/10.1016/j.jhazmat.2023.132203.

Secchi, E.R., Cremer, M.J., Danilewicz, D., Lailson-Brito, J., 2021. A Synthesis of the Ecology, Human-Related Threats and Conservation Perspectives for the Endangered Franciscana Dolphin. Front. Mar. Sci. 8, 617956. https://doi.org/10.3389/fmars.2021.617956

Sepulveda, M., Martinez, T. et al 2018. Factors affecting the operational interaction between the South American sea lions and artisan gillnet fishery in Chile. Fisheries Research https://doi.org/10.1016/j.fishres.2018.01.014

Starr M, Lair S, Michaud S, Scarratt M, Quilliam M, Lefaivre D, et al. (2017) Multispecies mass mortality of marine fauna linked to a toxic dinoflagellate bloom. PLoS ONE 12(5): e0176299. https://doi.org/10.1371/journal.pone.0176299

Stroeve, J., Crawford, A., Ferguson, S., Stirling, I., Archer, L., York, G., Babb, D. & Mallett, R. 2024. Ice-free period is too long for Southern and Western Hudson Bay polar bear populations if global warming exceeds 1.6 to 2.6 °C. Communications Earth & Environment 5: 296.

Trotzuk, E., Allen, K., Cockcroft, V., Findlay, K., Gaylard, A., Marsh, H. Matos, L., West, L. and Guissamulo, A. (2022). Dugong dugon (Eastern Africa subpopulation). The IUCN Red List of Threatened Species 2022. https://www.iucnredlist.org/species/218582764/218589142.

Uhart, M.M., Vanstreels, R.E.T., Nelson, M.I. *et al.* Epidemiological data of an influenza A/H5N1 outbreak in elephant seals in Argentina indicates mammal-to-mammal transmission. *Nat Commun* **15**, 9516 (2024). https://doi.org/10.1038/s41467-024-53766-5.

Ulloa, M. et al. 2023. Mass mortality event in South American sea lions correlated to highly pathogenic avian influenza (HPAI) H5N1 outbreak in Chile. 43, 8–18.

United Nations Environment Programme (2022). **The Environmental Impact of the Conflict in Ukraine: A Preliminary Review**. Nairobi, Kenya. Available at https://wedocs.unep.org/bitstream/handle/20.500.11822/40746/environmental_impact_Ukraine_conflict.pdf

Van Bressem, M., Duignan, P.J., Banyard, et al. 2014. Cetacean morbillivirus: Current knowledge and future directions. Viruses 6: 5145-5181.

Van Parijs, SM, DeAngelis, AI, et al. 2023. Establishing baselines for predicting change in ambient sound metrics, marine mammal, and vessel occurrence within a US offshore wind energy area. ICES Journal of Marine Science https://doi.org/10.1093/icesjms/fsad148

Węgrzyn, E., Rusev, I., Tańska, N., Miedviedieva, I., Kagalo, A.A., Leniowski, K., 2023. The use of social media in assessing the impact of war on cetaceans. **Biology Letters** 19, 20220562. https://doi.org/10.1098/rsbl.2022.0562

Winkler, C., Panigada, S., Murphy, S., and F. Ritter. 2020. Global numbers of ship strikes: An assessment of collisions between vessels and cetaceans using available data in the IWC ship strike database. https://archive.iwc.int/pages/download.php?direct=1&noattach=true&ref=17562&ext=pdf&k=c9f67e8c17

Zantis, LJ, Carroll, EL, Nelms, SE, and T. Bosker. 2021. Marine mammals and microplastics: A systematic review and call for standarisation. Environmental Pollution https://doi.org/10.1016/j.envpol.2020.116142

Zelli, E., Ellis, J., et al. 2025. Identifying climate refugia for vulnerable marine ecosystem indicator taxa under future climate change scenarios. Journal of Environmental Management https://doi.org/10.1016/j.jenvman.2024.122635

Section 4

Sub-chapter 4f: Marine reptiles

Key findings:

- Updates were identified across various marine reptile taxa, with some species maintaining their global conservation status while others (e.g., Green turtles) have new classifications ranging from Least Concern to Endangered.
- This assessment includes saltwater crocodiles, classified as Least Concern due to stable global populations resulting from effective regional management in the species' range.
- Ongoing threats like incidental fisheries by-catch remain significant, and additional challenges such as habitat degradation, marine pollution, and climate change require more comprehensive conservation strategies.
- Gaps remain in long-term monitoring and the gathering of population trend data for marine reptiles, particularly sea snakes and marine iguanas.

4.4f.1. Introduction

This subchapter updates the global and regional statuses of the four major marine reptile groups: marine turtles (7 species), sea snakes (71 species), marine iguanas (1 species), and saltwater crocodiles (1 species). These species range from widely distributed (e.g., sea snakes) to highly localised (e.g., marine iguanas in the Galápagos), and inhabit environments from the open ocean (e.g., marine turtles) to coastal and estuarine habitats (e.g., saltwater crocodile). World Oceans Assessment I (WOAI; Wallace and others, 2016) and II (WOAII; Schuyler and others, 2021) outlined baselines and trends for these groups (except saltwater crocodile) until 2018. WOAII highlighted variable changes in marine turtle populations; some recovering (Loggerhead), others stable (Green), and some declining (Kemp's Ridley). It highlighted the reclassification of two Critically Endangered (CE) sea snake species (Short-nosed and Leaf-scaled) to Data Deficient (DD), added three new species (Mosaic, Shark Bay and Rough-scaled) assessed as DD, and highlighted subspecies reclassification in marine iguana without altering their overall status (MacLeod and others, 2020a; Miralles and others, 2017). This will be the first assessment to include saltwater crocodiles.

4.4f.2. Overall status of marine reptiles

4.4f.2.1. Marine turtles

There have been no updates to the global status of any of the seven marine turtle species since WOAII, but Green turtle (*Chelonia mydas*) subpopulations were newly assessed. Four subpopulations were classified as Least Concern (LC) (Southwest Indian Ocean), Near Threatened (NT)(Mediterranean), Vulnerable (VU) (East Pacific), and Endangered (EN) (Central South Pacific). Loggerhead (*Caretta caretta*), Leatherback (*Dermochelys coriacea*) and Olive Ridley (*Lepidochelys olivacea*) turtles remain VU (Casale and Tucker, 2017; Abreu-Grobois and Plotkin, 2008). Hawksbill (*Eretmochelys imbricata*) and Kemp's Ridley (*Lepidochelys kempii*) turtles are still CE (Mortimer and Donnelly, 2008; Wibbels and Bevan, 2019), and Flatback turtles (*Natator depressus*) remain DD, with no updates since 1996. The Marine Turtle Specialist Group (MTSG) has revised regional management units (RMUs) to define biologically meaningful populations (Wallace and others, 2023), and updated conservation priorities for all species and RMUs (Wallace and others, ~~in press~~2025).

4.4f.2.2. Sea snakes

Since WOAII, the status has not been updated, but a newly described subspecies, the Yellow sea snake (*Hydrophis platurus xanthos*), has been assessed as EN under the IUCN Red List (Bessesen and others, 2024). Among the 71 species and one subspecies currently recognised, one species (*Aipysurus fuscus*) and one subspecies (*Hydrophis platurus xanthos*) are EN, three are VU (*Hydrophis semperi*, *Laticuda crockeri*, *Laticauda schistorhynchus*), four are NT (*Hydrophis pacificus*, *Laticauda semifaciata*, *Laticauda frontalis*, *Laticauda guineai*), and 35 are LC, while the remaining 27 species are either DD or have yet to be assessed. Marine surveys in Northwestern Australia have recorded populations previously thought locally extinct (*Aipysurus apraefrontalis*) at greater depths (Somaweera and others, 2021).

4.4f.2.3. Marine iguanas

The conservation status of the marine iguana (*Amblyrhynchus cristatus*) was updated in 2019, with the global status remaining VU (MacLeod and others, 2020a). The Isla Fernandina subspecies was assessed as VU (MacLeod and others, 2020b), six subspecies from Santiago, Española, San Cristóbal, Wolf, Marchena and Santa Cruz islands as EN (MacLeod and Steinfartz, 2016), and the four remaining subspecies from Isla Santa Fé, Pinta, Genovesa and Punta Pitt are CE (MacLeod and others, 2020a).

4.4f.2.4. Saltwater crocodiles

The saltwater crocodile (*Crocodylus porosus*) was last assessed in 2019 by the IUCN Red List, retaining its LC global status with a stable global population exceeding 400,000 non-hatchlings (Webb and others, 2021). This species breeds mainly in rivers and swamps, undertaking long sea journeys associated with foraging and mate-searching (Manolis, 2005). The species is widely distributed across South and Southeast Asia, Australia and Melanesia, however, its population is now extinct in the wild in Seychelles, and 'possibly extinct' in Cambodia, Thailand, and Vietnam (Webb and others, 2018).

4.4f.3. Regional trends

Regional trends in nesting and foraging marine turtle populations have shown positive developments since WOAII. A review by the MTSG assessed population status between 2011 and 2024, scoring risk factors and threats within RMUs (Wallace and others, ~~in press~~2025). While 74% of RMUs improved since 2011, with notable increases in Hawksbill and Green turtle populations in the Chagos Archipelago (Mortimer and others, 2020) and the Red Sea (Shimada and others, 2021), 26% of RMUs worsened in both risk and threat categories (Table 4.4f.1). Fisheries by-catch remains the highest-ranked threat (Wallace and others, ~~in press~~2025). A meta-analysis of 61 long-term nesting surveys, showed increasing or stable trends for most populations, however, highlighting declines in Leatherback and Loggerhead populations (Hays and others, 2024).

For sea snakes, decreasing population trends have been identified in locations where data are available (Gulf of Thailand, India, New Caledonia), while several other locations lacked sufficient data to define trends (Table 4.4f.2). Overall population trend information is lacking for marine iguanas, with some subpopulations undergoing extreme fluctuations (MacLeod and others, 2020a). Indicative subspecies trends were identified in 2019 with either decreasing or unknown trends in population abundance (Table 4.4f.2). Saltwater crocodile populations have stabilised since historical exploitation, with the species' global status improving from EN status in 1982 to LC in 2019 (Webb and others, 2021). This is largely due to their effective regional management in Australia, Papua New Guinea, and Indonesia. Regional assessments highlight increasing trends in the Solomon Islands, Sarawak, and Sabah due to effective protection measures, but declines in Myanmar and the Philippines (Table 4.4f.2).

Table 4.4f.1. Summary of marine turtle regional population trends (2018-2023) by RMUs, with references. Metrics include nesting counts and individual observations across five major regions.

Region	Green	Loggerhead	Hawksbill	Olive Ridley	Kemp's Ridley	Leatherback
North Atlantic Ocean, Caribbean Sea and Mediterranean	*Increasing* North-West Atlantic Ocean, Caribbean [1] Mediterranean [2] *Decreasing* Costa Rica [3]	*Stable* North-West Atlantic Ocean [4]	*Increasing* Gulf of Mexico [1] *Stable* Caribbean, St. Croix [5] *Decreasing* Caribbean, St. Croix [5]	*No updates*	*Stable* Gulf of Mexico [6]	*Decreasing* North-West Atlantic Ocean, Caribbean [7]
South Atlantic Ocean	*Stable* São Tomé and Príncipe [8]	*No updates*	*No updates*	*Increasing* West Africa [7] *Stable* French Guiana [9]	*Stable* Gulf of Mexico [6]	*Increasing* Brazil [10] *Decreasing* Brazil [7]
Indian Ocean, Red Sea, Arabian Sea and Persian Gulf	*Increasing* Saudi Arabia [11] *Stable* Egypt, Iran, Kuwait, Pakistan [11] South-West Indian Ocean [12] Maldives [13] North-West Indian Ocean [11] *Decreasing*	*Increasing* South-West Indian Ocean [12] *Stable* South-West Indian Ocean [12] Maldives [13] *Decreasing* Oman [11]	*Increasing* Maldives, Saudi Arabia [11] Bangladesh [11] *Stable* North-West Indian Ocean [11]	*Increasing* Bangladesh [11] *Stable* North-East Indian Ocean, West Indian Ocean [11]	*Outside range*	*Stable* India [11] South-West Indian Ocean [12] *Decreasing* Bangladesh [11]

	Bangladesh, Maldives [11]					
North Pacific	*Increasing* North central Pacific Ocean RMU [14] North Mariana Islands [15] *No trend* Guam [16]	*No updates*	*No updates*	*Stable* Costa Rica, Mexico [7]	*Outside range*	*Decreasing* Costa Rica [17]
South Pacific	*Increasing* French Polynesia [18] New Caledonia [19] *Stable* Australia [7] *Decreasing* Raine Island, Australia [20]	*No updates*	*Decreasing* Great Barrier Reef, Australia [21]	*No updates*	*Outside range*	*No updates*

References: [1] López-Castro and others, 2022a; [2] Casale and others, 2018; [3] Restrepo and others, 2023; [4] Ceriani and others, 2019; [5] Gulick and others, 2022; [6] Arendt and others, 2023; [7] Hays and others, 2024; [8] Ferreira-Airaud and others, 2022; [9] Nalovick and others, 2018; [10] Colman and others, 2019; [11] Phillott and Rees, 2021; [12] Dalleau and others, 2020; [13] Hudgins and others, 2023; [14] Chaloupka and Pilcher, 2019; [15] Summers and others, 2018; [16] Valdivia and others, 2019; [17] The Laúd OPO Network, 2020; [18] Touron and others, 2018; [19] Fretey and others, 2023; [20] Dunstan and others, 2020; [21] Bell and others, 2020.

Table 4.4f.2. Summary of regional population trend for sea snakes, marine iguanas, and saltwater crocodiles (2018-2023), as increasing, stable, decreasing or unknown. Key references indicated, and background trends for saltwater crocodiles are provided, marking their first assessment.

Region	Sea Snake	Marine Iguana	Saltwater Crocodile
Indian Ocean, Red Sea, Arabian Sea and Persian Gulf	*Decreasing* Gulf of Thailand [1] India [2] *Unknown trend* Western Australia [3] Persian Gulf [4]	*Outside range*	*Increasing* Western Australia [5] India [6] Peninsular Malaysia [7] *Decreasing* Myanmar [8, 9] *Unknown trend* Bangladesh [10] Indonesia [11] Sri Lanka [12]
North Pacific	*Unknown trend* Costa Rica [13]	*Outside range*	*Increasing* Malaysian Borneo, Brunei [14] Philippines [23] *Stable* Palau [14] Singapore [25]
South Pacific	*Decreasing* New Caledonia [15] Eastern Australia [16]	*Decreasing* Isla Punta Pitt, Genovesa, Pinta and Santa Fé subspecies [17] *Unknown trend* Isla Fernandina, Santa Cruz, Marchena, Wolf, San Cristóbal, Española, Santiago subspecies [18]	*Increasing* Northern Australia [19] Papua New Guinea [20] Solomon Islands [21] Timor-Leste [22] Vanuatu [14] *Unknown trend* Indonesia [24]

References: [1] Cao and others, 2014; [2] Rao and others 2021; [3] Speed and others, 2022; [4] Yaghmour and others 2022; [5] Parke, 2015; WMI, 2018; [6] Kar, 2024; [7] Kwan, 2017; [8] Platt and others, 2015; [9] Than and others, 2024; [10] Somaweera, pers. comm; [11] CITES, 1994; [12] Amarasinghe and others, 2015; [13] Bessesen and others 2022; [14] Webb and others, 2021; [15] Shine and others 2021; [16] Edgar and others 2020; [17] MacLeod and others, 2020a; [18] MacLeod and others, 2020b; [19]

1 Saalfeld and others, 2016; [20] Solmu and others, 2014; [21]Van der Ploeg and others, 2019; [22] Crocodile Task Force, 2017; [23] CITES, 2022; [24] Saragih and others,
2 2020; [25] Figueroa and others, 2023.

4.4f.3. Changes in key threats

Key threats to marine reptiles, such as by-catch and targeted harvest, remain significant, with emerging threats like light pollution, habitat modification and climate change also becoming increasingly impactful (Senko and others, 2022; Fukuda and others 2022; See Chapter 4.6).

4.4f.3.1. Targeted harvest and by-catch

Fisheries by-catch remains the greatest threat to marine turtles, with large numbers caught annually across multiple gear types (Lewison and others, 2014; Wallace and others, 2013~~b~~). Data gaps in regions like West Africa (de la Hoz Schilling and others, 2023; Segniagbeto and others, 2017), Eastern Pacific (Griffiths and others, 2024), continental Europe (Marco and others, 2020, Casale and others, 2018) and North America (Savoca and others, 2020), limit effective management. The Secretariat of the Convention on Migratory Species (CMS) has adopted several region- and species-specific action plans for marine turtles for West Africa, South-east Asia and Western Pacific. Sea snake populations in the Gulf of Thailand and India have declined due to an increased fishing effort and unregulated fishing practices (Rao and others, 2021). Including sea snakes and marine turtles in the Marine Stewardship Council (MSC) certification process could help limit fisheries impacts on these populations (Good and others, 2024; See Chapter 5A.1a). Saltwater crocodiles still face legal and illegal take (Webb and others, 2021), and while egg harvesting has minimal impact, adult harvesting (Fukuda and others, 2020) and drowning as by-catch in fishing nets remains concerning. Legal hunting for meat poses a comparatively smaller and localised threat to the species (Brackhane and others, 2019).

4.4f.3.2. Habitat degradation, marine pollution and coastal modification

Marine debris, particularly plastics, impacts marine turtle reproductive ecology, though population-level impacts remain unclear (Duncan and others, 2021; Fuentes and others, 2023). Habitat loss due to oil and gas developments (Nelms and others 2016), renewable energy technologies (Maxwell and others, 2022), and seabed mining (Williams and others, 2022) continues to threaten marine turtles. Coastal artificial lighting disorients marine turtle hatchlings and deters nesting females (Leader and others, 2024).

however, species-specific guidelines to mitigate these impacts have been developed (e.g., CMS International Light Pollution Guidelines). Oil spills have caused mass mortalities of sea snakes in the Gulf of Oman (Yaghmour and others, 2022). Marine iguanas face threats from habitat degradation (Pizzitutti and others, 2017; Walsh and Mena, 2016), oil spills (Wikelski and others, 2002), alien species (Wikelski and Nelson, 2004), and tourism-induced stress (French and others, 2010; See Chapter 5A.4). Plastic pollution has emerged as a serious threat to marine iguana populations through ingestion and entanglement (Muñoz-Pérez and others, 2023). Saltwater crocodile nesting habitats are increasingly threatened by urban encroachment, sand mining, aquaculture, and coastal agriculture (Fukuda and others, 2022).

4.4f.3.3. Climate change associated impacts

Climate change threatens marine turtles by reducing nesting habitat and reproductive success, with warmer nest temperatures leading to more female hatchlings than males (Patrício and others, 2021). Impacts from altered reproductive periodicity, reduced foraging quality, and range shifts, are also anticipated (Fuentes and others, 2023). However, nesting populations farther from the equator show greater resilience to temperature increases (Laloë and Hays, 2023). Sea level rise poses a major threat to saltwater crocodiles, particularly coastal mound-nesting populations (Fukuda and others, 2022). Marine iguanas are vulnerable to climate fluctuations, especially during strong El Niño years when increased water temperatures reduce the abundance of marine algae, their primary food source (Dueñas and others, 2021). The frequency of climate fluctuation events is predicted to increase due to climate change, further threatening marine iguana survival and reproductive success (Cai and others, 2014; MacLeod and others, 2020a).

4.4f.4. Key knowledge and capacity gaps

4.4f.4.1. Marine turtles

Data gaps persist for Loggerhead, Green, Leatherback, Hawksbill, and Olive Ridley turtles across various RMUs (Wallace and others, 2025~~in press~~). Variability in subpopulation status and threats require ongoing species and regional assessments. Stock-assessment models are needed to understand the levels of mortality the population can sustain without declines (Putman and others, 2020). Greater understanding is needed of the effects of climate change on migratory patterns, cumulative impacts and the effectiveness of conservation strategies[17]. Standardised methods for plastic impact studies and for measuring sociocultural aspects of traditional turtle harvesting are also necessary (Poti and others, 2021). Further studies are needed to understand the benefits of by-catch management (Arlidge and others, 2020; Gilman and others, 2023), fishery closures, nesting beach management (e.g., nest shading), and hatchery practices (Phillott and others, 2021) for population recovery.

4.4f.4.2. Sea snakes

Most sea snake populations lack long-term monitoring, thus data on trends and distribution, as well as threats like by-catch, habitat degradation, and climate change is lacking (Udyawer and others, 2018). Rising ocean temperatures will affect sea snake physiology, reducing diving capacity and increasing mortality during incidental by-catch within trawl nets (Udyawer and others, 2016). Research shows shifts in sea snake assemblages due to unregulated fishing (Rao and others, 2021), but there are gaps in tracking population trends. A better understanding of national and international regulations on sea snake trade is needed for assessing actual global harvesting levels (Báez and others, 2024).

4.4f.4.3. Marine iguanas

The lack of long-term monitoring and the collection of census data for marine iguanas hinders evaluation of population trends and threats (Alava and others, 2023). Knowledge of plastic pollution impacts on population health is still lacking (Jones and others, 2021; Muñoz-Pérez and others, 2023). Galápagos experienced El Niño events in 2015/16 and 2023/24 (NOAA, 2022), climatic phenomena known to significantly impact iguana population health by increasing metabolic stress and reducing food availability (Varela-Jaramillo and others, 2023). While no census data exists for the 2015/16 event,

[17] CMS Parties adopted Resolution 12.21 (Rev.COP14) on Climate Change and Migratory Species, including a list of priority actions to address this issue.

drone-based surveys established before the latest El Niño event will allow for future assessment of population trends in response to El Niño events (Varela-Jaramillo and others, 2023).

4.4f.4.4. Saltwater crocodiles

Assessments of wild saltwater crocodile populations are lacking across much of their range, with basic population estimates absent in countries such as Brunei, Cambodia, Timor-Leste, and Indonesia. A growing number of human-crocodile conflicts (Baker and others, 2024) highlights the need for locally tailored management programs (Webb and others, 2021). The close link between the production and trade of crocodilian products in Southeast Asia underscores the need for coordinated management, conservation, and regulatory efforts. Captive breeding programs exist, but lack survival assessments, which would require reviews of restocking practices and release site protocols (Corey and others, 2018).

4.4f.5. References

Abreu-Grobois, A and P. Plotkin (2008). *Lepidochelys olivacea*. The IUCN Red List of Threatened Species 2008: e.T11534A3292503. https://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T11534A3292503.en.

Alava, J.J, and others (2023). Multiple anthropogenic stressors in the Galápagos Islands' complex social–ecological system: Interactions of marine pollution, fishing pressure, and climate change with management recommendations. *Integrated Environmental Assessment and Management* 19(4), 870–95. https://doi.org/10.1002/ieam.4661.

Amarasinghe, T.A.A., and others (2015). Human-crocodile conflict and conservation implications of Saltwater Crocodiles *Crocodylus porosus* (Reptilia: Crocodylia: Crocodylidae) in Sri Lanka. *Journal of Threatened Taxa*, 7(5), 7111-7130.

Arendt, M.D., and others (2023). Climate-mediated population dynamics for the world's most endangered sea turtle species. *Science Reports* 13, 14444. https://doi.org/10.1038/s41598-023-41647-8

Arlidge, W.N.S., and others (2020). A mitigation hierarchy approach for managing sea turtle captures in small-scale fisheries. *Frontiers in Marine Science*, 7, 49. https://doi.org/10.3389/fmars.2020.00049

~~Auliya, M., and others (2024). Challenges of regulating commercial use of marine elapid snakes in the Indo-Pacific. *Conservation Biology*, 38, e14336. https://doi.org/10.1111/cobi.14336~~

Báez, J.C., and others (2024). Specific marine policies are needed to prevent the extinction of marine reptiles. *Frontiers in Marine Science*, 11, 1416178. https://doi.org/fmars.2024.1416178

Baker, C.J., and others (2024). The influence of crocodile density on the prevalence of human attacks. *People and Nature*, 6, 1922–1932. https://doi.org/10.1002/pan3.10693

Bell, I.P., and others (2020). Twenty-eight years of decline: Nesting population demographics and trajectory of the north-east Queensland endangered hawksbill turtle (*Eretmochelys imbricata*). *Biological Conservation*, 241, 108376. https://doi.org/10.1016/j.biocon.2019.108376

Bessesen, B.L., and others (2022). Population abundance and density estimates for Costa Rica's endemic sea snake, *Hydrophis platurus xanthos*. *Frontiers in Marine Science* 9, 924966. https://doi.org/10.3389/fmars.2022.924966

Bessesen, B.L., and others (2024). *Hydrophis platurus* ssp. *xanthos*. The IUCN Red List of Threatened Species 2024: e.T239753560A239753681. https://www.iucnredlist.org/species/239753560/239753681

Brackhane, S., and others (2019). Crocodile management in Timor-Leste: Drawing upon traditional ecological knowledge and cultural beliefs. *Human Dimensions of Wildlife*, 24(4), 314–331. https://doi.org/10.1080/10871209.2019.1614240

Cai, W., and others (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4, 111–116. https://doi.org/10.1038/nclimate2100

Cao, N.V., and others (2014). Sea snake harvest in the Gulf of Thailand. *Conservation Biology*, 28, 1677-1687. https://doi.org/10.1111/cobi.12387

Casale, P. and A. D. Tucker (2017). *Caretta caretta* (amended version of 2015 assessment). The IUCN Red List of Threatened Species 2017: e.T3897A119333622. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T3897A119333622.en

Casale, P., and others (2018). Mediterranean sea turtles: Current knowledge and priorities for conservation and research. *Endangered Species Research*, 36, 229–267. https://doi.org/10.3354/esr00901

Ceriani, S.A., and others (2019). Conservation implications of sea turtle nesting trends: Elusive recovery of a globally important loggerhead population. *Ecosphere*, 10(11), e02936. http://doi.org/10.1002/ecs2.2936

Chaloupka, M.Y. and N.L. Pilcher (2019). *Chelonia mydas* (Hawaiian subpopulation). The IUCN Red List of Threatened Species 2019: e.T16285718A142098300. https://dx.doi.org/10.2305/IUCN.UK.2019-2.RLTS.T16285718A142098300.en

Colman, L.P., and others (2019). Thirty years of leatherback turtle *Dermochelys coriacea* nesting in Espírito Santo, Brazil, 1988-2017: reproductive biology and conservation. *Endangered Species Research*, 39, 147-158. https://doi.org/10.3354/esr00961

Corey, B., and others (2018). Commercial harvests of saltwater crocodile *Crocodylus porosus* eggs by Indigenous people in northern Australia: Lessons for long-term viability and management. *Oryx*, 52(4), 697-708. http://doi.org/10.1017/S0030605317000217

CITES. (1994). Maintenance of the Indonesian population of Saltwater Crocodiles (*Crocodylus porosus*) on Appendix II of CITES pursuant to Resolution Conf. 3.15 throughout Indonesia. Ninth meeting of the Conference of the Parties, Fort Lauderdale, USA, 7-18 November 1994

CITES. (2022). CoP19 Proposition 12 – transfer of the Philippine population of saltwater crocodiles (*Crocodylus porosus*) in Palawan Islands, Philippines from Appendix I to Appendix II, with a zero export quota for wild specimens, in accordance with Conference Resolution 9.24 (Rev. CoP17). Nineteenth meeting of the Conference of the Parties, Panama City, Panama, 14–25 Nov 2022

Dalleau, M., and others, eds. (2020). Sea Turtles in the East Africa and the West Indian Ocean Region: MTSG Annual Regional Report 2020. Report of the IUCN-SSC Marine Turtle Specialist Group. https://static1.squarespace.com/static/5e4c290978d00820618e0944/t/5fc53511fa04221c71c8fca4/1606759713452/MTSG+Regional+Report_East+Africa+%26+West+Indian+Ocean_2020.pdf

de la Hoz Schilling, C. and others (2023). Nowhere to hide: Sea turtle bycatch in Northwest Africa. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 33(10), 1131-1153. https://doi.org/10.1002/aqc.3983

Dueñas, A., and others (2021). The effects of climate change on wildlife biodiversity of the Galapagos Islands. *Climate Change Ecology*, 2, 100026. https://doi.org/10.1016/j.ecochg.2021.100026

Duncan, E.M., and others (2021). Plastic pollution and small juvenile marine turtles: A potential evolutionary trap. *Frontiers in Marine Science*, 8, 699521. https://doi.org/10.3389/fmars.2021.699521

Dunstan, A., and others (2020). Use of unmanned aerial vehicles for mark-resight nesting population estimation of adult female green sea turtles at Raine Island. *PLOS One*, 15(6), e0228524. https://doi.org/10.1371/journal.pone.0228524

Edgar, G.J., and others (2020). Establishing the ecological basis for conservation of shallow marine life using Reef Life Survey. *Biological Conservation*, 252, 108855. https://doi.org/10.1016/j.biocon.2020.108855

Ferreira-Airaud, B., and others (2022). The sea turtles of São Tomé and Príncipe: Diversity, distribution, and conservation status. In: *Biodiversity of the Gulf of Guinea Oceanic Islands: Science and Conservation* Eds: L.M.P Ceríaco, R.F. de Lima, M. Melo & R.C. Bell. Springer Nature, Switzerland, pp 535-553.

Figueroa, A., and others (2023). Singapore's herpetofauna: updated and annotated checklist, history, conservation, and distribution. *Zootaxa*, 5287(1), 1–378. https://doi.org/10.11646/zootaxa.5287.1.1

French, S.S., and others (2010). Human disturbance alters endocrine and immune responses in the Galapagos marine iguana (*Amblyrhynchus cristatus*). *Hormones and Behavior*, 58(5), 792-799. https://doi.org/10.1016/j.yhbeh.2010.08.001

Fretey, J., and others (2023). From terra incognita to hotspot: The largest South Pacific green turtle nesting population in the forgotten reefs of New Caledonia. *Oryx*, 57(5), 626-636. https://dx.doi.org/10.1017/S0030605323000108

Fuentes, M.M.P.B., and others (2023). Key issues in assessing threats to sea turtles: Knowledge gaps and future directions. *Endangered Species Research,* 52, 303-341. https://doi.org/10.3354/esr01278

~~Fuentes, M.M.P.B., and others (2024). Adaptation of sea turtles to climate warming: Will phenological responses be sufficient to counteract changes in reproductive output?. *Global Change Biology*, 30(1), e16991. https://doi.org/10.1111/gcb.16991~~

Fukuda, Y., and others (2020). Harvesting predators: Simulation of population recovery and controlled harvest of Saltwater Crocodiles *Crocodylus porosus*. *Wildlife Research*, 48(3), 252-263. https://doi.org/10.1071/WR20033

Fukuda, Y., and others (2022). Lost to the sea: Predicted climate change threats to Saltwater Crocodile nesting habitat. *Frontiers in Ecology and Evolution,* 10, 839423. https://doi.org/10.3389/fevo.2022.839423

Gilman, E., and others (2023). Bycatch-neutral fisheries through a sequential mitigation hierarchy. *Marine Policy*, 150, 105522. https://doi.org/10.1016/j.marpol.2023.105522

Good, S.D., and others (2024). Adapting the Marine Stewardship Council risk-based framework to estimate impacts on seabirds, marine mammals, marine turtles and sea snakes. *Marine Policy*, 163, 106118. https://doi.org/10.1016/j.marpol.2024.106118

Griffiths, S.P., and others (2024). Vulnerability of the Critically Endangered leatherback turtle to fisheries bycatch in the eastern Pacific Ocean. II. Assessment of mitigation measures. *Endangered Species Research*, 53, 295-326. https://doi.org/10.3354/esr01305

Gulick, A.G., and others (2022). Trends in abundance and reproductive success of the hawksbill turtle nesting population at Buck Island Reef National Monument, St. Croix, US Virgin Islands. *Endangered Species Research*, 48, 191-198. https://doi.org/10.3354/esr01199

Hays, G.C., and others (2024). A pulse check for trends in sea turtle numbers across the globe. *iScience*, 27, 109071. https://doi.org/10.3389/fevo.2022.839423

Hudgins, J.A., and others (2023). A brighter future? Stable and growing sea turtle populations in the Republic of Maldives. *PLoS One*, 18, e0283973. https://doi.org/10.1371/journal.pone.0283973

Jones, J.S., and others (2021). Plastic contamination of a Galapagos Island (Ecuador) and the relative risks to native marine species. *Science of The Total Environment,* 789, 147704. https://doi.org/10.1016/j.scitotenv.2021.147704

Kar, S. (2024). Fifty years of successful implementation of estuarine crocodile conservation and research programme in Bhitarkanika National Park, Odisha, India: An analysis. *Crocodile Specialist Group Newsletter*, 43(3), 10-17.

Kwan, L. (2017). Crocodile spotted in Klang River. Retrieved from http://www.worldofbuzz.com/crocodile-spotted-klang-river/.

Laloë, J.-O., and G.C. Hays (2023). Can a present-day thermal niche be preserved in a warming climate by a shift in phenology? A case study with sea turtles. *Royal Society Open Science*, 10(2), 221002. https://doi.org/10.1098/rsos.221002

Leader, N., and others (2024). Artificial light at night on nesting beaches of the green turtle, *Chelonia mydas*, in the eastern Mediterranean and its possible effect on populations. *Turkish Journal of Zoology*, 48(4), 203–210. https://doi.org/10.55730/1300-0179.3176

Lewison, R. L., and others (2014) Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences*, 111:5271−5276. https://doi.org/10.1073/pnas.131896011

López-Castro, M.C, and others (2022a). Trends in reproductive indicators of green and hawksbill sea turtles over a 30-Year monitoring period in the southern Gulf of Mexico and their conservation implications. *Animals*, 12, 3280. https://doi.org/10.3390/ani12233280

MacLeod, A., and S. Steinfartz (2016). The conservation status of the Galápagos marine iguanas, *Amblyrhynchus cristatus*: A molecular perspective. *Amphibia-Reptilia*, 37(1), 91-109. https://doi.org/10.1163/15685381-00003035

MacLeod, A., and others (2020a). *Amblyrhynchus cristatus* (errata version published in 2020). The IUCN Red List of Threatened Species 2020: e.T1086A177552193. https://dx.doi.org/10.2305/IUCN.UK.2020-2.RLTS.T1086A177552193.en

MacLeod, A., and others (2020b). *Amblyrhynchus cristatus* ssp. *cristatus* (errata version published in 2020). The IUCN Red List of Threatened Species 2020: e.T152328291A177563889. https://dx.doi.org/10.2305/IUCN.UK.2020-2.RLTS.T152328291A177563889.en

Manolis, C. (2005). Long-distance movement by a Saltwater Crocodile. *Crocodile Specialist Group Newsletter*, 24(4), 18.

Marco, A., and others (2020). Sea turtle bycatch by different types of fisheries in southern Spain. *Basic and Applied Herpetology*, 34, 33-45. https://doi.org/10.11160/bah.187

Maxwell S.M., and others (2022). Potential impacts of floating wind turbine technology for marine species and habitats. *Journal of Environmental Management*, 307, 114577. https://doi.org/10.1016/j.jenvman.2022.114577

Miralles, A., and others (2017). Shedding light on the Imps of Darkness: An integrative taxonomic revision of the Galápagos marine iguanas (genus *Amblyrhynchus*). *Zoological Journal of the Linnean Society*, 181(3), 678–710. https://doi.org/10.1093/zoolinnean/zlx007

Mortimer, J.A and M. Donnelly eds. (2008). *Eretmochelys imbricata.* The IUCN Red List of Threatened Species 2008: e.T8005A12881238. https://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T8005A12881238.en

Mortimer, J.A., and others (2020). Estimates of marine turtle nesting populations in the south-west Indian Ocean indicate the importance of the Chagos Archipelago. *Oryx*, 54, 332-343. https://doi.org/10.1017/S0030605319001108

Muñoz-Pérez JP, and others (2023). Galápagos and the plastic problem. *Frontiers in Sustainability*, 4, 1091516. https://doi.org/10.3389/frsus.2023.1091516

Nalovic, M., and others. eds. (2018). Sea Turtles in the North-West Atlantic & Caribbean Region MTSG Regional Report. Report of the IUCN-SSC Marine Turtle Specialist. Group.https://static1.squarespace.com/static/5e4c290978d00820618e0944/t/5e4d93350c9a2e591ab353df/1582142262640/mtsg-annual-regional-report-2018_nw-atlantic-caribbean.pdf

Nelms, S. E., and others (2016). Seismic surveys and marine turtles: An underestimated global threat? *Biological Conservation*, 193, 49–65. https://doi.org/10.1016/j.biocon.2015.10.020

NOAA (2022). Climate Prediction Center. Retrieved from: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Parke, E. (2015). Kimberley crocodile numbers triple in biggest survey in three decades. Retrieved from: http://www.abc.net.au/news/2015-08-16/biggest-croc-survey-in-30-years-shows-numbers-havetripled/6699532.

Patrício, A.R., and others (2021). Climate change and marine turtles: recent advances and future directions. *Endangered Species Research*, 44,363-395. https://doi.org/10.3354/esr01110

Phillott, A.D., and A.F. Rees. eds. (2021). Sea Turtles in the Middle East and South Asia Region: MTSG Annual Regional Report 2021. Report of the IUCN-SSC Marine Turtle Specialist Group. https://static1.squarespace.com/static/5e4c290978d00820618e0944/t/6202b7a3558d77165b8d82f1/1644345273467/MTSG-RR_Middle-East-South-Asia_2021.pdf

Phillott, A.D., and others (2021). Are sea turtle hatcheries in India following best practices? *Herpetological Conservation and Biology*, 16, 652-670. https://www.herpconbio.org/Volume_16/Issue_3/Phillott_etal_2021.pdf

Pizzitutti, F., and others (2017). Scenario planning for tourism management: A participatory and system dynamics model applied to the Galapagos Islands of Ecuador. *Journal of Sustainable Tourism*, 25, 1117–1137. https://doi.org/10.1080/09669582.2016.1257011

Platt, S.G., and others (2015). Marine turtles and estuarine crocodiles in Lampi Marine National Park, Myanmar: A conservation and threat assessment with recommendations. *Herpetological Review*, 46, 319-327.

Poti, M., and others (2021). Changing trends and perceptions of sea turtle egg consumption in Redang Island, Malaysia. *Ecology and Society*, 26, 14. https://doi.org/10.5751/ES-12717-260414

Putman, N.F., and others (2020). Managing fisheries in a world with more sea turtles. *Proceedings of the Royal Society B*, 287, 20200220. http://dx.doi.org/10.1098/rspb.2020.0220

Rao, C., and others (2021). Fisheries induced shift in sea snake community assemblages along the Konkan coast, India. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31, 2402– 2411. https://doi.org/10.1002/aqc.3658

Restrepo, J., and others (2023). Recent decline of green turtle *Chelonia mydas* nesting trend at Tortuguero, Costa Rica. *Endangered Species Research,* 51, 59-72. https://doi.org/10.3354/esr01237

Saalfeld, K., and others (2016). Management Program for the Saltwater Crocodile (*Crocodylus porosus*) in the Northern Territory of Australia, 2016-2020. Northern Territory Department of Environment and Natural Resources: Darwin.

Saragih, G., and others (2020). A preliminary study on the population and habitat of Saltwater Crocodile (*Crocodylus porosus*) in Timor Island, East Nusa Tenggara. IOP Publishing, p. 012044.

Savoca, M. S., and others (2020). Comprehensive bycatch assessment in US fisheries for prioritizing management. *Nature Sustainability*, 3(6), 472-480. https://doi.org/10.1038/s41893-020-0506-9

Schuyler, Q., and others (2021). Chapter 6E Marine Reptiles In *The Second World Ocean Assessment: World Ocean Assessment II (Volume 1)*. United Nations, New York. pp 198 – 209. https://www.un.org/regularprocess/sites/www.un.org.regularprocess/files/2011859-e-woa-ii-vol-i.pdf

Segniagbeto G.H., and others (2017). Sea turtle bycatch analysis revealed that site influenced mortality more than net types along the coast of Togo. *Vie et Milieu – Lide and Environment*, 67(3-4), 227-234.

~~Seminoff, J.A. (2023). *Chelonia mydas* (amended version of 2004 assessment). The IUCN Red List of Threatened Species 2004: e.T4615A247654386. https://dx.doi.org/10.2305/IUCN.UK.2023-1.RLTS.T4615A247654386.en~~

Senko, J.F., and others (2022). Global patterns of illegal marine turtle exploitation. *Global Change Biology*, 28, 6509-6523. https://doi.org/10.1111/gcb.16378

Shimada, T., and others (2021). Distribution and temporal trends in the abundance of nesting sea turtles in the Red Sea. *Biological Conservation*, 261, 109235. https://doi.org/10.1016/j.biocon.2021.109235

Shine, R., and others (2021). Population dynamics of the sea snake *Emydocephalus annulatus* (Elapidae, Hydrophiinae). *Scientific Reports,* 11, 20701. https://doi.org/10.1038/s41598-021-00245-2

Solmu, G., and others (2014). The ecological status of the *C. porosus* and *C. novaeguineae* wild populations trends in Papua New Guinea, 1981-2014. In *Proceedings of the 23rd Working Meeting of the IUCN-SSC Crocodile Specialist Group* (pp. 317-324). IUCN: Gland, Switzerland.

Somaweera, R., and others (2021). Pinpointing drivers of extirpation in sea snakes: A synthesis of evidence from Ashmore Reef. *Frontiers in Marine Science*, 8(559), 658756. https://doi.org/10.3389/fmars.2021.658756

Speed, C. W., and others (2022). Video surveys of sea snakes in the mesophotic zone shed light on trends in populations. *Frontiers in Marine Science*, 9, 921542. https://doi.org/10.3389/fmars.2022.921542

Summers, T.M., and others (2018). Endangered green turtles (*Chelonia mydas*) of the northern Mariana Islands: Nesting ecology, poaching, and climate concerns. *Frontiers in Marine Science*, 4, 428. https://doi.org/10.3389/fmars.2017.00428

Than, K.Z., and others (2024). Biodiversity conservation in Myanmar's coastal wetlands: Focusing on Saltwater Crocodile habitats and connectivity. *Biological Conservation*, 289, 110396. https://doi.org/10.1016/j.biocon.2023.110396

The Laúd OPO Network (2020). Enhanced, coordinated conservation efforts required to avoid extinction of critically endangered Eastern Pacific leatherback turtle. *Scientific Reports*, 10, 4772. https://doi.org/10.1038/s41598-020-60581-7

Touron, M., and others (2018). Final report on the green sea turtle egg-laying season of 2017-2018 (*Chelonia mydas*) on the atoll of Tetiaroa, French Polynesia. Te mana o te moana. p. 54. https://www.temanaotemoana.org/wp-content/uploads/2019/03/EN_2017_2018S_Green_sea_turtles_nesting_sites_Tetiaroa_FINAL_REPORT.pdf

Udyawer, V., and others (2016). Coming up for air: thermal-dependence of dive behaviours and metabolism in sea snakes. *The Journal of Experimental Biology*, 219, 3447-3454. https://doi.org/10.1242/jeb.146571

Udyawer, V., and others (2018). Future directions in the research and management of marine snakes. *Frontiers in Marine Science*, 5, 399. https://doi.org/10.3389/fmars.2018.00399

Valdivia, A., and others (2019). Marine mammals and sea turtles listed under the US Endangered Species Act are recovering. *PloS One*, 14(1), e0210164. https://doi.org/10.1371/journal.pone.0210164

Van der Ploeg, J., and others (2019). Human-crocodile conflict in Solomon Islands. Penang, Malaysia: WorldFish. Program Report: 2019-02.

Varela-Jaramillo, A., and others (2023). A pilot study to estimate the population size of endangered Galápagos marine iguanas using drones. *Frontiers in Zoology*, 20, 4. https://doi.org/10.1186/s12983-022-00478-5

~~Wallace, B.P., and others (2013a). *Dermochelys coriacea*. The IUCN Red List of Threatened Species 2013: e.T6494A43526147. https://dx.doi.org/10.2305/IUCN.UK.2013-2.RLTS.T6494A43526147.en~~

Wallace, B.P., and others (2013~~b~~). Impacts of fisheries bycatch on marine turtle populations worldwide: toward conservation and research priorities. *Ecosphere*, 4(3), 40. http://dx.doi.org/10.1890/ES12-00388.1

Wallace B.P, and others (2016). Chapter 39 Marine Reptiles In *The First Global Integrated Marine Assessment: World Ocean Assessment I*. United Nations, New York. pp 14. https://www.un.org/depts/los/global_reporting/WOA_RPROC/Chapter_39.pdf

~~Wallace B.P., and others (2020). Oil spills and sea turtles: Documented effects and considerations for response and assessment efforts. *Endangered Species Research,* 41, 17–37. https://doi.org/10.3354/esr01009~~

Wallace, B.P., and others (2023). Marine turtle regional management units 2.0: An updated framework for conservation and research of wide-ranging megafauna species. *Endangered Species Research*, 52, 209-223. https://doi.org/10.3354/esr01243

Wallace, B.P. and others. (2025~~in press)~~. Updated global conservation status and priorities for marine turtles. *Endangered Species Research*, 56, 247-276. https://doi.org/10.3354/esr01385

Walsh, S.J., and C. F. Mena (2016). Interactions of social, terrestrial, and marine sub-systems in the Galapagos Islands, Ecuador. *Proceedings of the National Academy of Sciences*, 113, 14536–14543. https://doi.org/10.1073/pnas.1604990113

Webb, G.J.W., and others (2018). Saltwater Crocodile *Crocodylus porosus*. In: Manolis, S.C. and Stevenson, C. (eds.), *Crocodiles*. Status Survey and Conservation Action Plan. Fourth Edition, pp. 20. Crocodile Specialist Group: Darwin.

Webb, G.J.W., and others (2021). *Crocodylus porosus*. The IUCN Red List of Threatened Species 2021: e.T5668A3047556. https://dx.doi.org/10.2305/IUCN.UK.2021-2.RLTS.T5668A3047556.en

Wibbels, T., and E. Bevan (2019). *Lepidochelys kempii* (errata version published in 2019). The IUCN Red List of Threatened Species 2019: e.T11533A155057916. https://dx.doi.org/10.2305/IUCN.UK.2019-2.RLTS.T11533A155057916.en

Wikelski, M., and others (2002) Marine iguanas die from trace oil pollution. *Nature*, 417, 607–608. https://doi.org/10.1038/417607a

Wikelski, M. and K. Nelson (2004) Conservation of Galápagos Marine Iguanas (*Amblyrhynchus cristatus*). *Iguana*, 11(4), 190–197. https://journals.ku.edu/iguana/article/view/17148

Wildlife Management International (2018). Results of Spotlight and Helicopter Surveys of Crocodiles in Cambridge Gulf, Lake Argyle and Lake Kunnunurra, 2008. Unpublished report to WA Department of Environment and Conservation, Perth.

Williams, and others, (2022). Noise from deep-sea mining may span vast ocean areas. *Science* 377,157-158. https://doi.org/10.1126/science.abo2804

Yaghmour, F., and others (2022). Oil spill causes mass mortality of sea snakes in the Gulf of Oman. *Science of The Total Environment*, 825, 154072. https://doi.org/10.1016/j.scitotenv.2022.154072

Section 4

Sub-chapter 4g: Seabirds

Contributors: Maria Dias (coordinating author), Martin Beal, Stephanie Borrelle, Tammy Davies, Esteban Frere, Carolina Hazin, Jana Jeglinski, Patricia Serafini, Ross Wanless

Keynote points

- Seabirds remain one of the most threatened species group at the global level, with thirty-one per cent considered threatened with extinction;
- Invasive alien species and incidental fisheries by-catch remain among the major threats to seabird species and the number of species affected by these threats increased since WOA II;
- Seabirds are increasingly facing the impacts of emerging processes, such as outbreaks of Highly Pathogenic Avian Influenza (HPAI)~~avian influenza~~, the development of offshore wind farms and the increase in plastic and light pollution;
- Research priorities include understanding the population trends and at-sea distribution of burrow-nesters (such as storm-petrels and other small petrels) and understanding the population-level effects of cumulative threats.

Introduction and context

Seabirds, bird species that depend on marine ecosystems for at least part of the year, are either top predators or skilled scavengers that play important roles in marine food webs (Brooke, 2004). They are found in all oceans, from coastal waters to the high seas. Although most seabirds are restricted to surface waters, they interact with other marine species living at different depth-layers, from the epi-pelagic to the meso- and bathypelagic zones (e.g. by preying upon marine animals such as fish, squid or crustaceans, or by foraging in association with marine mammals). There are currently 366 extant seabird species recognized, across nine different orders (Table 1). Many species are migratory and travel great distances from their breeding colonies to their foraging grounds. For this reason, seabirds are recognized as key biological vectors of nutrients, which they collect from large wide oceanic areas and concentrate at their colonies (Graham and others, 2018; Benkwitt and others, 2022).

Seabirds are relatively well studied compared to other marine species, allowing for the compilation of extensive information on their conservation status, population trends and main threats, with global assessments led by BirdLife International (Croxall and others, 2012; Dias and others, 2019). These studies have revealed that seabirds are severely impacted by human activities worldwide, with 31% per cent of species threatened with extinction and 57 per cent with declining population trends (Table 4.4g.1).

Changes in the status of seabirds since WOA II

An overview of the conservation status of seabird species in 2024 is provided in Table 4.4g.1 (BirdLife International, 2024). The procellariiforms (tubenoses such as albatrosses and petrels) are the largest group of seabirds and have the highest number of globally threatened ('critically endangered', 'endangered' and 'vulnerable') and near-threatened species of any vertebrate group, according to the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species. Sphenisciformes, i.e. penguins, stand out as the group with the highest percentage of threatened species (50 per cent), and of declining population trends (excluding the tropical birds and grebes, which have few species) (Table 4.4g.1).

The overall conservation status of seabirds (measured as the percentage of species classified as threatened by the IUCN) has remained relatively stable since WOA II (30.8 per cent and 30.6 per cent, respectively). However, an improving trend is reflected in the slight decrease in the percentage of threatened species in some groups (Figure 4.4g.1) and in the decrease in the number of "uplisted" species between 2018 and 2024 (Table 4.4g.2). Six species were uplisted (i.e., their conservation status has deteriorated) between 2021 and 2025 (an average of 1 species per year), while 28 species were uplisted between 2010 and 2018 (an average of 3.5 per year). However, these numbers should be interpreted with caution, as changes can be due to improved knowledge (e.g. taxonomy changes; new colonies found) rather than a genuine change in status. In fact, the percentage of species with declining population trends has increased since the last assessment, from 47per cent (Dias and others, 2019) to 57per cent (Table 4.4g.1). It should be also noted that the last assessment of the IUCN Red List status of most seabird species was carried out before the recent outbreaks of ~~High Pathogenicity Avian Influenza~~Highly Pathogenic Avian Influenza (HPAI), which caused the mortality of significant proportions of the populations in some seabird colonies (e.g. Falchieri and others, 2022; Leguia and others, 2023).

Changes in pressures since WOA II

The main threats affecting seabird populations are well known and can mostly be attributed to human activities in both marine and terrestrial habitats (Section 4, Chapter 5) (Dias and others, 2019). At sea, the fisheries sector has been have been the main cause of population declines (Figure 4.4g.2), in particular the incidental capture of seabirds in fishing gear (incidental bycatch) and prey depletion due to overfishing (Votier and others, 2023; Phillips and others, 2024) (Section 5A) , followed by pollution. At colonies, the introduction of invasive species (Section 4, Chapter 6) is causing severe declines, particularly for species that breed on isolated islands (e.g. predation by cats and rodents,

habitat degradation by introduced herbivores; e.g. Spatz and others, 2017). Another ongoing threat at colonies is the direct harvest of eggs, chicks or adult birds for human consumption (e.g. Dias and others, 2019). The number of threatened species affected by these pressures has increased since the first WOA assessment (Figure 4.4g.2).

In addition, seabirds increasingly face emerging threats, such as the development of offshore wind farms (Section 4, Chapter 6 and Section 5A), the increase in plastic and light pollution (Section 4, Chapter 6 and Section 5A) and the spread of highly lethal diseases such as avian influenza (Phillips and others, 2023). As numerous studies have reported the negative impacts of these emerging threats since the WOA II, the following paragraphs focus on them, along with updated information since WOA II on fisheries bycatch and prey depletion.

Pollution (special focus on plastics and light)

Seabirds continue to be affected by pollution from marine and terrestrial sources (Lavers and others, 2014; Provencher and others, 2019; Clark and others, 2023). While reductions in oil spills affecting seabird species have been noted (Dias and others, 2019), plastic pollution remains a threat to many seabirds through ingestion and toxic chemical release (Provencher and others, 2018; Hamilton and others, 2023; Navarro and others, 2023; Vanstreels and others, 2023). Seabirds foraging in the Mediterranean and Black seas are at particularly high risk of exposure to plastic pollution, although data is still lacking to evaluate the risk of encountering and ingesting plastic in other regions with high levels of plastic pollution, such as the coastal waters around East and Southeast Asia and the South Pacific and North Atlantic gyres (Clark and others, 2023).
Sub-lethal responses of seabirds to plastics have begun to be explored (e.g. Charlton-Howard and others, 2023; Kreitsberg and others, 2023; Serafini and others, 2024). However, the consequences of plastic ingestion and associated chemical contamination at the population level are still poorly understood.
Light pollution poses a significant risk to some species near colonies and marine structures through disorientation, collision or grounding, which can result in injury or mortality (Rodríguez, 2023). In contrast, the effects of light pollution at sea (e.g., from ships, offshore infrastructure, light-attracting fisheries) are poorly documented. Mitigating these effects requires large-scale reduction and management of light pollution sources.

Offshore windfarm development

The demand for renewable sources of energy is leading to an exponential increase in the development of offshore wind farms (OWF). Seabirds are particularly vulnerable to these

and can be affected directly by collision with turbines and indirectly through habitat loss due to displacement effects (e.g. Dierschke and others, 2016). Of particular concern is the potential cumulative impact of multiple facilities, especially for migratory species that travel hundreds or thousands of kilometres per year. Recent studies have assessed this concern (e.g. Goodale and others, 2019; Garthe and others, 2023), although the vast majority of these are limited to relatively small regions often located in northern countries (Europe and North America) and focus on breeding species. Potential impacts of OWFs on migrating seabirds (via the barrier effect, i.e., when the wind farms cause an obstacle to the regular movement of the birds) are still poorly understood.

Highly Pathogenic Avian Influenza~~High Pathogenicity Avian Influenza~~

~~High Pathogenicity Avian Influenza~~Highly Pathogenic Avian Influenza (HPAI) has emerged as a new threat with serious implication for seabirds on a global scale. In contrast to low pathogenicity avian influenza (LPAI) which circulate asymptomatically in waterbirds (Gass and others, 2023), HPAI causes severe illness and high mortality. Prior to 2017, positive HPAI cases in seabirds were localized and sporadic and the overall prevalence of active infection was considered very low (Lang and others, 2016). However, in 2017 the Goose/Guangdong (Gs/GD) avian influenza lineage clade 2.3.4.4.b H5N8 caused mass die-offs of coastal seabird species, such as terns and African penguins (*Spheniscus demersus*) along the southern South African coasts (Peyrot and others, 2022) and was confirmed in 15 seabird species by 2018. It then reappeared in 2021 (Roberts and others, 2023), when the HPAI sub-clade 2.3.4.4.b H5N1 caused mass die-offs of Great Skuas (*Stercorarius skua*) in Scotland (Banyard and others, 2022) and was dwarfed by the reemergence of H5N1 in early 2022, which spread throughout the North Atlantic, affecting at least 10 seabird species in Great Britain alone (Caliendo and others, 2022; Falchieri and others, 2022). In late 2022, H5N1 spread to South America and caused unprecedented mass die-offs of seabirds in Peru (Leguia and others, 2023), and in early 2023, HPAI spread to Chile and Uruguay, and worryingly jumped to marine mammals causing parallel mass die-offs (Ulloa and others, 2023). In late 2023, positive samples were detected in several bird species in the Antarctic region (Banyard and others, 2024).

In addition, the impact of HPAI appears to vary among species, with some being particularly affected (i.e., higher levels of mortality, or incidence at the colonies, when compared with other species), such as the northern gannets (*Morus bassanus*), common guillemots (*Uria aalge*), and the great skuas in the North Atlantic, as well as Peruvian pelicans (*Pelecanus thagus*) and Peruvian boobies (*Sula variegata*) in the southern Pacific (Banyard and others, 2022; Gamarra-Toledo and others, 2023; Lane and others, 2023; McPhail and others, 2024).

Fisheries bycatch and overfishing

Severe impacts of fishing activities on seabirds (due to birds getting caught as bycatch or to direct competition for food resources) have been highlighted since the WOA I. Following the WOA II, new studies have provided further detail on the magnitude of these impacts. A review of the impact of fisheries on seabirds by Voitier and others (2023) concluded that, although the problem of seabird by-catch was recognized in the late 1980s (Brothers, 1991), it continues to have significant impacts. Suggested avenues to address this threat include improved compliance monitoring of bycatch mitigation measures (including on small-scale fleets and with a special focus on less-known, poorly studied species and regions). Voitier and others (2023) also highlighted the urgent need to understand the combined effects of fisheries and other threats, in particular emerging issues such as climate change and offshore windfarms. Ramírez and others (2024) provided for the first time estimates of the number of seabirds bycaught annually in European waters (195,000 individual birds, ranging from 130,000 to 380,000). These authors pinpointed the Northeast Atlantic as the region with the highest bycatch, and gillnet fisheries as responsible for the highest bycatch levels, while highlighting significant knowledge gaps in the Eastern Atlantic, Mediterranean Sea and Black Sea.

Phillips and others (2024) reviewed the global incidental mortality of seabirds in trawl fisheries, conservatively estimating that 44,000 birds are caught every year, with albatrosses, large petrels and Northern gannets being the most affected species. The authors agreed with others, that the actual mortality is likely to be much higher, given the extent of cryptic mortality and poor or non-existent monitoring (Brothers and others, 2010).

The potential impact of mesopelagic fisheries on seabirds should also be regarded as an emerging concern (Dias and others, 2019). Mesopelagic species (i.e., those inhabiting depths of 200-1000 m) are considered as one of the most promising future human food resources (e.g. Webb and others, 2010) and several countries are exploring the viability of exploiting these species. Mesopelagic species potentially have enormous importance in the global ocean through a fundamental role in marine food webs and their function as biological carbon pumps, helping to mitigate climate change (e.g. St. John and others, 2016). Recent studies have shown that the diet of several seabird species– including members of the most threatened groups (e.g. procellariiformes and penguins; Wapp and others, 2017; Watanuki and Thiebot, 2018; Alho and others, 2022) is largely comprised of mesopelagic species, raising concerns about the potentially devastating consequences of unregulated mesopelagic fisheries on seabirds and broader marine biodiversity.

Responses to pressures on seabirds

Incidental fisheries by-catch remains one of the major threats to seabird species despite~~By-catch continues to be a major threat to seabird species, despite~~ decades of understanding of the nature of the problem, and the mandatory use of ~~highly effective~~ by-catch reduction measures by all tuna Regional Fisheries Management Organisations (RFMOs). This is particularly true for longline fisheries, which poses high risks to seabirds~~, even though compliance with these measures is reportedly high~~. Parties to other international multilateral instruments ~~(e.g. Convention on Biological Diversity)~~ have also committed to halt~~ing~~ adverse impacts on threatened species~~, from by-catch~~, including impacts attributed to fisheries bycatch (e.g. Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity). However, the global target has not yet been met (Secretariat of the Convention on Biological Diversity, 2020). Therefore, long-term responses to seabird conservation challenges, especially those related to cross-border and high seas threats, should focus on improved monitoring and compliance with bycatch mitigation measures by RFMO Members. For example, the Agreement on the Conservation of Albatrosses and Petrels (ACAP) has established a by-catch working group that evaluates current by-catch rates across fisheries, examines mitigation solutions, and provides best practice advice to RFMOs and others. It is recommended that RFMOs update their seabird bycatch mitigation requirements to reflect the current ACAP best practice advice. Additionally, the Commission for the Conservation of Southern Bluefin Tuna (CCSCBT) is implementing a multifaceted seabird conservation initiative funded by the Common Oceans Tuna Project (2023-2026) specifically targeting its members. Despite these efforts, the implementation of scientifically proven mitigation measures in RFMOs remains slow. Beyond fisheries, several intergovernmental organizations are funding seabird conservation projects and/or actively supporting national governments to implement actions tackling major threats. Examples include programs for controlling and eradicating invasive species (particularly mammalian predators such as cats and rodents) in key seabird colonies, as well as initiatives to minimize the impacts of light pollution. Furthermore, specific guidance has been provided by the Convention on the Conservation of Migratory Species of Wild Animals (CMS) on reducing known key pressures to seabirds such as light pollution (CMS Resolution 13.5, CMS International Light Pollution Guidelines for Migratory Species), avian influenza (CMS Resolution 14.18), climate change (CMS Resolution 12.21), disturbance (specially via tourism; International Guidelines for Sustainable Marine Wildlife Interactions: Boat-Based and In-Water Activities) and harvesting in West Africa (CMS Resolution 14.15, Action Plan to Address Aquatic Wild Meat Harvests in West Africa). Additionally, guidance has also been provided on conservation actions to reduce seabird vulnerability to climate change in the North-East Atlantic (Häkkinen and others, 2023) and on strategies to mitigate the impact of offshore wind farms on seabirds (Croll and others, 2022).

Knowledge gaps

Although seabirds are a relatively well-studied group of birds, there are still some major knowledge gaps. Some groups are poorly known due to their small sizes, nocturnal

behaviour and breeding habits (e.g. burrow-nesters such as storm-petrels and other small petrels), making population estimates and trends for most of these species unreliable. Another priority is to understand the population-level effects of pollution, overfishing, offshore wind farms and climate change; in addition to the cumulative effect of these threats and those causing direct mortality of seabirds (such as bycatch, predation by invasive species, diseases, hunting and egg harvesting). Regarding diseases, particular attention should be paid to managing the spread and impact of HPAI. Due to its novelty, ~~even the most~~ basic understanding of transmission dynamics and basic epidemiological characteristics (such as mortality rates and levels of post-infection immunity) is lacking in most regions, but these are critical for predicting the recovery and long-term viability of seabird populations.

Knowledge of seabird ecology comes still mostly from temperate and polar regions, while seabirds inhabiting tropical areas have received considerably less attention, particularly with respect to their at-sea distributions, especially in the Pacific Ocean (Carneiro and others, 2024).

Tables and Figures

Table 4.4g.1. Number of seabird species, in each IUCN Red List category in 2024, and percentage of species with declining population trends. Source: BirdLife International, 2024. EX = Extinct, CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern, DD = Data Deficient. Threatened species are those classified as CR, EN or VU. In parenthesis (column "Total"), is number of species with known population trends.

Seabird Order	EX	CR	EN	VU	NT	LC	DD	Threatened species* (CR+EN+VU)	Declining species **	Total
Procellariiformes (tubenoses)	2	17	20	29	20	57	3	46%	59%	148 (130)
Charadriiformes (gulls and auks)	1	1	4	11	10	95		13%	48%	122 (103)
Suliformes (gannets and boobies)	1	1	5	9	2	28		33%	61%	46 (36)
Anseriformes (sea ducks)	1			4	3	14		19%	67%	22 (18)
Sphenisciformes (penguins)			5	4	2	7		50%	71%	18 (17)
Gaviiformes (loons)					1	4		0%	60%	5 (5)
Podicipediformes (grebes)				1		3		25%	100%	4 (2)
Phaethontiformes (tropicbirds)						3		0%	100%	3 (3)
Pelecaniformes (pelicans)					1	2		0%	0%	3 (2)
Total	5	19	34	58	39	213	3	31%	57%	371 (316)

** The calculation of the percentage of threatened species excluded EX and DD species.*
*** Only species with known population trends were considered.*

1
2

Table 4.4g.2. Summary of changes in the IUCN Red List status of seabirds between 2018 and 2024* Source: Dias and others (2019) for 2018; BirdLife International (2024) for 2024. "Uplisting" means a worse conservation status in 2024 than in 2018, while "downlisting" means a better conservation status.

Seabird order	Uplisted**	Unchanged	Downlisted	Data deficient	Total
Procellariiformes (tubenoses)	3 (11)	130	5	2	140
Charadriiformes (gulls and auks)	2 (8)	115	3		120
Suliformes (gannets and boobies)	(2)	43	2		45
Anseriformes (sea ducks)	1 (5)	20			21
Sphenisciformes (penguins)	(1)	15	3		18
Gaviiformes (loons)		5			5
Podicipediformes (grebes)	(1)	4			4
Phaethontiformes (tropicbirds)		3			3
Pelecaniformes (pelicans)		3			3
Total	6 (28)	338	13	2	359

** Only included the 359 extant seabird species analysed in Dias and others (2019).*
*** In parenthesis, the number of uplisted species reported in WOA II.*

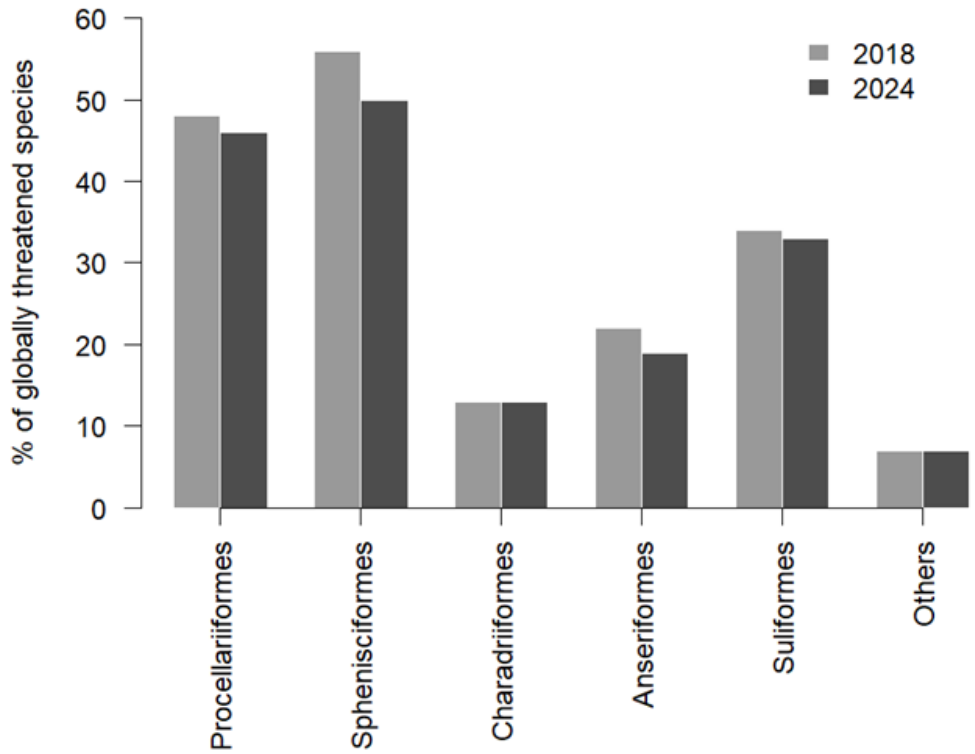


Figure 4.4g.1: Percentage of species categorized as globally threatened (i.e., CR, EN or VU, following IUCN classification), by seabird order, in 2018 (reported in WOA II) and in 2024 (WOA III). "Others" include the orders with 5 species or less (Gaviiformes, Phaethontiformes, Pelecaniformes and Podicipediformes; see Table 4.4g.1). Source: BirdLife International, 2024

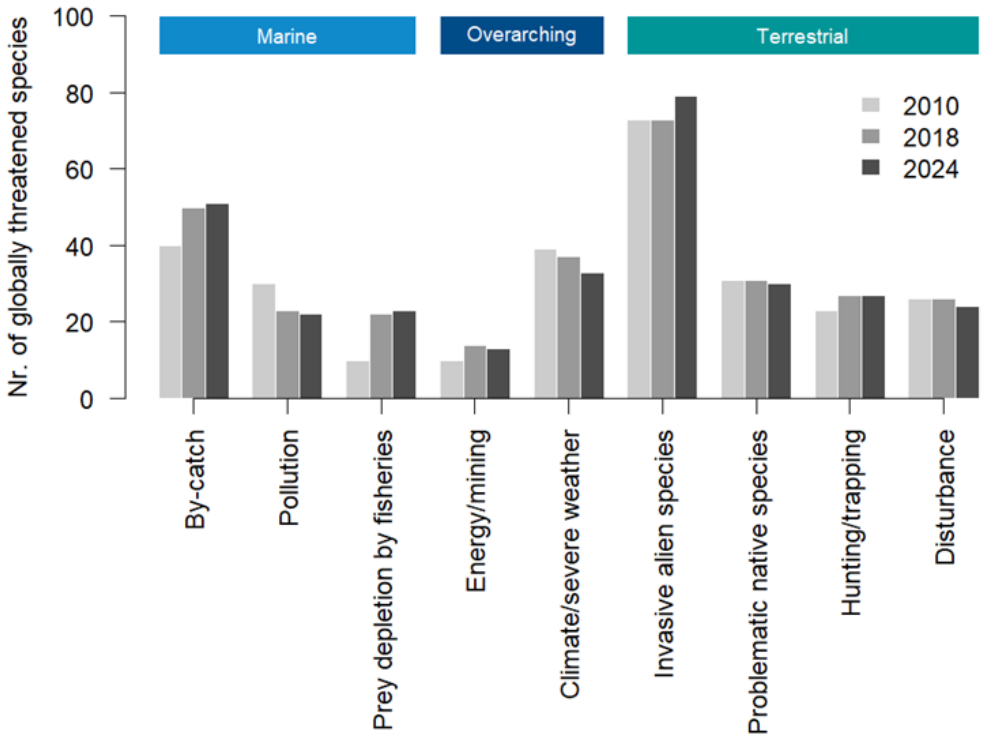


Figure 4.4g.2. Number of globally threatened seabird species negatively affected by marine, terrestrial and overarching processes in 2010, 2018 and 2024

References

Alho, Maria, and others. Revealing the foraging movements and diet of the White-faced Storm Petrel *Pelagodroma marina* in the NE Atlantic. Marine Biology, vol. 169, art. 91, 2022.

Banyard, Ashley C., and others. Detection of Highly Pathogenic Avian Influenza Virus H5N1 Clade 2.3.4.4b in Great Skuas: A Species of Conservation Concern in Great Britain. Viruses, vol. 14, No. 2, art. 212, 2022

Banyard, Ashley C., and others. Detection and spread of high pathogenicity avian influenza virus H5N1 in the Antarctic Region. Nature Communications, vol. 15, art. 7433, 2024

Benkwitt, Cassandra E., and others. Seabird diversity and biomass enhance cross-ecosystem nutrient subsidies. Proceedings of the Royal Society B, vol. 289, art. 20220195, 2022.

BirdLife International. IUCN Red List for birds. https://datazone.birdlife.org/home, 2024.

Brothers, Nigel, and others. Seabird bycatch in pelagic longline fisheries is grossly underestimated when using only haul data. PLoS One, vol. 5, No. 8, art. e12491, 2010.

Brooke, Michael de L. The food consumption of the world's seabirds. Proceedings of the Royal Society B, vol. 271, pp. S246–S248, 2004.

Caliendo, Valentina, and others. Transatlantic spread of highly pathogenic avian influenza H5N1 by wild birds from Europe to North America in 2021. Scientific Reports, vol. 12, art. 11729, 2022.

Carneiro, A.P.B., and others. The BirdLife Seabird Tracking Database: 20 years of collaboration for marine conservation. Biological Conservation, vol. 299, art. 110813, 2024.

Charlton-Howard, Hayley, and others. 'Plasticosis': characterising macro-and microplastic-associated fibrosis in seabird tissues. Journal of Hazardous Materials, vol. 450, art. 131090, 2023.

Clark, Bethany L., and others. Global assessment of marine plastic exposure risk for oceanic birds. Nature Communications, vol. 14, art. 3665, 2023.

Croll, Donald A., and others. Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds. Biological Conservation, vol. 276, art. 109795, 2022.

Croxall, John P., and others. Seabird conservation status, threats and priority actions: a global assessment. Bird Conservation International, vol. 22, pp. 1–34, 2012.

Dias, Maria P., and others. Threats to seabirds: A global assessment. Biological Conservation, vol. 237, pp. 525–537, 2019.

Dierschke, Volker. Seabirds and offshore wind farms in European waters: Avoidance and attraction. Biological Conservation, vol. 202, pp. 59–68, 2016.

Falchieri, Marco, and others. Shift in HPAI infection dynamics causes significant losses in seabird populations across Great Britain. The Veterinary Record, vol. 191, pp. 294–296, 2022.

Gamarra-Toledo, Víctor, and others. Avian flu threatens Neotropical birds. Science, vol. 379, pp. 246–246, 2023.

Garthe, Stefan, and others. Large-scale effects of offshore wind farms on seabirds of high conservation concern. Scientific Reports, vol. 13, art. 4779, 2023.

Gass, Jonathon D., and others. Global dissemination of influenza A virus is driven by wild bird migration through arctic and subarctic zones. Molecular Ecology, vol. 32, pp. 198–213, 2023.

Goodale, Michael W., and others. Assessing the cumulative adverse effects of offshore wind energy development on seabird foraging guilds along the East Coast of the United States. Environmental Research Letters, vol. 14, art. 074018, 2019.

Graham, Nicholas A. J., and others. Seabirds enhance coral reef productivity and functioning in the absence of invasive rats. Nature, vol. 559, pp. 250–253, 2018.

Häkkinen, Henry, and others. Co-developing guidance for conservation: An example for seabirds in the North-East Atlantic in the face of climate change impacts. Conservation Science and Practice, vol. 5, art. e12985, 2023.

Hamilton, Bonnie, and others. Monitoring to conservation: The science–policy nexus of plastics and seabirds. Cambridge Prisms: Plastics, vol. 1, art. e3, 2023.

Kreitsberg, Randel, and others. The effect of environmental pollution on gene expression of seabirds: A review. Marine Environmental Research, vol. 189, art. 106067, 2023.

Lane, Jude V., and others. High pathogenicity avian influenza (H5N1) in Northern Gannets: Global spread, clinical signs, and demographic consequences. Ibis, vol. 166, pp. 633-650, 2023.

Lang, Andrew S., and others. Assessing the Role of Seabirds in the Ecology of Influenza A Viruses. Avian Diseases, vol. 60, pp. 378–386, 2016.

Lavers, Jennifer L., and others. Plastic ingestion by Flesh-footed Shearwaters (*Puffinus carneipes*): Implications for fledgling body condition and the accumulation of plastic-derived chemicals. Environmental Pollution, vol. 187, pp. 124-129, 2014.

Leguia, Mariana, and others. Highly pathogenic avian influenza A (H5N1) in marine mammals and seabirds in Peru. Nature Communications, vol. 14, art. 5489, 2023.

McPhail, Gretchen M., and others. Geographic, ecological, and temporal patterns of seabird mortality during the 2022 HPAI H5N1 outbreak on the island of Newfoundland. Canadian Journal of Zoology, in press, 2024.

Navarro, Alberto, and others. Microplastics ingestion and chemical pollutants in seabirds of Gran Canaria (Canary Islands, Spain). Marine Pollution Bulletin, vol. 186, art. 114434, 2023.

Peyrot, Belinda M., and others. Evolutionary dynamics of the clade 2.3.4.4B H5N8 high-pathogenicity avian influenza outbreaks in coastal seabirds and other species in southern Africa from 2017 to 2019. Transboundary and Emerging Diseases, vol. 69, pp. 3749–3760, 2022.

Phillips, Richard A., and others. “Conservation status and overview of threats to seabirds”, in *Conservation of Marine Birds*, Lindsay Young and Eric VanderWerf, eds. (London, Academic Press, 2023).

Phillips, Richard A., and others. Incidental mortality of seabirds in trawl fisheries: A global review. Biological Conservation, vol. 296, art. 110720, 2024.

Provencher, Jennifer F., and others. Assessing plastic debris in aquatic food webs: what we know and don’t know about uptake and trophic transfer. Environmental Reviews, vol. 27, pp. 304-317, 2019.

Provencher, Jennifer F., and others. Are ingested plastics a vector of PCB contamination in northern fulmars from coastal Newfoundland and Labrador? Environmental Research, vol 167, pp. 184-190, 2018.

Ramírez, Ivan, and others. Seabird bycatch in European waters. Animal Conservation, in press, 2024.

Roberts, Laura C. and others. Descriptive Epidemiology of and Response to the High Pathogenicity Avian Influenza (H5N8) Epidemic in South African Coastal Seabirds, 2018. Transboundary and Emerging Diseases, vol. 2023, art. 708458, 2023.

Rodríguez, Airam. “Mitigating light attraction”, in *Conservation of Marine Birds*, Lindsay Young and Eric VanderWerf, eds. (London, Academic Press, 2023).

Secretariat of the Convention on Biological Diversity, Global Biodiversity Outlook 5. Montreal, 2020

Serafini, Patrícia P., and others. Biochemical and molecular biomarkers and their association with anthropogenic chemicals in wintering Manx shearwaters (*Puffinus puffinus*). Marine Pollution Bulletin, vol. 203, art. 116398, 2024.

Spatz, Dena R., and others. Managing Invasive Mammals to Conserve Globally Threatened Seabirds in a Changing Climate: Threatened seabird conservation on islands. Conservation Letters, vol. 10, pp. 736–747, 2017.

St. John, Michael A., and others. A dark hole in our understanding of marine ecosystems and their services: perspectives from the mesopelagic community. Frontiers in Marine Science, vol. 3, art. 31, 2016.

Ulloa, Mauricio, and others. Mass mortality event in South American sea lions (*Otaria flavescens*) correlated to highly pathogenic avian influenza (HPAI) H5N1 outbreak in Chile. Veterinary Quarterly, vol. 43, pp. 1–10, 2023.

Vanstreels, Ralph E. T., and others, Phthalate esters (plasticizers) in the uropygial gland and their relationship to plastics ingestion in seabirds along the coast of Espírito Santo, eastern Brazil. Journal of Zoo and Wildlife Medicine, vol. 53, pp. 733-743, 2023.

Votier, Stephen C., and others. An overview of the impacts of fishing on seabirds, including identifying future research directions. ICES Journal of Marine Science, vol. 80, pp. 2380–2392, 2023.

Waap, Silke, and others. The diet of a nocturnal pelagic predator, the Bulwer's petrel, across the lunar cycle. Scientific Reports, vol. 7, art. 1384, 2017.

Watanuki, Yutaka and Jean-Baptiste Thiebot. Factors affecting the importance of myctophids in the diet of the world's seabirds. Marine Biology, vol. 165, art. 79, 2018.

Webb, Thomas J., and others. Biodiversity's big wet secret: the global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. PLoS One, vol. 5, art. e10223, 2010.

Section 4
Sub-chapter 4h: Marine plants

Contributors: Jason M Hall-Spencer (coordinating author), Joel C Creed, Erik van Doorn, José Souto Rosa Filho, Dorsaf Kerfahi, Emad Koochaknejad, Nahid Osman, Edwin Lanfranco, Wenhai Lu, Mario Luiz Gomes Soares, Nata Tavonvunchai, Mathew A Vanderklift, Lu Yang

1 Keynotes

Marine plant species are spreading poleward due to climate heating, with mangroves encroaching onto saltmarshes.

Restoration has established marine plants in small areas but not at a scale to match historical losses; preservation of existing marine plants provides many benefits.

Rates of mangrove loss have slowed as policies to conserve and maintain existing mangroves are beginning to work. Some losses have been offset by low biodiversity reforestation projects.

Sabkha plants, not covered in previous UN World Ocean Assessments, are overlooked but form important marine wetland ecosystems in arid/semi-arid regions.

2 Introduction

Vascular marine plants create biodiverse habitats providing goods and services that are essential for achieving the UN Sustainable Development Goals (S4.C5g, S4.C5h, S4.C5i; see Table 4H.1 below). There are 72 **seagrass** species, and their diversity is highest in the tropical Indo-Pacific. Some meadows have several seagrass species, but most are monospecific. *Thalassodendron pachyrhizum* is the deepest living marine plant and occurs down to 63 m depth (Martin and others, 2023). **Mangrove** diversity and extent peaks in tropical Asia with 69 species (and 13 hybrids) belonging to 18 families including trees, shrubs, palms, and ferns (Leal and Spalding, 2024). *Rhizophora mangale* is the most common mangrove tree species worldwide. **Saltmarshes** occur from the tropics to the Arctic, with over 500 known species including grasses, shrubs, and herbs (Adam, 2016; Fitzgerald and Hughes, 2021). **Sabkhas** are often used for salt extraction (Alshenawy and others, 2021; Ghazanfar, 2024); their flora e.g. *Atriplex*, *Salicornia, Salsola* and *Suaeda* spp. tolerates high salinity, freshwater scarcity, and extreme temperatures with adaptations that include succulence, salt secretion, and osmoregulation (Flowers and Colmer, 2008; Chenchouni, 2017).

3 The environmental change since WOAII

3.1 Changes in the overall status

Seagrass: 22 species are in decline due to the impacts of fishing, poor water quality, mariculture and coastal urban/industrial development (UNEP, 2020). Ten are 'vulnerable' and *Phyllospadix japonicus* and *Zostera geojeensis* are 'endangered' (IUCN, 2024). Some seagrass meadows suffer

from over-consumption by herbivores such as sea urchins (C4f) or turtles where their numbers have grown locally thanks to conservation measures (C5g). Seagrasses can recover when pressures on coastal systems are reduced; *Halodule wrightii* and *Zostera japonica* are increasing (UNEP, 2020) although invasive species are a growing threat (Beca-Carretero and others, 2024). 'Blue Carbon' and the role of marine plants in the carbon cycle are explained in Chapter 5B.C1. The only seagrass blue carbon project is in the USA where 3,151 ha of *Zostera marina* has been restored since WOAII.

Mangrove: rates of loss have slowed since WOAII yet some, such as *Bruguiera hainesii,* remain 'critically endangered' (Bunting and others, 2022; IUCN, 2024; Leal and Spalding, 2024). A global campaign, launched in 2022 and supported by 50 governments, aims to protect 15 million hectares of mangroves worldwide. Some recent losses have been offset by restoration projects (Leal and Spalding, 2024; C5h) which mainly focus on the following mangrove species: *Rhizophora mangle, R. mucronata, Brugueira gymnorhiza, Ceriops tagal, B. cylindrica, R. apiculata, Avicennia germinans, L. racemosa,* and *A. marina* (Verra, Plan Vivo; Climate Action Reserve; Clean Development Mechanism). The biodiversity of these plantations is lower than in natural mangrove forests (Lovelock and others, 2024).

Saltmarsh: these habitats are declining worldwide (for estimates of the rate see C5i), often due to land reclamation, conversion to agriculture, increased erosion, sea level rise, eutrophication (Niner and others, 2019, Roman and others, 2023, C5a) and invasive species (C6sub1). Saltmarsh species are spreading poleward due to recent climate heating (Cavanaugh and others, 2019; Cohen and others, 2020; C3) and planting/restoration work has had success in some regions (Xiao and others, 2020; Liu and others, 2024).

4 Region-specific changes in biodiversity

4.1 The Arctic Ocean

Zostera marina is the only seagrass reported in the Arctic. This region has *ca* 17% of the global extent of saltmarshes, with least 113 species of vascular plants (12% of the Arctic flora); information on recent changes in their status is lacking (Serigionko, 2013; Worthington and others, 2024) although the region is warming rapidly which is expected to favour the northward spread of temperate marine plants but threaten those adapted to survive seasonal freezing conditions (C3).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Phragmites australis has invaded western North Atlantic saltmarshes; it is expensive and difficult to remove but can provide ecosystem benefits (Macy and others, 2021). Extensive areas of previously degraded seagrass *Zostera marina, Ruppia maritima* (Chesapeake Bay) and *Thalassia testudinum* (Tampa Bay) have recovered in the USA thanks to reductions in nutrient pollution. *Avicennia germinans* and *Rhizophora mangle* mangroves are expanding northwards in the western North Atlantic (Cavanaugh and others, 2019; Vervaeke and others, 2024).

Blue Carbon projects in the eastern North Atlantic are using *A. germinans, A. africana, Laguncularia racemosa* and *R. mangle*. Sabkhas can provide habitat for a wide diversity of vascular plant taxa (from 29 families) including endemics, e.g. *Echiochilon simonneaui* and *E. chazaliei* (Qninba and others, 2020) and critically endangered species, e.g. *Limonium mucronulatum* which is only found in Cyprus (Sinni and De Belair Gerard, 2020).

Endemic *Posidonia oceanica* meadows are receding in the Mediterranean, due to human impacts, although some meadows of this and *Cymodocea nodosa* are expanding due to implemented legislation and restoration (De Los Santos and others, 2019; see also Table 4H.2) and the use of best practices in transplantation (Pergent-Martini and others, 2024). *Halophila stipulacea* has spread in the region and *H. decipiens,* first reported in the Mediterranean in 2018, is expected to spread (Gerakaris and others, 2020) raising calls for improved biosecurity to prevent the arrival of non-native species (Galil and others, 2017, C6sub1).

4.3 The South Atlantic Ocean and the Wider Caribbean

The main 'Blue Carbon' species now being planted in this region are the mangroves *Laguncularia racemosa, Rhizophora mangle, Conocarpus erectus, Avicennia germinans*, and *Rhizophora harisonii.* Several mangrove species are at elevated risk of extinction in the Caribbean (IUCN, 2024). Collection and commercial trade in *Rhizophora mangle* is regulated in the Caribbean (Table 4H.2). In Brazil 80-90% of mangroves are in protected areas and the species are listed as of 'least concern' (IUCN, 2024). The mangroves *Avicennia germinans, A. schaueriana, Rhizophora mangle, Laguncularia racemosa* are all expanding southwards causing the loss of saltmarsh *Spartina alterniflora*, *S. densiflora,* and *Acrosticum* plants (Cohen and others, 2020). The mangrove *Sonneratia apetala* has been introduced from the Indo-Pacific (Eysink and others, 2023). The seagrasses *Halodule wrightii* and *Halophila decipens* have expanded south by ca 250 km this century due to climate heating. The South Atlantic has vegetated hypersaline tidal flats (locally called 'apicuns' or 'salgados') with Qninbats that are easily damaged by human activities (Alberquerque and others, 2014). The west African coast has one of the highest rates of recent mangrove plant loss worldwide, due to agriculture, urbanization and cutting wood to burn (FAO, 2023) as well as oil pollution and the spread of invasive Nipa palm. The Calabar Protocol on Sustainable Mangrove Management to the 1981 Abidjan Convention (Table 4H.2), adopted in 2019, establishes rules for the environmental protection and conservation of mangroves as well as their use.

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Since 2018, the main species planted in blue carbon projects in this region are *Avicennia marina, Brugueira gymnorhiza, Ceriops tagal, Rhizophora apiculata* and *R. mucronata.* The Sundarbans is the largest mangrove forest in the world (10,200 km^2) and is a World Heritage site (Table 4H.1). Hwhere around 50 % of the trees have been felled for timber and to create space for agriculture and shrimp farms and the forest is being rapidly altered due to sea level rise (IPCC, 2022). Salt tolerant species are increasing and spreading (e.g. *Avicennia marina* and *Phoenix pelludosa)* with no plans in place to allow for the natural inland retreat of mangrove plants (Khan et al.,

2020). The Indian Ocean mangroves *Brugulera hainessii* and *Sonneratia griffithii* are critically endangered (Nuevo-Diego and others, 2021; IUCN, 2024).

Around the Persian Gulf and Sea of Oman conservation and restoration has contributed to the expansion of mangrove plants (Milani, 2018; Erfanifard and others, 2022), in Iran they are expanding with sea level rise where landward margins remain unimpeded by coastal development (Hamzeh and Lahijani, 2022; Irani and others, 2024). Mangrove extent is now increasing in the Red Sea and Gulf of Aden (RSGA) (Blanco-Sacristán and others, 2022) with *A. marina* plantations in Saudi Arabia, Egypt and Sudan. Restoration of *A. marina, Bruguiera gymnorrhiza, Ceriops tagal* and *Rhizophora mucronata* mangroves is underway in Somalia, Mozambique, Madagascar, Tanzania, and Kenya.

Middle Eastern coastal sabkhas host 12 marine plant families which form biodiversity hotspots and carbon sinks (Ghazanfar and others; 2019, Dar and others, 2022; Eid and others, 2023). Some are native to this region, such as *Arthrocnemum macrostachyum* and *Halopeplis perfoliata.* The few sabkha plants that have had their conservation status are listed as of 'least concern' (IUCN, 2024). Several types of sabkha plants are economically important (e.g. *Aeluropus lagopoides, Juncus rigidus*, *Phoenix dactylifera, Sueada vermiculata*).

The first seagrass restoration initiative for this region was announced in 2024 to rescue and transplant eight Red Sea seagrass species. In Tanzania, best practices for transplantation of *Syringodium isoetifolium* are being promoted (Wegoro and others, 2022). In Mozambique and South Africa, experimental transplantation of the regionally endangered *Zostera capensis* was recently achieved (Amone-Mabuto and others, 2022; Mokumo and Adams, 2023; Watson and Pillay, 2023). In Kenya, there are attempts to restore the seagrasses *Thalassodendron ciliatum, Thalassia hemprichii, Enhalus acoroides,* and *Syringodium isoetifolium*. Under the framework of the 1985 Nairobi Convention (Table 4H.2), detailed guidelines on seagrass and mangrove ecosystem restoration were published in 2020. Trial transplantations of *Thalassodendron ciliatum* and *Thalassia hemprichii* confirm that protecting existing meadows is more effective than planting new ones.

4.5 The North Pacific Ocean

This region has around 250-300 **saltmarsh** taxa, including species of *Suaeda*, *Triglochin*, and *Salicornia;* some, such as *T. maritima,* are vulnerable (IUCN, 2024). Over 200 saltmarsh plant species grow along the west North Pacific (Wang and Chen, 2013) where invasive *Spartina alterniflora* has colonised and altered 63% of China's coastal marshes (Zhang and others, 2023; Liu and others, 2024). The use of *S. alterniflora* for coastal protection has threatened indigenous marine plants, birds, fisheries, and tourism (Xia and others, 2021; Zhu and others, 2024) so it is now being removed; 68000 ha had been removed in China by 2025 according to the Special Action Plan for Spartina Removal and Coastal Marsh Restoration (2022-2025) by State Forestry and Grassland Administration of China. There has also been~~with~~ large scale replantation of native species such as the mangrove *Kandelia obovata*, saltmarsh plants like *Suaeda salsa, Spartina salsa, Scirpus mariqueter*, and seagrass *Zostera marina* (Feng and others, 2017; Yang

and others, 2024). Invasive *S. alterniflora* is also spreading in Japan and the Republic of Korea where large-scale eradication projects are ongoing (Maebara and others, 2020; Kim and others, 2023; Matsuda and others, 2023; Koyama and others, 2024).

Climate heating has caused recent northward expansion of the mangroves *Conocarpus erectus* in Mexico (Ochoa-Gómez and others, 2021) and *Kandelia candel* in Taiwan Province of China ~~(Lee & Yeh, 2009)~~. In Japan, mangroves peak in diversity with 11 species at Iriomote Island which has nearly 70% of the national mangrove area (Inoue and others, 2022). Here, species include *Kandelia obovata*, *Bruguiera gymnorrhiza*, and *Rhizophora stylosa* which are conserved well in a Natural World Heritage Site (UNESCO, 2021; Table 4H.1). Some mangrove species are at an elevated threat of extinction along North Pacific coasts of Central America (IUCN, 2024). China, home to 3~~2~~7 mangrove species, is reversing habitat loss with the Governmental *Special Action Plan for Spartina Removal and Coastal Marsh Restoration (2022–2025)* to plant over 8~~restoring 7~~,8~~0~~00 hectares of new forest and restore ~~juvenating 85~~,2~~6~~00 hectares of mangroves~~by 2023~~ (Ouyang and others, 2024). Restoration efforts also include rare and endangered species like *Lumnizera littorea*, *Sonneratia hainanensis* and *S. ovata* (Zhang~~Long~~ and others, 2024).

Zostera, Ruppia and *Phyllospadix* seagrasses are widely distributed in the North Pacific where they are under pressure from some of the most densely populated areas in the world (Su and others, 2020; Xu and others, 2021). Species such as *Zostera caespitosa, Phyllospadix iwatensis, Halophila beccarii* are listed as vulnerable (Yoshida and others, 2019; Du and others, 2023; Zhou and others, 2023; IUCN, 2024). In the eastern North Pacific, eel grass decline has been exacerbated by marine heatwaves, sea star wasting disease, reduced water clarity, and physical damage from human activities such as boating and coastal development (Christiaen and others 2022; Nahirnick et al. 2020)~~In Puget Sound, USA, eelgrass decline has been exacerbated by marine heatwaves, wasting disease, reduced water clarity, and physical damage from boating activities (Christiaen and others, 2022)~~. Similarly, between 2015 and 2021, over 1,000 hectares of *Zostera japonica* were lost in China's Yellow River estuary due to *Spartina alterniflora* invasion and typhoons; restoration efforts aim to mitigate this damage (Zhou and others, 2023; Liu and Ma, 2024).

4.6 The South Pacific Ocean

Improved water quality has resulted in recent regrowth of the seagrasses *Posidonia australis* and *Posidonia sinuosa* (Fernandes and others, 2022). *Avicennia marina*, the only mangrove species in New Zealand, is expanding south throughout the South Pacific, encroaching upon saltmarshes (Whitt and others, 2020). In Australia, subtropical and temperate coastal saltmarsh plants are threatened (IUCN, 2024) but taxa are being conserved and recovered, such as *Sarcocornia quinqueflora*, *Suaeda australis* and *Sporobolus virginicus* in Australia (Biswas and Dittman, 2022; Rankin and others, 2023). *Posidonia australis* restoration has worked in small areas (Sinclair and others, 2021) but not yet at a scale to match historical losses. *Zostera chilensis* is considered endangered in the South East Pacific.

Note: there are no marine plants in the Southern Ocean.

5 Remaining key knowledge and capacity changes and any new gaps

Much of what is known about changes in marine plants worldwide comes from remote sensing. A lack of *in situ* monitoring, due to a lack of marine botanists and funding, means that there are knowledge gaps about the status of marine plants in most regions, with sabkhas especially overlooked. Molecular techniques have been developed for marine plant identification but the infrastructure and human resources to do this work is lacking in many regions. The resilience of most marine plants to changing climate and ocean conditions has not been assessed.

Increased protection of marine plants requires international attention, support, and cooperation. Marine plants provide biodiversity and ecosystem function support, coastal protection, and contribute to livelihoods and improved water quality (Macreadie and others, 2019). In some areas mangroves have been so damaged that these services have been lost and the habitats have become a source, rather than a sink, of greenhouse gasses (Bruederle and Hodler, 2019; Ochoa-Gómez and Keke, 2022). Carbon market criticisms largely centre around the integrity and additional benefit of carbon credits and certification schemes (Guizar-Coutiño and others, 2022; West and others, 2020; Comte and others, 2023). Assessments of carbon stored by marine plants present difficulties in submersed ecosystems (Macreadie and others, 2022; Niner and Randalls, 2021). Many Blue Carbon projects depend on philanthropy, rather than carbon credit finance; the viability of carbon finance for marine plant conservation is a current knowledge gap.

Table 4H.1 Global legal & policy instruments applicable to marine plants

Global / categories	Species	Habitats
Marine biological diversity	1982 UN Convention on the Law of the Sea	
	1992 Convention on Biological Diversity	
	2023 BBNJ Agreement	
Wetlands		1971 Ramsar Convention
Natural heritage		1972 World Heritage Convention
Trade in endangered species	1973 Convention on International Trade in Endangered Species of Wild Fauna and Flora~~Washington Convention~~[18]	
Climate		1992 UN Framework Convention on Climate Change
Shipping	2001 Anti-Fouling Systems Convention	
	2004 Ballast Water Management Convention	
Non-binding		2015 Sustainable Development Goal 14

[18] ~~The appendices of the Washington Convention so far do not list any marine plants.~~

Table 4H.2 Regional legal instruments applicable to marine plants

Region	Species	Habitats
Europe	1979 Bern Convention	
European Union		1992 Habitats Directive
	2008 Marine Strategy Framework Directive	
	2024 EU Nature Restoration Regulation	
Baltic Sea		1974 Helsinki Convention
North-East Atlantic Ocean		1992 OSPAR Convention
Mediterranean Sea	1976 Barcelona Convention	
South-East Atlantic Ocean		1981 Abidjan Convention
Western Indian Ocean		1985 Nairobi Convention
Red Sea & Gulf of Aden		1982 Jeddah Convention
Caspian Sea	2003 Tehran Convention	
South Pacific Ocean	1976 Apia Convention	
Caribbean Sea	1983 Cartagena Convention	

List of international legal & policy documents in chronological order[19]

Year of adoption	Name	Abbreviation
1971	Convention on Wetlands	~~1971~~ Ramsar Convention
1972	Convention Concerning the Protection of the World Cultural and Natural Heritage	~~1972~~ World Heritage Convention
1973	Convention on International Trade in Endangered Species of Wild Fauna and Flora	~~1973~~ CITES~~Washington Convention~~
1974	Convention on the Protection of the Marine Environment of the Baltic Sea Area	~~1974~~ Helsinki Convention
1976	Convention for the Protection of the Mediterranean Sea Against Pollution	~~1976~~ Barcelona Convention
1976	Convention on Conservation of Nature in the South Pacific	~~1976~~ Apia Convention
1979	Convention on the Conservation of European Wildlife and Natural Habitats	~~1979~~ Bern Convention
1981	Convention for Co-operation in the Protection and Development of the Marine and Coastal environment of the West and Central African Region	~~1981~~ Abidjan Convention
1982	Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment	~~1982~~ Jeddah Convention
1982	United Nations Convention on the Law of the Sea	~~1982~~ UNCLOS ~~Convention on the Law of the Sea~~
1983	Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region	~~1983~~ Cartagena Convention
1985	Convention for the Protection, Management and Development of Coastal and Marine Environment of the Western Indian Ocean	~~1985~~ Nairobi Convention

[19] For the sake of simplicity, protocols that are adopted under any of the legal instruments above are, for the purposes of this table, understood as part of the instruments under which they were adopted.

1992	Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora	~~1992~~ Habitats Directive
1992	United Nations Framework Convention on Climate Change	~~1992~~ UN Framework Convention on Climate Change
1992	Convention on Biological Diversity	
1992	Convention for the Protection of the Marine Environment of the North-East Atlantic	~~1992~~ OSPAR Convention
2001	International Convention on the Control of Harmful Anti-fouling Systems on Ships	~~2001~~ Anti-Fouling Systems Convention
2003	Framework Convention for the Protection of the Marine Environment of the Caspian Sea	~~2003~~ Tehran Convention
2004	International Convention for the Control and Management of Ships' Ballast Water and Sediments	~~2004~~ Ballast Water Management Convention
2008	Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy	~~2008~~ Marine Strategy Framework Directive
2015	Sustainable Development Goals	
2022	Kunming-Montreal Global Biodiversity Framework	
2023	*Agreement under the* United Nations Convention on the Law of the Sea *on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction*	BBNJ Agreement

7 References

Adam, Paul. Saltmarshes. In: Kennish, M. J. (ed) Encyclopedia of Estuaries. Encyclopedia of Earth Sciences Series. Springer, Dordrecht, 2016. Albuquerque, Antonia G.B.M., and others. Hypersaline tidal flats (apicum ecosystems): the weak link in the tropical wetlands chain. Environmental Reviews, 22, 99-109, 2014

Alshenawy, Abdulhafiz O., and others. A review on the characteristics of sabkha soils in the Arabian Gulf Region. Arabian Journal of Geosciences, 14, 1-15, 2021.

Amone-Mabuto, Manuela, and others. A field experiment exploring disturbance-and-recovery, and restoration methodology of *Zostera capensis* to support its role as a coastal protector. Nordic Journal of Botany, e03632, 2022.

Beca-Carretero, Pedro, and others. Climate change and the presence of invasive species will threaten the persistence of the Mediterranean seagrass community. Science of The Total Environment, 910, 168675, 2024.

Beaumont, Kieren P., and Dittman, Sabine. Early seed dynamics and tidal marsh revegetation of a salt pond following tidal reconnection. Applied Vegetation Science 25, e12661, 2022.

Blanco-Sacristán, Javier, and others. Mangrove distribution and afforestation potential in the Red Sea. Science of the Total Environment, 2022.

Bruederle, Anna, and Hodler, Roland. Effect of oil spills on infant mortality in Nigeria. Proceedings of the National Academy of Sciences 116, 5467-5471, 2019.

Bunting, Pete, and others. Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. Remote Sensing, 14, 3657, 2022.

Cavanaugh, Kyle C., and others. Climate-driven regime shifts in a mangrove–saltmarsh ecotone over the past 250 years. Proceedings of the National Academy of Sciences 116: 21602–21608, 2019.

Chenchouni, Haroun. Assessing the ecology of halophytes for developing salt-tolerant crops in arid and semiarid regions. In Plant Adaptation to Environmental Change: Significance of Amino Acids and their Derivatives (pp. 75-90). Springer, 2017.

Christiaen, Bart, and others. Puget Sound Seagrass Monitoring Report, monitoring year 2018-2020. Nearshore Habitat Program. Washington State Department of Natural Resources, Olympia, WA, 2022.

Cohen, Marcelo C.L., and others. Southward migration of the austral limit of mangroves in South America. CATENA, 195: 104775, 2020.

Comte, Adrien, and others. Blue carbon credits: a lot of promises but even more uncertainties for the Global South. Policy Brief, COP28, UAE, 1-4., 2023.

Dar, Basharat A., and others. Vegetation composition of the halophytic grass *Aeluropus lagopoides* communities within coastal and inland sabkhas of Saudi Arabia. Plants 2022, 11, 666, 2022.

De Los Santos, Carmen B., and others. Recent trend reversal for declining European seagrass meadows. Nature Communications, 10(1), 3356, 2019.

Du, Jianguo, and others. Protect seagrass meadows in China's waters. Science, 379(6631), 447-447, 2023.

Eid, Ebrahem M., and others. Modeling soil organic carbon at coastal sabkhas with different vegetation covers at the Red Sea coast of Saudi Arabia. Journal of Marine Science and Engineering, 11, 295, 2023.

Erfanifard, Yousef, and others. Assessment of Iran's Mangrove Forest Dynamics (1990–2020) Using Landsat Time Series. Remote Sensing, 14(19), Article 19, 2022.

Eysink, Geraldo, and others. First Occurrence in Mangroves of South America of the Exotic Species *Sonneratia apetala* Buch.-Ham. From The Indo-Malayan Region. Biota Neotropica, 23, 4, 1-5, 2023.

FAO. The world's mangroves 2000–2020. Rome, 2023. https://doi.org/10.4060/cc7044en.

Feng, JianXiang, and others. Ecological restoration by native-invasive species replacement for mangrove wetlands in Zhangjiang River Estuary, Fujian. Oceanologia et Limnologia Sinica, 48(2), 266-275, 2017.

Fernandes, Milena B., and others. Landsat historical records reveal large-scale dynamics and enduring recovery of seagrasses in an impacted seascape. Science of The Total Environment, 813,152646, 2022.

Fitzgerald, Duncan M., and Hughes, Zoe J. Salt Marshes: Function, Dynamics, and Stresses. Cambridge University Press, 2021.

Flowers, Timothy J., and Colmer, Timothy D. Salinity tolerance in halophytes. New Phytologist, 179(4), 945-963, 2008.

Galil, Bella, and others. The enlargement of the Suez Canal - Erythraean introductions and management challenges. Management of Biological Invasions, 8, 141-152, 2017.

Gerakaris, Vasilis, and others. First record of the tropical seagrass species *Halophila decipiens Ostenfeld* in the Mediterranean Sea. Aquatic Botany, 160, 103151, 2020.

Ghazanfar, Shahina A., and others. Plants of Sabkha Ecosystems of the Arabian Peninsula. In: B. Gul and others (eds.), Sabkha Ecosystems, Tasks for Vegetation Science V I, 2019.

Ghazanfar, Shahina A. Biogeography and Conservation in the Arabian Peninsula: A Present Perspective. Plants, 13, 2091, 2024.

Guizar-Coutiño, Jones, and others. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. Conservation Biology, 36, e13970, 2022.

Hamzeh, M.A., and Lahijani, H.A.K. Soil and Vegetative Carbon Sequestration in Khuran Estuary Mangroves, Strait of Hormoz, During the Last 18 Centuries. Estuaries and Coasts, 45, 1583-1595, 2022.

Inoue, Tomomi, and others. Mangroves of Japan. In Mangroves: Biodiversity, Livelihoods and Conservation, (pp. 463-487). Singapore: Springer Nature Singapore, 2022.

IPCC. Climate Change ~~2022~~: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck,

A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, 2022.

Irani, Maryam, and others. A framework for coastal flood hazard assessment under sea level rise: Application to the Persian Gulf. Journal of Environmental Management, 349, 119502.Hogarth, PJ. 2015. The Biology of Mangroves and Seagrasses, 3rd ed. Oxford, Oxford University Press, 2024.

IUCN. The IUCN Red List of Threatened Species. Version 202401. https://www.iucnredlist.org, 2024.

Khan, Md F. A., and others. Mangrove forest policy and management: Prevailing policy issues, actors' public claims and informal interests in the Sundarbans of Bangladesh. Ocean & coastal management, 186, 105090, 2020.

Kim, Sungtae, and others. Vertical distribution of the salt marsh invader *Spartina alterniflora* and native halophytes on the west coast of Korea in relation to tidal regimes. Aquatic Invasions, 18(3), 331-349, 2023.

Koyama, Akihiko, and others. Sub-habitat classification of temperate salt marshes in Japan based on aquatic fauna. Global Ecology and Conservation, e03211, 2024.

Leal, M., and Spalding, M.D. The State of the World's Mangroves 2024. Global Mangrove Alliance, 2024.

~~Lee Tsai-Ming and Hui-Chung Yeh. Applying remote sensing techniques to monitor shifting wetland vegetation: A case study of Danshui River estuary mangrove communities, Taiwan. Ecological Engineering, 35, 487-496, 2009~~

Liu, Ningning, and Ma, Zhijun. Ecological restoration of coastal wetlands in China: Current status and suggestions. Biological Conservation, 291, 110513, 2024.

Liu, Zezheng, and others. A global meta-analysis on the drivers of salt marsh planting success and implications for ecosystem services. Nature Communications, 15(1), 3643, 2024.

Long, Kexin, and others. Spatiotemporal disturbances and attribution analysis of mangrove in southern China from 1986 to 2020 based on time-series Landsat imagery. Science of The Total Environment, 912, 169157, 2024.

Lovelock, Catherine E., and others. Mangrove ecology guiding the use of mangroves as nature-based solutions. Journal of Ecology, 2024.

Macreadie, Peter I., and others. The future of Blue Carbon science. Nature Communications, 10(1), 3998, 2019.

Macreadie, Peter I., and others. Operationalizing marketable blue carbon. One Earth. 5, 485–492, 2022.

Macy, Aaron, and others. Changes in Ecosystem Nitrogen and Carbon Allocation with Black Mangrove (*Avicennia germinans*) Encroachment into *Spartina alterniflora* Salt Marsh. Ecosystems, 24, 1007–1023, 2021.

Maebara, Yu, and others. Genetic diversity of invasive *Spartina alterniflora* Loisel. (Poaceae) introduced unintentionally into Japan and its invasion pathway. Frontiers in Plant Science, 11, 556039, 2020.

Martin, Belinda C., and others. Deep Meadows: Deep-Water Seagrass Habitats Revealed. Ecology 104(10): e4150, 2023.

Matsuda, Ryuya, and others. Effects of salinity, temperature, and immersion conditions on seed germination of invasive *Spartina alterniflora* Loisel (smooth cordgrass) in Japan. Regional Studies in Marine Science, 57, 102738, 2023.

Milani, Alireza S. Mangrove Forests of the Persian Gulf and the Gulf of Oman. In C. Makowski and C. W. Finkl (Eds.), Threats to Mangrove Forests (Vol. 25, pp. 53–75). Springer International Publishing, 2018.

Mokumo, Mosihla F., and Adams, J. B. Investigating transplantation as a mechanism for seagrass restoration in South Africa. Restoration Ecology, 31(7), e13941, 2023.

Murray, Nicholas J., and others. The global distribution and trajectory of tidal flats. Nature, 565(7738), 222-225, 2019.

Nahirnick, Natasha K. and others. Long-Term Eelgrass Habitat Change and Associated Human Impacts on the West Coast of Canada. *Journal of Coastal Research* 36 (1), 30-40, 2020

Niner, Holly J., and Randalls, Samuel. Good enough for governance? Audit and marine biodiversity offsetting in Australia. Geoforum 120, 38–45, 2021.

Nuevo-Diego, Christine E., and others. Pollinators necessary for the reproductive success of critically endangered mangrove, *Sonneratia griffithii*. Aquatic Botany, 169, 103340, 2021.

Obuah, Emmanuel E., and Keke, R. C. Mitigating the negative externalities of oil drilling activities in the Niger Delta, Nigeria. Open Access Library Journal, 9(5), 1-21, 2022.

Ochoa-Gómez, Jonathan G., and others. Distribution and structure of *Conocarpus erectus L.* (Combretaceae) in the northern limit of the Pacific Ocean (Gulf of California). Ocean & Coastal Management 209, 105645, 2021.

Ouyang, Xiaoguang, and others. Mangrove restoration in China's tidal ecosystems. Science, 385(6711), 836-836, 2024.

Pergent-Martini Christine, and others. Guidelines for *Posidonia oceanica* restoration. Report Cooperation agreement Mediterranean Posidonia Network (MPN), French Biodiversity Agency (OFB) & University of Corsica Pasquale Paoli (UCPP) N°OFB-22-1310, 29 pp, 2024.

Qninba, Abdeljebbar, and others. Sabkhat Imlili (Région Dakhla-Oued Eddahab), une zone humide saharienne relique. 152pp. 2020.

Rankin, Caleb, and others. Innovative tidal control successfully promotes saltmarsh restoration. Restoration Ecology 31:e13774, 2023.

Roman, Charles T., and others. Twenty Year Record of Salt Marsh Elevation Dynamics in Response to Sea Level Rise and Storm Driven Barrier Island Geomorphic Processes: Fire Island, NY, USA. Estuaries and Coasts, SI Wetland elevation dynamics, 2023.

Senni, Rachida, and De Belair, Gerard, A. H. Biodiversity of halophytes in semi-arid regions: case of Zharez Gharbi and Zahrez Chergui (Zaafrane-Djelfa) in Algeria. Ponte International Journal of Science and Research, 76(11), 2020.

Sergienko, Liudmila. Salt marsh flora and vegetation of the Russian Arctic coasts. Czech Polar Reports 3, 30-37, 2013.

Sinclair, Elizabeth A., and others. Advances in approaches to seagrass restoration in Australia. Ecological Management & Restoration, 22(1), 10-21, 2021.

Su, Zhinan, and others. Changes in carbon storage and macrobenthic communities in a mangrove-seagrass ecosystem after the invasion of smooth cordgrass in southern China. Marine Pollution Bulletin, 152, 110887, 2020.

UNESCO World Heritage Center. Four natural and three cultural sites added to UNESCO's World Heritage List. Retrieved from https://whc.unesco.org/en/news/2318/, 2021.

United Nations Environment Programme. Out of the blue: The value of seagrasses to the environment and to people. UNEP, Nairobi: 96 p, 2020.

Vervaeke, William, and others. Ongoing range shift of mangrove foundation species: *Avicennia germinans* and *Rhizophora mangle* in Georgia, USA. 10.21203/rs.3.rs-4601188/v1, 2024.

Wang, Wen Qing, and Chen, Qiong. Salt-tolerant plant resources from coastal areas of South China. Xiamen University Press, pp 444, 2013.

Watson, Katie M., and others (2023). Using transplantation to restore seagrass meadows in a protected South African lagoon. PeerJ, 11, 2023.

Wegoro, January, and others. Seagrass restoration in a high-energy environment in the Western Indian Ocean. Estuarine, Coastal and Shelf Science, 278, 108119, 2022.

West, Thales A.P., and others. Overstated carbon ER from voluntary REDD+ projects in the Brazilian Amazon. PNAS. 117, 24188–24194, 2020.

Whitt, Ashley, and others. March of the mangroves: Drivers of encroachment into southern temperate saltmarsh. Estuarine, Coastal and Shelf Science, 240, 106776, 2020.

Worthington, Thomas A., and others. The distribution of global tidal marshes from Earth observation data. Global Ecology and Biogeography, 33, e13852, 2024.

Xia, Shaopan, and others. *Spartina alterniflora* invasion controls organic carbon stocks in coastal marsh and mangrove soils across tropics and subtropics. Global Change Biology, 27(8), 1627-1644, 2021.

Xiao, Rong, and others. Stronger network connectivity with lower diversity of soil fungal community was presented in coastal marshes after sixteen years of freshwater restoration. Science of the Total Environment, 744, 140623, 2020.

Xu, Shaoshun, and others. Diversity, distribution and conservation of seagrass in coastal waters of the Liaodong Peninsula, North Yellow Sea, northern China: Implications for seagrass conservation. Marine Pollution Bulletin, 167, 112261, 2021.

Yang, Le, and others. Effects of the comprehensive elimination of *Spartina alterniflora* along China's coast on blue carbon and scenario prediction after ecological restoration. Journal of Environmental Management, 369, 122283, 2024.

Yoshida, Goro, and others. Carbon sequestration by seagrass and macroalgae in Japan: estimates and future needs. Blue carbon in shallow coastal ecosystems: carbon dynamics, policy, and implementation, 101-127, 2019.

Zhang, Xi, and others. Continual expansion of *Spartina alterniflora* in China's temperate and subtropical coastal zones from 1985 to 2020. International Journal of Applied Earth Observation and Geoinformation, 117, 103192, 2023.

Zhang Y., and others. Research on endangered mangrove species and recovery status in China. Journal of Applied Oceanography, 40(1), 142-153, 2021.

Zhou, Yi, and others. Distribution status, degradation reasons and protection countermeasures of seagrass resources in China. Oceanologia et Limnologia Sinica, 54, 1248-1257, 2023.

Zhu, Xudong, and others. Impacts of intensive smooth cordgrass removal on net ecosystem exchange in a saltmarsh-mangrove ecotone of Southeast China. Science of The Total Environment, 934, 173202, 2024.

Section 4

Sub-chapter 4i: Macroalgae, not including phytoplankton

Lead: Carmen Mifsud

Co-Lead: Felicia Mogo

Cottier-Cook, Elizabeth J[1], Brodie, Juliet[2], Corrigan, Sophie[2], De Clerck, Olivier[3], Lim, Phaik-Eem[4], Maggs, Christine A[5], Msuya, Flower E[6], Pellizzari, Franciane[7], Liu, Tao[8], Wernberg, Thomas[9], Verbruggen, Heroen[10,11], Wilbraham, Joanna[2], Yokoya, Nair S[12]

[1] Scottish Association for Marine Science, Scottish Marine Laboratory, Oban, Argyll, PA37 1QA, UK

[2] Natural History Museum, Research, Cromwell Road, London, SW7 5BD, UK

[3] Phycology Research Group, Department of Biology, Ghent University, Krijgslaan281 S8, Ghent, B-9000, Belgium

[4] Institute of Ocean and Earth Sciences, University of Malaya, Jalan Lembah Pantai, 50603 Kuala Lumpur, Wilayah Persekutuan, Malaysia

[5] School of Biological Sciences, Queen's University Belfast, Belfast BT9 5DL, UK

[6] Zanzibar Seaweed Cluster Initiative, Tanzania

[7] Paraná State University, Biological Science Department, Phycology and Marine Water Quality Laboratory, Paranaguá, Brazil

[8] State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences and State Key Laboratory of Mariculture Breeding, Xiamen University, Xiamen 361102, China

[9] Indian Ocean Marine Research Centre, University of Western Australia, Perth 6009, Australia

[10] School of BioSciences, University of Melbourne, Victoria 3010, Australia

[11] CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Campus de Vairão, Universidade do Porto, 4485-661 Vairão, Portugal

[12] Environmental Research Institute, Biodiversity Conservation Centre, São Paulo, Brazil

1. Keynotes

- Rapidly warming oceans combined with anthropogenic-related stressors, will lead to further significant losses of certain macroalgal species and changes in distribution patterns of others.
- The distribution of temperate and warmer water species is likely to shift to polewards into temperate boreal and deeper waters, conditional on dispersal capacity and substrate availability.
- The incidence of invasive macroalgal blooms and turfs is likely to increase, leading to changes in ecosystem function.
- Less than 1% of macroalgal species described to date have been evaluated for their extinction risk using the IUCN Red List assessment and nearly 76% of the 99 macroalgal entries on the List are data deficient. This significant gap poses substantial challenges for assessing risk status.
- Significant gaps in taxonomic and distribution knowledge for many macroalgae is impeding progress in effective monitoring for changes in population size and geographical range.

2. Introduction

This chapter presents the overall status of the red, green and brown macroalgae (commonly known as seaweed), and any changes between 2018 – 2024. Here, the macroalgae are considered in their own sub-chapter, having been considered as a food source and as an ecosystem in WOA I (UNEP, 2016) and included with marine plants in WOA II (UN, 2021). To 2024, only 99 macroalgae, from a total of over 11,400 species described (Guiry, 2024) are in the IUCN Red List (IUCN, 2024) and 76% of these are categorised as data deficient (Fig. 1). Recognising the macroalgae in WOA III is, therefore, timely and critically important, given that the maximum potential area of ocean for seaweeds to occupy is an estimated 6-7 million km^2 (Duarte *et al.*, 2022). Seaweeds also play a crucial role in marine ecosystem functioning and many species are being significantly impacted by climate change and other anthropogenic stressors (Cottier-Cook *et al.*, 2023).

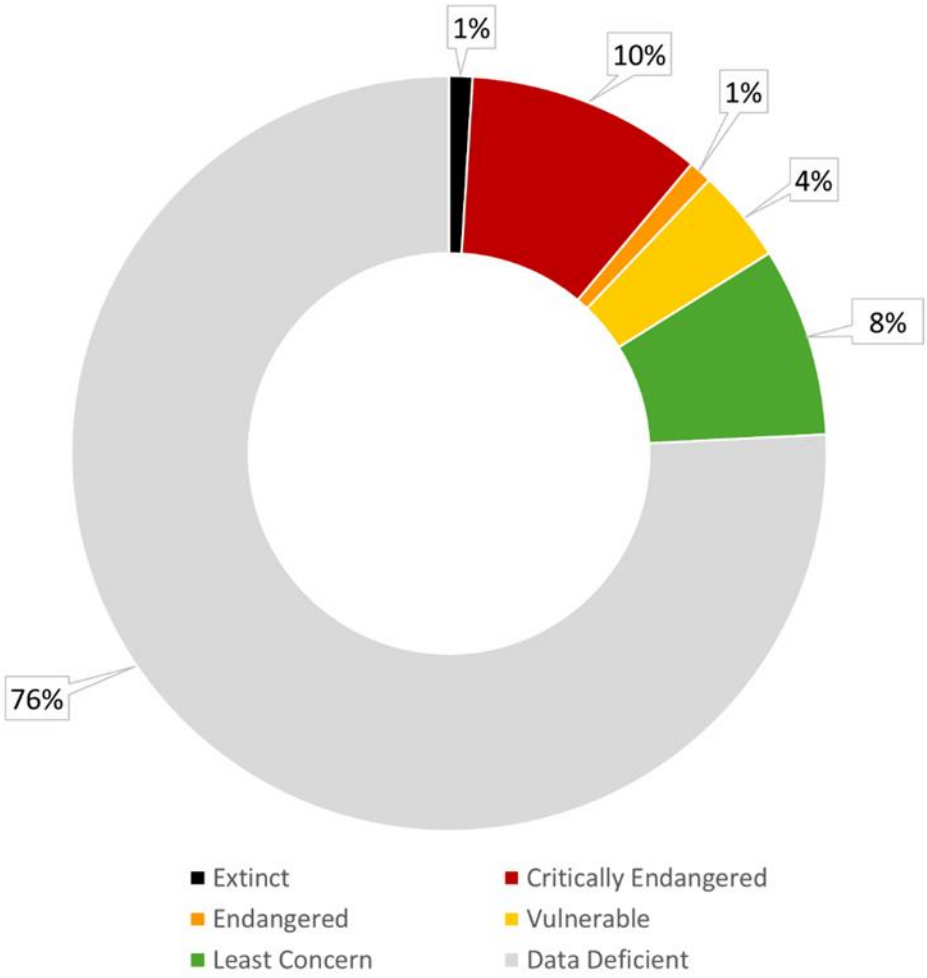


Figure 1. Categorisation of 99 macroalgal species in the IUCN Red List, reported from the Pacific Northwest, Pacific Southeast and Pacific Southwest. No macroalgal species in the other marine regions have been IUCN Red List categorised (IUCN, 2024).

3. The environmental change since WOAII

3.1 Changes in overall status

Red macroalgae

The red macroalgae (Rhodophyta) occur from the poles to the tropics and from the intertidal to 290 m deep (Littler *et al.*, 1991). Most red macroalgae are marine (97%) (Sutherland *et al.*, 2011); they are habitat-forming (e.g., rhodolith beds; Fig. 2) and are integral components of other habitats (e.g., coral reefs and temperate and arctic rocky reefs) (see Section 4, Sub-chapter 5d). Red macroalgae provide ecosystem services, including serving as breeding, spawning and nursery grounds for ecologically and commercially important marine species (Rendina *et al.*, 2022). They are also harvested and/or farmed, primarily in Southeast Asia for their gelling and emulsifying colloidal agents and in East Asia for food and aquaculture feed (Cottier-Cook *et al.*, 2021) (see Section 5A, Sub-chapter 1d). The maximum potential area for red macroalgae globally is estimated as 6.69 million km^2 (Duarte et al., 2022), including 4.12 million km^2 of rhodolith beds (Fragkopoulou et al., 2021).

Currently (as of 2024), 7,698 red macroalgal species are described (Guiry, 2024), although high levels of (pseudo-) cryptic diversity mean that many still need to be described and new species are continuously being discovered (Leliaert et al., 2018). Since, WOAII, two new orders have been established, the Corallinapetrales (Jeong et al., 2021) and the Inkyuleeales (Díaz-Tapia et al., 2019). Many larger genera (e.g., *Pyropia*) have been split into smaller units to better reflect their evolutionary relationships (Yang et al., 2020) and many species have been moved between genera based on recent research (Hughey et al., 2020).

The role of coralline red algae in carbon sequestration remains contested, as the calcification process also releases CO_2. New research suggests that coralline macroalgae recycle 40% of the carbon from calcification into photosynthesis (Mao *et al.*, 2024). Given the longevity of coralline macroalgae and the extent of the rhodolith beds, globally they could represent an important store of carbon (400-38,000 tons of carbonate deposits) (Schubert *et al.*, 2024) (see Section 5B, Chapter 1).

Figure 2. – Rhodolith (Maerl) Bed in Ireland © Peter Tinsley

Green macroalgae

The green macroalgae, most of which belong to the Class Ulvophyceae (Chlorophyta), consist of 1,900 species and are distributed worldwide (El-Manaway and Rashedy, 2022). They are typically found in shallow waters, although species have been recorded at > 210 m (Littler *et al*., 1985). They provide a wide variety of ecosystem services, including an important food source for marine grazers, nutrient cycling and reef building (e.g., *Halimeda* spp.). Although, the total coverage of green macroalgae has not been estimated, the global coverage associated with soft/sandy and coral habitats is estimated at 1.2 million km^2 (McNeil *et al.*, 2016) ~~and floating rafts at 1,000 km^2 (Liu *et al.*, 2013)~~. *Halimeda* spp. produce reef-like habitats (bioherms) and their carbonate production ranges from 0.8 to over 17,500 g m^{-2} yr^{-1} in the Indo-Pacific (Schubert *et al.*, 2023). These habitats

are now considered to be major contributors to carbonate production in tropical and subtropical regions (Schubert *et al.*, 2023).

A few opportunistic *Ulva* spp. can form extensive blooms (known as 'green tides'), which have increased in frequency and can cause biodiversity loss, health risks and a reduction in ecosystem services in the affected area (Smetacek and Zingone, 2013, Joniver *et al.*, 2021). The introduced *Halimeda incrassata* has also spread rapidly in shallow subtidal habitats of the western Mediterranean Sea (Vergruggen and Ballesteros, 2024).

Progress in resolving evolutionary relationships in the green macroalgae is continuing. Since WOAII, studies have indicated that not all green macroalgae of the class Ulvophyceae may descend from a common evolutionary ancestor (Del Cortona *et al.*, 2020, Hou *et al.*, 2022). The Bryopsidales is likely to be more closely related to the Chlorophyceae, a class of predominantly freshwater green microalgae, than to the remaining Ulvophyceae.

Several studies focusing on local diversity of green macroalgae have discovered many undescribed taxa (Lagourgue *et al.*, 2022, Tran *et al.*, 2022), particularly in tropical regions. The sequencing of *Ulva* types has resulted in several name changes (Hughey et al., 2020, Hughey et al., 2021, Gabrielson et al., 2024), with *U. fenestrata* being the correct name of the temperate species often reported as *Ulva lactuca*, and *U. lactuca* being the correct name for the pan-tropical *U. fasciata* (Hughey et al. 2019).

Brown macroalgae

The brown macroalgae or Phaeophyceae (Ochrophyta) provide several ecosystem services, including food and habitat provision, nutrient cycling, and carbon fixation with an estimated value of ~$500 billion USD globally (Eger *et al.*, 2023). The number of brown macroalgal species has been estimated at 1,800 (Guiry, 2024), with the vast majority inhabiting the marine environment. Their distribution is global, although they are mainly temperate and polar, except for *Sargassum* spp. and the Dictyotales, which are often abundant in the tropics. They occur from the intertidal to 30-40 m depth, although they can extend down to > 200 m (Žuljević *et al.*, 2016). The overall estimate of the total potential area for brown macroalgae based on distribution models is 2.68 million km^2, including 0.13 million km^2 for intertidal (Duarte *et al.*, 2022), 2.5 million km^2 for subtidal (Gattuso *et al.*, 2006), and a maximum of 6,000~~0.05 million~~ km^2 for floating *Sargassum spp.* (Wang *et al.*, 2019,

Zhang *et al.*, 2019). The latter includes > 20 million tons of floating *Sargassum* extending from West Africa to the Gulf of Mexico (Wang *et al.*, 2019).

Since WOAII, a novel brown macroalgal genus and species *Setoutiphycus delamareoides* (Ectocarpales) has been described in Japan (Kawai and Hanyuda, 2021). Numerous other new species have also been described, including 15 new *Lobophora* species (Sun *et al.*, 2021, Vieira *et al.*, 2021, Jurejan *et al.*, 2024) and two new species of *Dictyota* (Win *et al.*, 2024).

Eger *et al.* (2023) recently estimated that six major forest-forming kelps (*Ecklonia, Laminaria, Lessonia, Macrocystis, Nereocystis,* and *Saccharina*) sequester 4.9 million tons of carbon from the atmosphere annually. Increased understanding of the role of brown macroalgae in the carbon cycle has also revealed new global estimates for seaweed-derived particulate carbon export below 200 m depth, which total 3–4% of the ocean carbon sink capacity and equate to 4.4–48.5 million tons of seaweed-derived carbon being sequestered annually for 100 years (Filbee-Dexter *et al.*, 2024).

Major threats

Changes in climate and the rapidly warming ocean (IPCC, 2023), together with anthropogenic stressors, such as overharvesting, eutrophication, ocean acidification and pollution, are predicted to lead to an unprecedented decline in many macroalgae speciesdistribution. Although, conversely Tthe incidence of certain macroalgal bloom-forming speciess and turfs is also likely to increase (Filbee-Dexter and Wernberg, 2018, Bermejo et al., 2023, Feng et al., 2023) (Fig. 3). Since WOAII, reports have warned, however, that ocean warming, thermohaline and circulation change, and marine heat waves combined with other anthropogenic stressors have resulted in the loss of > 90% of certain kelp species in regions of Australia, USA and Mexico, with significant implications for associated biodiversity and local economies (Dalmau *et al.*, 2024). By 2100, depending on the warming scenario, brown seaweeds are predicted to lose 6-11% of their present estimated global coverage (Manca et al., 2024) and calcified red algal distribution is estimated to decline by 26–44% (Fragkopoulou et al., 2021), the latter being more susceptible to threats like ocean acidification than the brown seaweeds (Cornwall *et al.*, 2021). Furthermore, due to their extremely slow growth rates (~1 mm yr^{-1}) rhodolith beds may take centuries to millennia to recover from damage and are consequently described as a non-renewable resource (Barbera *et al.*, 2003).

Seaweed loss is also predicted to increase in tropical regions (e.g., tropical red algae in Southeast Asia), due to the effects of climate change and the associated pest, disease and invasive species outbreaks (Brakel et al., 2021) (see Section 4, Chapter 6), increased incidence of typhoons, ocean acidification (Page et al., 2022) and overharvesting (Mac Monagail et al., 2017). Range shifts are also likely to increase into more Arctic, temperate boreal and deeper waters (Lebrun et al., 2022, La Guardia et al., 2023). ~~The incidence of macroalgal blooms and turfs is also likely to increase (Filbee-Dexter and Wernberg, 2018, Bermejo et al., 2023, Feng et al., 2023) (Fig. 3).~~

Figure 3. *Ulva* spp. bloom in Songosongo, Tanzania © Flower Msuya

4. Region-specific changes

4.1 The Arctic Ocean

Arctic macroalgae are experiencing significant changes, due to rapid warming, declining sea ice, and increased habitat availability. Many species, particularly brown and red macroalgae, are predicted to expand their distributional ranges northwards from more temperate regions, with a predicted loss of existing high latitude macroalgae occupying similar habitats (Bringloe, *et al*. 2022). It is also likely that the potential calcified algal coverage will decline in the region, as a

consequence of increasing temperatures and lower pH levels leading to a reduced ability to calcify (Chan *et al*. 2020).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Marine heat waves in this region have led to a marked range shift or population-level change in a number of kelp species, such as *Laminaria digitata*, which is predicted to undergo a poleward range contraction and experience declines in growth performance (Leathers *et al*., 2024). Declines in the fucoid *Fucus vesiculosus* and increases in filamentous turfing algae *Pyaiella littoralis* and *Ectocarpus siliculosus* have been attributed to increased eutrophication in the Baltic Sea (Hall *et al.*, 2024). In the Mediterranean Sea, *Fucus virsoides* has seen a significant decline (Descourvières *et al.*, 2024) and species which favour warmer waters (i.e., invasive species from tropical and sub-tropical regions, e.g., *Rugulopteryx okamurae*) have increased and spread (Falace *et al.*, 2024, Wesselmann *et al.*, 2024) (see Section 4, Chapter 6).

4.3 The South Atlantic Ocean and the Wider Caribbean

Increases in macroalgal cover on hard coral reefs have been reported in the Mexican Caribbean (Contreras-Silva *et al.*, 2020) and in floating, invasive, 'pelagic' *Sargassum* spp., which has extended beyond the Sargasso Sea (see Sub-chapter 5q) (Wang *et al*. 2019) and proliferated in the tropical Atlantic between West Africa, Brazilian Oceanic islands (Pellizzari *et al.* 2020) and South America (Robledo *et al.*, 2021, Sissini *et al.* 2017) (see Section 4, Chapter 6).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

As in the Caribbean, more temperature tolerant macroalgae are becoming increasingly dominant on coral reefs following incidences of coral bleaching (Gonzalez *et al.*, 2024).

4.5 The North Pacific Ocean

Twenty red macroalgal species are reported in the IUCN Red List for this region and all are endemic to the Republic of Korea (North-Western Pacific). Four of these species are categorised as Least Concern and sixteen are categorised as Data Deficient (IUCN, 2024). The green macroalga *Codium spinulosum* (Bryopsidales) and three species of brown macroalgae are also endemic to the Republic of Korea (Yim and Won, 2023) and are categorised as Data Deficient (IUCN, 2024).

4.6 The South Pacific Ocean

The IUCN Red List lists 58 red macroalgal species for the South Pacific Ocean. This includes one Extinct species from the South-western Pacific and 57 species from the South-eastern Pacific categorised as: Critically Endangered (6), Vulnerable (3), Least Concern (4) and Data Deficient (44) (IUCN, 2024). The brown macroalga *Nereia lophocladia* is endemic to New South Wales, Australia (Mamo *et al.*, 2021), in the South-western Pacific and two green macroalgal species, *Rhizoclonium robustum* (Cladophorales) and *Entocladia thivyae,* are both endemic to the Galapagos Islands in the South-eastern Pacific (Ruiz and Ziemmeck, 2013). All three species are categorised as Data Deficient (IUCN, 2024). Fifteen species of brown macroalgae from the South-eastern Pacific are thought to be endemic to the Galapagos and are categorised as Endangered (1), Critically Endangered (4), Vulnerable (1) and Data Deficient (9) in the IUCN Red List (IUCN, 2024).

4.7 The Southern Ocean

Records have recently been compiled for this region, which include 151 macroalgal species (85 Rhodophyta, 34 Ochrophyta and 32 Chlorophyta) for Antarctica, South Shetland Islands (Pellizzari *et al.* 2023, Oliveira *et al.* 2020), King George Island and Adelaide Island (Nelson *et al.*, 2022). Distributional shifts and a reduction in endemism rate have been reported in this region (Pellizzari *et al.,* 2017) and a recent modelling study has predicted that there is a high potential for macroalgal expansion into this region, as a consequence of climate change (Manca *et al.*, 2024).

5 Remaining key knowledge gaps

Despite the substantial evidence showing that macroalgal species and their habitats are declining, significant numbers of species remain undescribed, undiscovered (Guiry, 2024) and/or inadequately protected or conserved. The lack of a sound taxonomic framework for identifying and monitoring species hampers efforts to determine their distribution, threats and changes to status (Brodie *et al.*, 2023), as well for implementing effective conservation, protection and restoration strategies. It also presents significant challenges in assessing species for the IUCN Red List, which can raise awareness and assist in the global conservation of a species, as clearly shown by the fact that <1% of macroalgae known are listed from a very limited number of regions globally. The contribution of many seaweeds (e.g., rhodolith beds and kelp forests) to larger scale processes, such as carbon sequestration (Schubert *et al.*, 2024) also requires further investigation (IOC-

UNESCO, 2024). There is urgent need, therefore, to (i) strengthen data-driven conservation efforts to ensure losses in macroalgal diversity are halted and habitats restored, whenever possible, (ii) ensure range shifts are reported and vulnerable species protected, (iii) identify undescribed species using the latest molecular approaches, and (v) ensure that the role of macroalgae in large-scale ocean processes is more widely understood.

6 References

Barbera, C., Bordehore, C., Borg, J. A., Glémarec, M., Grall, J., Hall-Spencer, J. M., De La Huz, C. H., Lanfranco, E., Lastra, M., Moore, P. G. and Mora, J. Conservation and management of northeast Atlantic and Mediterranean maerl beds. Aquatic conservation: marine and freshwater ecosystems, vol. 13, pp. S65-S76, 2003.

Bermejo, R., Green-Gavrielidis, L. and Gao, G. Macroalgal blooms in a global change context. Frontiers in Marine Science, vol., pp. 1204117, 2023.

Brakel, J., Sibonga, R., Dumilag, R.V., Montalescot, V., Campbell, I., Cottier-Cook, E.J., Ward, G., Le Masson, V., Liu, T., Msuya, F.E., Brodie, J., Lim, P.E. and Gachon, C.M.M. Exploring, harnessing, and conserving genetic resources towards a sustainable seaweed aquaculture. Plants, People, Planet, vol. 3, pp. 337-349, 2021.

Bringloe, T. T., Wilkinson, D. P., Goldsmit, J., Savoie, A. M., Filbee-Dexter, K., Macgregor, K. A., Howland, K. L., McKindsey, C. W., Verbruggen, H. Arctic marine forest distribution models showcase potentially severe habitat losses for cryophilic species under climate change. Global Change Biology, vol. 28, pp. 3711-3727, 2022.

Brodie, J., Wilbraham, J., Maggs, C. A., Baldock, L., Bunker, F., Mieszkowska, N., Scanlan, C., Tittley, I., Wilkinson, M. and Yesson, C. Red List for British seaweeds: evaluating the IUCN methodology for non-standard marine organisms. Biodiversity Conservation, vol. 32, pp. 3825–3843, 2023.

Chan, P.T.W, Halfar, J., Adey, W.H., Lebednik, P.A., Steneck, R., Norley, C.J.D. and Holdsworth, D.W. Recent density decline in wild-collected subarctic crustose coralline algae reveals climate change signature. Geology, vol. 48, pp. 226-230, 2020.

Cornwall, C. E., Harvey, B. P., Comeau, S., Cornwall, D. L., Hall-Spencer, J. M., Pena, V., Wada, S. and Porzio, L. Understanding coralline algal responses to ocean acidification: Meta-analysis and synthesis. Global Change Biology, vol. 28, pp. 362-374, 2021.

Cottier-Cook, E. J., Lim, P. E., Mallinson, S., Yahya, N., Poong, S., Wilbraham, J., Nagabhatla, N., Brodie, J., Nations, U., Policy, U. I. O. C. R. I. S. and Brief. Striking a balance: wild stock protection and the future of our seaweed industries. *Policy Brief* [Online]. 2023.

Cottier-Cook, E. J., Nagabhatla, N., Asri, A., Beveridge, M., Bianchi, P., Bolton, J., Bondad-Reantaso, M. G., Brodie, J., Buschmann, A., Cabarubias, J., Campbell, I., Chopin, T., Critchley, A., De Lombaerde, P., Doumeizel, V., Gachon, C. M. M., Hayashi, L., Hewitt, C. L., Huang, J., Hurtado, A. Q., Kambey, C., Kim, G. H., Le Masson, V., Lim, P.-E., Liu, T., Malin, G., Matoju, I., Montalescot, V., Msuya, F. E., Potin, P., Puspita, M., Qi, Z., Shaxson, L., Sousa Pinto, I., Stentiford, G. D., Suyo, J. and Yarish, C. Ensuring the sustainable future of the rapidly expanding global seaweed aquaculture industry – a vision. *Policy Brief* [Online]. 2021.

Contreras-Silva, A. I., Tilstra, A., Migani, V., Thiel, A., Pérez-Cervantes, E., Estrada-Saldívar, N., Elias-Ilosvay, X., Mott, C., Alvarez-Filip, L. & Wild, C. A meta-analysis to assess long-term spatiotemporal changes of benthic coral and macroalgae cover in the Mexican Caribbean. Scientific Reports, vol. 10, pp. 8897, 2020.

Dalmau, N. A., Cebrian, E., Dunga, L. V., Horta, P., Layton, C., Macaya, E. C., Mangialajo, L., Moore, P. J., Mora-Soto, A., Reddy, M. M., Smit, A. J., Spector, P., Nguyen, V. T., Verdura, J. and Pocklington, J. B. Introducing the Seaweed Specialist Group of the IUCN Species Survival Commission, Cambridge, PRESS, C. U., 2024.

Del Cortona, A., Jackson, C. J., Bucchini, F., Van Bel, M., D'hondt, S., Skaloud, P., Delwiche, C. F., Knoll, A. H., Raven, J. A., Verbruggen, H., Vandepoele, K., De Clerck, O. and Leliaert, F. Neoproterozoic origin and multiple transitions to macroscopic growth in green seaweeds. Proceedings of the National Academy of Sciences of the United States of America, vol. 117, pp. 2551, 2020.

Descourvières, E., Bandelj, V., Sfriso, A., Orlando-Bonaca, M., Mačić, V., Iveša, L., Kipson, S., Gljušćić, E., Battelli, C., Moro, I., Solidoro, C. & Falace, A. Toward the first documented extinction of a marine macroalga in the Mediterranean Sea? Regional Environmental Change, vol. 24, pp., 2024.

Díaz-Tapia, P., Pasella, M. M., Verbruggen, H. and Maggs, C. A. Morphological evolution and classification of the red algal order Ceramiales inferred using plastid phylogenomics. Molecular Phylogenetic Evolution, vol. 137, pp. 76-85, 2019.

Duarte, C. M., Gattuso, J.-P., Hancke, K., Gundersen, H., Filbee-Dexter, K., Pedersen, M. F., Middleburg, J. J., Burrows, M. T., Krumhansl, K. A., Wernberg, T., Moore, P., Pessarrondona, A., Orberg, S. B., Pinto, I. S., Assis, J., Queiros, A. M., Smale, D., Bekkby, T., Serrao, E. A. and Krause-Jensen, D. Global estimates of the extent and production of macroalgal forests. Global Ecology and Biogeography, vol. 31, pp. 1422-1439, 2022.

Eger, A. M., Marzinelli, E. M., Beas-Luna, R., Blain, C. O., Blamey, L. K., Byrnes, J. E. K., Carnell, P. E., Choi, C. G., Hessing-Lewis, M., Kim, K. Y., Kumagai, N. H., Lorda, J., Moore, P., Nakamura, Y., Perez-Matus, A., Ponjtier, O., Smale, D., Steinberg, P. E. and Verges, A. The value of ecosystem services in global marine kelp forests. Nature Communications, vol. 14, pp. 1894, 2023.

El-Manaway, I. M. and Rashedy, S. H. The ecology and physiology of seaweeds: An Overview. In: RAO, A. R. and RAVISHANKAR, G. A. (eds.) *Sustainable Global Resources of Seaweeds.* Cham, Switzerland: Springer, 2022.

Falace, A., Alongi, G., Orlando-Bonaca, M. and Becvilacqua, S. Species loss and decline in taxonomic diversity of macroalgae in the Gulf of Trieste (Northern Adriatic sea) over the last six decades. Marine Environmental Research, vol. 202, pp. 106828, 2024.

Feng, Y., Xiong, Y., Hall-Spencer, J. M., Liu, K., Beardall, J., Gao, K., Ge, J., Xu, J. and Gao, G. Shift in algal blooms from micro- to macroalgae around China with increasing eutrophication and climate change. Global Change Biology, vol. 30, pp. e17018, 2023.

Filbee-Dexter, K. and Wernberg, T. Rise of Turfs: A New Battlefront for Globally Declining Kelp Forests. Bioscience, vol. 68, pp. 64-76, 2018.

Filbee-Dexter, K., Pessarrodona, A., Pedersen, M.F., Wernberg, T., Duarte, C. M., Assis, J., Bekkby, T., Burrows, M. T., Carlson, D. F., Gattuso, J. P., Gundersen, H., Hancke, K., Krumhansl, K. A., Kuwae, T., Middelburg, J. J., Moore, P. J., Queirós, A. M., Smale, D., Sousa Pinto, I., Suzuki, N. and Krause-Jensen, D. Carbon export from seaweed forests to deep ocean sinks. Nature Geoscience, vol. 17, pp. 552-559, 2024.

Fragkopoulou, E., Serrão, E. A., Horta, P. A., Koerich, G. and Assis, J. Bottom trawling threatens future climate refugia of rhodoliths globally. Frontiers in Marine Science, vol. 7, pp. 594537, 2021.

Gabrielson, P. W., Smith, A. C., Bruno, J. F., Vision, T. J. and M, B. Taxonomic assessment of blade-forming *Ulva* species (Ulvales, Chlorophyta) in the Galápagos Archipelago, Ecuador using DNA sequencing. Botanica Marina, vol. 67, pp. 153-164, 2024.

Gattuso, J.-P., Gentili, B., Duarte, C. M., Kleypas, J. A., Middelburg, J. J. and Antoine, D. Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and contribution to primary production. Biogeosciences Discussions, vol. 3, pp. 895–959, 2006.

Gonzalez, K., Daraghmeh, N., Lozano-Cortés, D., Benzoni, F., Berumen, M. L. and Carvalho, S. Differential spatio-temporal responses of Red Sea coral reef benthic communities to a mass bleaching event. Scientific reports, vol. 14, pp. 24229, 2024.

Guiry, M. D. How many species of algae are there? A reprise. Four kingdoms, 14 phyla, 63 classes and still growing. Journal of Phycology, vol. 60, pp. 214-228, 2024.

Hall, J. R., Herkül, K., Baltar, F., Hepburn, C. D. and Martin, G. Shifts in macroalgae composition alters carbon flow in Coastal Baltic Sea ecosystems: implications for dissolved organic carbon bioavailability and flux. Frontiers in Marine Science, vol. 11, pp., 2024.

Hou, Z., Ma, X., Shi, X., Li, X., Yang, L., Xiao, S., De Clerck, O., Leliaert, F. and Zhong, B. Phylotranscriptomic insights into a Mesoproterozoic-Neoproterozoic origin and early radiation of green seaweeds (Ulvophyceae). Nature Communications, vol. 13, pp. 1610, 2022.

Hughey, J. R., Gabrielson, P. W., Maggs, C. A. and Mineur, F. Genomic analysis of the lectotype specimens of European *Ulva rigida* and *Ulva lacinulata* (Ulvaceae, Chlorophyta) reveals the ongoing misapplication of names. European Journal of Phycology, vol. 57, pp. 143-153, 2021.

Hughey, J. R., Gabrielson, P. W., Maggs, C. A., Mineur, F. and Miller, K. A. Taxonomic revisions based on genetic analysis of type specimens of *Ulva conglobata, U. laetevirens, U.*

pertusa and *U. spathulata* (Ulvales, Chlorophyta). Phycological Research, vol. 69, pp. 148-153, 2020.
Hughey, J. R., Maggs, C. A., Mineur, F., Jarvis, C., Miller, K. A., Shabaka, S. H. and Gabrielson, P. Genetic analysis of the Linnaean *Ulva lactuca* (Ulvales, Chlorophyta) holotype and related type specimens reveals name misapplications, unexpected origins, and new synonymies (Letter). Journal of Phycology vol. 55, pp. 503-508, 2019.
IOC-UNESCO. State of the Ocean Report, Paris, IOC-UNESCO, 2024.
IPCC. Climate Change 2023: Synthesis Report, Geneva, Switzerland, 2023.
IUCN. 2024. The IUCN Red List of Threatened Species [Online]. Available: https://www.iucnredlist.org/en, 2024.
Jeong, S. Y., Nelson, W. A., Sutherland, J. E., Peña, V., Le Gall, L., Diaz-Pulido, G., Won, B. Y. and Cho, T. O. Corallinapetrales and Corallinapetraceae: a new order and family of coralline red algae including *Corallinapetra gabrielii* comb. nov. Journal of Phycology, vol. 57, pp. [1-14] 849-862R, 2021.
Joniver, C. F. H., Photiades, A., Moore, P. J., Winters, A. L., Woolmer, A. and Adams, J. M. M. The global problem of nuisance macroalgal blooms and pathways to its use in the circular economy. Algal Research, vol. 58, pp. 102407, 2021.
Jurejan, N., Draisma, S., Vieira, C., Sun, Z., Avakul, P., Klomjit, A., Chirapart, A. and Muangmai, N. Three new *Lobophora* species (Dictyotales, Phaeophyceae) from Phuket on the west coast of Thailand. Botanica Marina, vol. 67, pp., 2024.
Kawai, H. and Hanyuda, T. Discovery of a novel brown algal genus and species *Setoutiphycus delamareoides* (Phaeophyceae, Ectocarpales) from the Seto Inland Sea, Japan. Scientific reports, vol. 11, pp. 13901, 2021.
Krause-Jensen, D., Archambault, P., Assis, J., Bartsch, I., Bischof, K., Filbee-Dexter, K., Dunton, K. H., Maximova, O., Ragnarsdottir, S. B., Sejr, M. K., Simakova, U., Spiridonov, V. A., Wegeberg, S., Winding, M. H. S. and Duarte, C. M. Imprint of Climate Change on Pan-Arctic Marine Vegetation. Frontiers in Marine Science, vol. 7, pp., 2020.
La Guardia, L. C., Filbee-Dexter, K., Reimer, J., Macgregor, K. A., Garrido, I., Singh, R. K., Bélanger, S., Konar, B., Iken, K., Johnson, L. E., Archambault, P., Sejr, M. K., Søreide, J. E. and Mundy, C. J. Increasing depth distribution of Arctic kelp with increasing number of open water days with light. Elementa: Science of the Anthropocene, vol. 11, pp. 00051, 2023.
Lagourgue, L., Gobin, S., Maele, B., Sylvette, V., Bonneville, C., Thierry, J., Simon, V. W. and Payri, C. E. Ten new species of *Ulva* (Ulvophyceae, Chlorophyta) discovered in New Caledonia: genetic and morphological diversity, and bloom potential. European Journal of Phycology, vol. 57, pp. 458-478, 2022.
Leathers, T., King, N.G., Foggo, A., Smale, D.A. Marine heatwave duration and intensity interact to reduce physiological tipping points of kelp species with contrasting thermal affinities. Annals of Botany, vol. 133, pp. 51-59, 2024.
Lebrun, A., Comeau, S., Gazeau, F. and Gattuso, J. P. Impact of climate change on Arctic macroalgal communities. Global and Planetary Change, vol. 219, pp. 103980, 2022.
Leliaert, F., Payo, D. A., Gurgel, C. F. D., Schils, T., Draisma, S. G., Saunders, G. W., Kamiya, M., Sherwood, A. R., Lin, S. M., Huisman, J. M., Le Gall, F., Anderson, R. J., Bolton, J. J., Mattio, L., Zubia, M., Spokes, T., Vieira, C., Payri Claude, E., Coppejans, E., D'Hondt, S.,

Verbruggen, H. and De Clerck, O. Patterns and drivers of species diversity in the Indo-Pacific red seaweed *Portieria.* Journal of Biogeography, vol. 45, pp. 2299, 2018.
Littler, M. M., Littler, D. S. and Hanisak, M. D. Deep-water rhodolith distribution, productivity, and growth history at sites of formation and subsequent degradation. Journal of experimental marine biology and ecology, vol. 150, pp. 163-182, 1991.
Littler, M. M., Littler, D. S., Blair, S.M. and Norris, J.N. Deepest known plant life discovered on an uncharted seamount. Science, vol. 227, pp. 57-59, 1985.
~~Liu, F., Pang, S., Chopin, T., Gao, S., Shan, T., Zhao, X. and Li, J. Understanding the recurrent large-scale green tide in the Yellow Sea: Temporal and spatial correlations between multiple geographical, aquacultural and biological factors. Marine Environmental Research, vol. 83, pp. 38-47, 2013.~~
Mac Monagail, M., Cornish, L., Morrison, L., Araújo, R. and Critchley, A. T. Sustainable harvesting of wild seaweed resources. European Journal of Phycology, vol. 52, pp. 371–390, 2017.
Mamo, L. T., Wood, G., Wheeler, D., Kelaher, B. P. and Coleman, M. A. Conservation genomics of a critically endangered brown seaweed. Journal Phycology, vol. 57, pp. 1345-1355, 2021.
Manca, F., Benedetti-Cecchi, L., Bradshaw, C. J. A., Cabeza, M., Gustafsson, C., Norkko, A. M., Roslin, T. V., Thomas, D. N., White, L. and Strona, G. Projected loss of brown macroalgae and seagrasses with global environmental change. Nature Communications, vol. 15, pp. 5344, 2024.
Mao, J., Burdett, H. L. and Kamenos, N. A. Efficient carbon recycling between calcification and photosynthesis in red coralline algae. Biology Letters, vol. 20, pp. 20230598, 2024.
McNeil, M. A., Webster, J. M., Beaman, R. J. and Graham, T. L. New constraints on the spatial distribution and morphology of the *Halimeda* bioherms of the Great Barrier Reef, Australia. Coral Reefs, vol. 35, pp. 1343–1355, 2016.
Murúa, P., Muñoz, L., Bustamante, D., Gauna, C., Hayashi, L., Robledo, D., Strittmatter, M., Arce, P., Westermeier, R., Müller, D. G. and Gachon, C. M. M. The first phycopathological atlas in Latin America unveils the underdocumentation of algal pathogens. Algal Research, vol. 82, pp. 103604, 2024.
Nelson, W. A., Neill, K. F., D'archino, R. and Sutherland, J. E. Marine macroalgae of the Balleny Islands and Ross Sea. Antarctic Science, vol. 34, pp. 298-312, 2022.
Oliveira, M.C., Pellizzari, F., Medeiros, A.S. and Yokoya, N. S. Diversity of Antarctic seaweeds. In I. Gómez and P. Huovinen, eds, Antarctic seaweeds, 1st edition. Cham: Springer International Publishing, 23–42, 2020.
Page, H. N., Bahr, K. D., Cyronak, T., Jewett, E. B., Johnson, M. D. and Mccoy, S. J. Responses of benthic calcifying algae to ocean acidification differ between laboratory and field settings. ICES Journal of Marine Science, vol. 79, pp. 1-11, 2022.
Pellizzari, F., Mello, J. P. S., Osaki, V. S., Santos-Silva, M. C., Brandini, F. P., Convey, P. and Rosa, L. H. New records and updated distributional patterns of macroalgae from the South Shetland Islands and northern Weddell Sea, Antarctica. Antarctic Science, vol. 35, pp. 243-255, 2023.
Pellizzari, F., Osaki, V.S. and Santos-Silva, M.C. New records of seaweeds and filamentous cyanobacteria from Trindade Island: an updated checklist to support conservation guidelines and monitoring of environmental changes in the southern Atlantic archipelagos. Scientia Marina, vol. 84, pp. 227-242, 2020.

Pellizzari, F., Santos-Silva, M.C, Medeiros, A., Oliveira, M.C., Yokoya, N.S., Pupo, D. and Rosa, L.. Diversity and spatial distribution of seaweeds in the South Shetland Islands, Antarctica: an updated database for environmental monitoring under climate change scenarios. Polar Biology, vol. 40, pp. 1671-1685, 2017.

Rendina, F., Buonocore, E., Di Montanara, A. C. and Russo, G. F. The scientific research on rhodolith beds: A review through bibliometric network analysis. Ecological Informatics, vol. 70, pp. 101738, 2022.

Robledo, D., Vazquez-Delfin, E., Freile-Pelegrin, Y., Vasquez-Elizondo, R. M., Qui-Minet, Z. N. and Salazar-Garibay, A. Challenges and Opportunities in Relation to *Sargassum* Events Along the Caribbean Sea. Frontiers in Marine Science, vol. 8, pp. 699664, 2021.

Ruiz, D. and Ziemmeck, F. CDF Checklist of Galapagos Heterokonts: Brown algae and related groups - FCD Lista de especies de Heterokonta: Algas pardas y grupos relacionados de Galápagos. In: Bungartz, F., Herrera, H., Jaramillo, P., Tirado, N., Jimenez-Uzcategui, G., Ruiz, D., Guezou, A. and Ziemmeck, F. (eds.) *Charles Darwin Foundation Galapagos Species Checklist - Lista de Especies de Galápagos de la Fundación Charles Darwin.* Puerto Ayora: Charles Darwin Foundation / Fundación Charles Darwin, 2013.

Schubert, N., Alvarez-Filip, L. and Hofmann, L. C. Systematic review and meta-analysis of ocean acidification effects in *Halimeda*: Implications for algal carbonate production. Climate Change Ecology, vol. 4, pp. 100059, 2023.

Schubert, N., Tuya, F., Peña, V., Horta, P. A., Salazar, V. W., Neves, P., Ribeiro, C., Otero-Ferrer, F., Espino, F., Schoenrock, K., Ragazzola, F., Olive, I., Giaccone, T., Nannini, M., Mangano, M. C., Sara, G., Mancuso, F. P., Tantillo, M. F., Bosch-Belmer, M., Martin, S., Le Gall, L., Santos, R. and Silva, J. Pink power—the importance of coralline algal beds in the oceanic carbon cycle. Nature Communications, vol. 15, pp. 8282, 2024.

Sissini, M. N., Barreto, M. B. B., Szechy, M. T. M., De Lucena, M. B., Oliverra, M. C., Gower, J., Liu, G., De Oliveria Bastos, E., Milstein, D., Gusmao, F., Martinelli-Filho, J. E., Alves-Lima, C., Colepicolo, P., Ameka, G., De Graft-Johnson, K., Gouvea, L., Torrano-Silva, G., Nauer, F., De Castro Nunes, J. M., Barufi, J. B., Rorig, L., Riosmena-Rodriguez, R., Mello, T. J., Lotufo, L. V. C. and Horta, P. A. The floating *Sargassum* (Phaeophyceae) of the South Atlantic Ocean - likely scenarios. Phycologia, vol. 56, pp. 321-328, 2017.

Smetacek, V. and Zingone, A. Green and golden seaweed tides on the rise. Nature, vol. 504, pp. 84-88, 2013.

Sun, Z., Dao, M. D., Tran, Q. T. and Dam, D. T. A new species *Lobophora tsengii* sp. nov. (Dictyotales; Phaeophyceae) from Bach Long Vy (Bailongwei) Island, Vietnam. Journal of Oceanography and Limnology, vol. 39, pp. 2363–2369, 2021.

Sutherland, J. E., Lindstrom, S., Nelson, W., Brodie, J., Lynch, M., Hwang, M. S., Choi, H.-G., Miyata, M., Kikuchi, N., Oliveira, M., Farr, T., Neefus, C., Mortensen, A., Milstein, D. and Müller, K. A new look at an ancient order: generic revision of the Bangiales. Journal of Phycology, vol. 47, pp. 1131-1151, 2011.

Tran, L.-A. T., Vieira, C., Steinhagen, S., Maggs, C. A., Hiraoka, M., Shimada, S., Van Nguyen, T., De Clerck, O. and Leliaert, F. An appraisal of *Ulva* (Ulvophyceae, Chlorophyta) taxonomy. Journal Applied Phycology, vol. 34, pp. 2689-2703, 2022.

UN. The second World Ocean Assessment - Volume 1, New York, 2021.

UNEP. The First Global Integrated Marine Assessment: World Ocean Assessment I, UNEP, 2016.

Verbruggen, H. and Ballesteros, E. An Atlantic origin for the introduced species *Halimeda incrassata* (Bryopsidales, Chlorophyta). Mediterranean Marine Science, 25(1), 55-57, 2024.

Vieira, C., Anderson, R. J., Engelen, A. H., D'hondt, S., Leliaert, F., Payri, C., Kawai, H. and De Clerck, O. *Lobophora* (Dictyotales, Phaeophyceae) from the western Indian Ocean: diversity and biogeography. South African Journal of Botany, vol. 142, pp. 230-246, 2021.

Wang, M., Hu, C., Barnes, B. B., Mitchum, G., Lapointe, B. and Montoya, J. P. The great Atlantic *Sargassum* belt. Science, vol. 365, pp. 83-87, 2019.

Wesselmann, M., Hendricks, I. E., Johnson, M. D., Jorda, G., Mineur, F. and Marba, N. Increasing spread rates of tropical non-native macrophytes in the Mediterranean Sea. Global Change Biology, vol. 30, pp. e17249, 2024.

Win, N. N. W., Hanyuda, T., Assuyuti, Y., Putri, L., Geraldino, P. J. and Kawai, H. Two new species of *Dictyota* (Dictyotales, Phaeophyceae), *D. dimorphosa* sp. nov . and *D. recumbens* sp. nov ., based on morphological and molecular investigations. Phycologia, vol. 63, pp. 290-302, 2024.

Yang, L.-E., Deng, Y. Y., Xu, G.-P., Russell, S., Lu, Q.-Q. and Brodie, J. Redefining Pyropia (Bangiales, Rhodophyta): four new genera, resurrection of *Porphyrella* and description of *Calidia pseudolobata* sp. nov. from China. Journal of Phycology, vol. 56, pp. 862-879, 2020.

Yim, D. and Won, S.-Y. 2023. *Codium spinulosum*. The IUCN Red List of Threatened Species 2023: e.T198113266A200405856 [Online]. IUCN. Available: https://www.iucnredlist.org/species/198113266/200405856, 2023.

Zhang, J., Ding, X., Zhuang, M., Wang, S., Chen, L., Shen, H. and He, P. An increase in new *Sargassum* (Phaeophyceae) blooms along the coast of the East China Sea and Yellow Sea. Phycologia, vol. 58, pp. 374–381, 2019.

Žuljević, A., Peters, A.F., Nikolić, V., Antolić, B., Despalatović, M., Cvitković, I., Isajlović, I., Mihanović, H., Matijević, S., Shewring, D.M. and Canese, S. The Mediterranean deep-water kelp *Laminaria rodriguezii* is an endangered species in the Adriatic Sea. Marine biology, vol. 163, pp. 1-12, 2016.

Contributing Authors - ORCID

Cottier-Cook - 0000-0002-1466-6802

Brodie - 0000-0001-7622-2564

Corrigan – 0000-0002-1929-995X

De Clerck – 0000-0002-3699-8402

Lim – 0000-0001-9186-1487

Maggs – 0000-0003-0495-7064

Msuya – 0000-0001-6578-6268
Pellizzari - 0000-0003-1877-2570
Liu - 0009-0002-1421-3253
Wernberg - 0000-0003-1185-9745
Verbruggen - 0000-0002-6305-4749
Wilbraham - 0000-0003-4101-0611
Yokoya - 0000-0001-8322-3178

Section 4 Chapter 5: Habitats (introduction)

This chapter consists of 18 subchapters.~~The present chapter is composed of 18 subchapters~~. It details the trends and state of a diverse range of marine and coastal habitats and ecosystems, providing insights into their characteristics, the changes they are undergoing, and the pressures they face. Building upon the previous global assessments,~~ they cover diverse marine habitats – from near-shore mangrove forests and salt marshes to the deepest trenches and seamounts.~~ it examines a wide range of marine habitats, from near-shore mangrove forests and salt marshes to the deepest trenches and seamounts. The change in state since the second World Ocean Assessment (WOAII) is provided on mangrove forests, salt marshes, estuaries and deltas, rocky shores, seagrass meadows, cold water corals, tropical and subtropical coral reefs, the Sargasso Sea, high-latitude ice, hydrothermal vents and cold seeps, and submarine habitats, such as seamounts, submarine canyons and trenches and abyssal plains .The baseline of the state of the habitat from the WOA II ~~second Assessment~~ was used as a basis for looking at change over the last decade.~~ -~~The baseline established in the second Assessment serves as a reference point for examining changes over the past decade. Key threats to habitats have been identified and their influence on changes observed has been discussed. When available, specific regional changes have also been highlighted, and an outlook for habitats ~~over the near to medium term has been provided~~ in the short to medium term is discussed

In this review, a new assessment is provided on "Fjord systems" (S4.C5r), including their ecological characteristics, as well as the effects of global warming and glacial changes.~~ecological characteristics and the impacts of global warming and glacial changes.~~ The previously termed "Open oceans" subchapter was renamed to Pelagic domains (S4.C5n) ~~domains(S4.C5n)~~, which covers its ecological zones, significance, and threats posed by pollution and climate change~~which includes its zones, ecological importance and threats from pollution and climate change~~. Given their widespread presence on hard substrates worldwide, sponges are now specifically examined in the 'Cold-Water Corals and Sponges' subchapter. ~~Sponges in view of their ubiquitous presence on hard substrata throughout the world, are now specifically discussed in the 'Cold water corals and sponges' sub-chapter.~~

All these ecosystems also face substantial anthropogenic pressures which are explored in greater detail both generally and within each subchapter. ~~which are then generally discussed more in detail and specifically in each sub-chapter~~. Despite all the challenges listed for each habitat type, efforts towards conservation and management are also discussed.

Section 4:

Chapter 5a: Intertidal Zone

Martin Zimmer - Leibniz Centre for Tropical Marine Research, ZMT, Bremen, Germany

Pilar Muñoz-Muga - Cultura Oceánica en 360°, FACIMAR-UV, Universidad de Valparaíso, Valparaíso, Chile

Sheila N Rioba - Kenya Fisheries Service, Kisumu, Kenya

Niki Evelpidou - Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece

1 Keynotes

The intertidal zone has undergone considerable transformations, primarily driven by climate change, pollution and coastal development. Sea level-rise and coastal squeeze have led to habitat loss and reduced ecosystem services, such as the provision of natural resources or coastal protection. Rising temperatures and extreme weather events have exacerbated these effects.

Efforts to integrate intertidal ecosystems into climate change mitigation initiatives and increased aquaculture activities have impacted intertidal zones. Mangrove forests, salt marshes and seagrass beds are increasingly recognized for their role as blue carbon sinks, with initiatives aiming to (re-)establish and protect these habitats for their ecological and economic value.

Regional differences in recent developments become obvious, with each biogeographical region facing distinct challenges. Arctic areas are impacted by sea ice retreat, while urbanisation in regions like the Mediterranean and Caribbean leads to eutrophication and habitat fragmentation. The vulnerability of intertidal ecosystems requires tailored conservation strategies that reflect regional socio-economic and environmental contexts.

(Re-)establishment efforts, such as (re-)introducing mangroves and seagrass, and implementing green-grey infrastructure, are promising for mitigating habitat loss. The shift towards high-intervention approaches, such as Ecosystem Co-Design, aims to create resilient socio-ecological systems that adapt to climate change while providing essential ecosystem services.

Increasing CO_2 concentrations of the seawater result in ocean acidification that increasingly affects inhabitants of intertidal ecosystems, particularly calcifying organisms like mollusks and corals.

2 Introduction

The intertidal zone is a dynamic interface between marine and terrestrial environments, characterised by large environmental variability due to regionally specific tidal regimes. This boundary includes diverse habitats (Fig. 1), such as rocky shores (with macroalgal forests), mudflats, seagrass beds, mangrove forests, saltmarshes, or sandy beaches, each providing essential services, such as shoreline stabilisation, carbon sequestration [Chapter S5B.C1], and habitat-provisioning for numerous species (Phang et al., 2015).

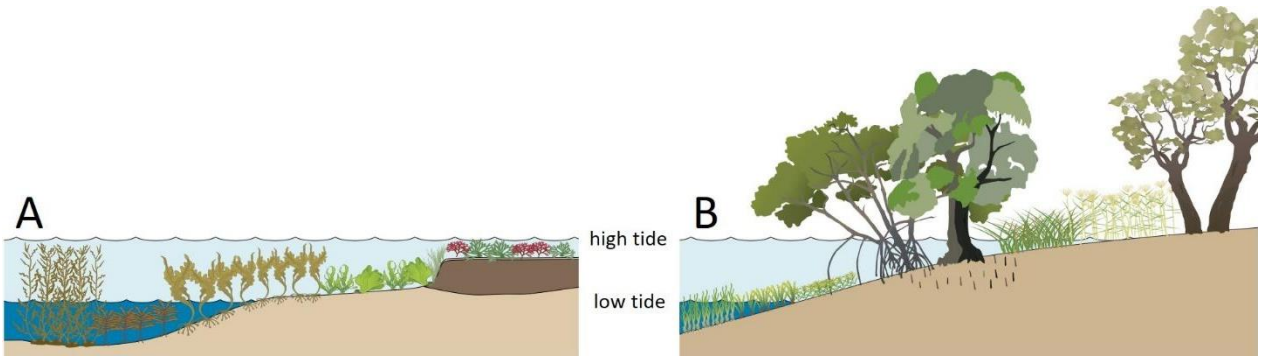


Fig. 1. Exemplary zonation of macrophytes in coastal and intertidal ecosystems. (A) temperate rocky shores: subtidal (e.g., *Macrocystis* spp., *Ecklonia* spp.), low-intertidal (e.g., *Laminaria* spp., *Lessonia* spp., *Ulva* spp.), mid-intertidal (e.g., *Chaetomorpha* spp.), high-intertidal (e.g., *Chondrus* spp., *Codium* spp.) macroalgal beds [Chapter S4.C4i]; (B) (sub-)tropical soft sediment shores: subtidal and intertidal seagrass beds (e.g., *Thalassia* spp., *Cymodocea* spp., *Halophila* spp.) [Chapter S4.C5g], mid- to high-intertidal mangrove forests (e.g., *Rhizophora* spp., *Avicennia* spp.) [Chapter S4.C5h], high-intertidal and low-supratidal saltmarshes (e.g., *Spartina* spp., *Phragmites* spp.) [Chapter S4.C5i], supratidal coastal forests (e.g., *Melaleuca* spp.). Symbols from ian.umces.edu/media-library.

The first World Ocean Assessment (United Nations, 2017) highlighted the ecological significance of this zone, emphasising its role as a unique interface between land and sea.

The second World Ocean Assessment (United Nations, 2021) documented substantial changes in intertidal ecosystems between 2010 and 2020, driven primarily by climate change, coastal development and invasion by non-native species. Key impacts included habitat degradation and biodiversity loss, notably in vegetated areas like mangrove forests, seagrass beds and salt marshes. These changes have impacted the provisioning of ecosystem services and revealed the vulnerability of intertidal zones to anthropogenic pressures.

This chapter provides an updated assessment of the state of intertidal ecosystems from 2018 to 2023, detailing the effects of sea level-rise, pollution, habitat fragmentation and socio-economic shifts. It discusses the importance of regional trends, (re-)establishment efforts and adaptive

strategies, such as Nature-based Solutions (NbS) and green-grey infrastructure, to address these challenges. The aim is to provide a comprehensive overview that supports policymakers in devising targeted conservation and (re-)establishment strategies, while promoting resilience through approaches like Ecosystem Co-Design (Zimmer 2018; Zimmer et al. 2022) and community-based management. This approach aligns with Sustainable Development Goal 14, aiming to conserve and sustainably use marine resources.

3 The environmental change since WOAII

3.1 Changes in the overall status

Climate change and its consequences have become increasingly prevalent, and changes are happening at faster rates than anicipated, posing imminent and rapidly growing threats on coastal ecosystems. Beyond warming itself, sea level-rise has become a tangible change in intertidal habitats.

From 2018 to 2023, sea level-rise has accelerated, averaging 3.2 mm per year globally (NOAA, 2024), and is now exceeding 6 mm per year in regions like Southeast Asia, where land subsidence and glacial melt exacerbate the effects (Idris & Munadi, 2022). Depending on topography, this rise either shifts intertidal habitats landward or compresses them against developed coastlines, resulting in "coastal squeeze" (Rilov et al., 2021). This reduces the extent of intertidal habitats along the tidal gradient, particularly in urban areas, and affects biodiversity and key ecosystem services, such as shoreline stabilisation or carbon sequestration. As sea-level rises, coastal areas become ever more vulnerable to coastal erosion (Evelpidou et al. 2022), especially those that undergo additional, non-climatic rise in sea-level, e.g., due to tectonic subsidence (Cai et al. 2022).

Among direct anthropogenic drivers, agricultural runoff and urban wastewater discharge are major contributors to eutrophication, causing harmful algal blooms and reduced oxygen levels in coastal waters (Tuholske et al., 2021). Heavy metals and hydrocarbons [Chapter S4.C6.sub5] from industries affect sediment characteristics, impact benthic species and reduce biodiversity (Rahmanpour et al., 2014, Moazampour et al., 2021). Urban expansion has increased pollutants, such as microplastics (Chen et al., 2023) that accumulate in many marine organisms (von Hellfeld et al., 2022) and pharmaceuticals, potentially affecting the endocrine system of many organisms (Arguello-Pérez et al., 2019) [Chapter S4.C6.sub5].

Despite these pressures, some regions have seen intertidal habitat expansion due to natural processes. Areas with minimal human interference experienced sediment deposition, partly due to sea level-rise and changed coastal hydrodynamics, forming new mudflats and sandbanks (e.g., ~~at the Jiangsu coast of the Yellow Sea, China:~~ Wang et al., 2012). These new flats provide habitats for diverse species, enhancing local biodiversity. However, such expansions are limited to regions

where natural sediment availability and transport are unaffected by human infrastructure (Braat et al., 2018).

Rising temperatures have been, and still are, affecting the distribution of intertidal species and the species composition of intertidal communities. Warming shifted thermally sensitive species poleward (Habary et al., 2017), invasive species often taking advantage of these conditions, outcompeting native sprecies (Nguyen et al., 2020) [Chapter S4.C6.sub1]. The spread of invasive species is accelerated by global trade and travel (O'Shaughnessy et al., 2020). Along with rising temperatures, the frequency and severity of extreme weather events —such as storms and heatwaves— increased [Chapter S5B.C4], contributing to ecosystem instability (Román et al., 2020).

Habitat fragmentation persists, especially in urbanising regions of Asia and the Middle East, where land reclamation replaces natural intertidal areas by artificial structures (Chee et al., 2017). This fragmentation reduces ecological connectivity needed for species resilience (Aiken et al., 2021), leading to declining species richness, altered ecosystem processes and unequilibrated ecosystems (Sedano et al., 2021). However, some positive efforts, like "green-grey" hybrid infrastructure that integrates natural elements —such as mangroves— into coastal defences, have mitigated erosion and created habitats that support intertidal species (Agardy & MacIntosh, 2023).

Significant socio-economic changes can be attributed to environmental pressures, climate change (Mieszkowska et al. 2021) and conservation and (re-)establishment strategies (Katsanevakis et al., 2020) in the intertidal zone.

In response to declining shellfish populations, aquaculture [S5A.C1c & d] has increasingly focused on regional species better adapted to local environmental conditions (Carranza & zu Ermgassen, 2020). This reduces the impact of non-native species that often disrupt communities and ecosystems as invasives (Lima et al., 2018). Supporting native aquaculture improves sustainability and provides a stable income, contributing to food security and economic resilience (Engle & van Senten, 2022). Integrated and multi-trophic aquaculture (IMTA) has gained popularity. IMTA combines different species, ideally of different trophic levels, of commercial interest to optimise resource use and to reduce environmental impacts (Barrington et al., 2008). For example, farming filter-feeding mollusks improves water quality (reduced nutrient load) and light conditions for primary producers (Du et al., 2023). Including mangroves in shrimp aquaculture also enhances coastal resilience by reducing erosion and improving water quality (Mahmudi et al., 2022), combining some of the many services and benefits of mangroves with food production. This approach aligns with global sustainability goals and offers new economic opportunities for coastal communities (Hossain et al., 2022).

The recognition of intertidal ecosystems, such as mangrove forests, salt marshes and seagrass beds, as important blue carbon sinks has led to efforts to protect and (re-)establish these ecosystems (Heimhuber et al., 2023). Integrating blue carbon valuation into coastal management has created incentives for conservation projects, potentially generating funding through carbon credits and international programs (Friess et al., 2022), provided that proper monitoring, reporting and verification (MRV) are assured (Van Dam et al. 2024).

The socio-economic impacts of rising sea levels and increased storm frequency highlight the need for effective coastal resilience strategies (Hoggart et al., 2014). Nature-based Solutions (NbS), such as mangrove forest (re-)establishment or salt marsh conservation, have been prioritised for their role in enhancing biodiversity and providing coastal defence (Van Coppenolle et al., 2018; Van der Meulen et al. 2023). These approaches can be complemented by engineering solutions, including sea walls, to improve infrastructure (Burcharth et al., 2015). Such green-grey hybrid infrastructure, combining natural elements with technical, architectural or engineering solutions, balances human needs with biodiversity conservation and the need for efficient coastal protection (Waryszak et al., 2021; Evelpidou & Spyrou, 2024).

Coastal tourism can have profound impacts on marine biodiversity (Alsaleh et al. 2023) and can cause pollution of the coastal sediments (Buzzi et al. 2022). Touristic activities on sandy beaches are often facilitated through deliberate destruction of intertidal habitats (Evelpidou et al. 2022; Andriolo & Gonçalves 2023) or removal of beach wrack, gravel, boulders or beach rocks, resulting in changed coastal morphodynamics and increased erosion (Johnston et al., 2023; Saitis, 2022). On the other hand, coastal tourism has faced challenges due to beach erosion, pollution and biodiversity loss, reducing the natural appeal of intertidal and coastal areas (Thinh et al., 2019). This can lead to a decline in tourism revenue, pushing communities to adapt by promoting conservation-focused or eco-tourism initiatives (Lukoseviciute & Panagopoulos, 2021). These adaptations provide new income opportunities and raise awareness of the importance of preserving intertidal ecosystems (Harahab et al., 2021) for both tourists and local actors.

Community-based management of coastal resources has gained emphasis, recognizing that local, traditional and ~~i~~Indigenous Peoples' knowledge and stakeholder engagement and involvement are key to sustainability (Tetelepta et al., 2023). Empowering communities to co-design measures to manage fisheries, (re-)establish ecosystems and participate in conservation programs has been effective in building coastal resilience. These participatory approaches foster a sense of ownership, leading to better stewardship (Galappaththi et al., 2022).

4 Region-specific changes

Intertidal zones across biogeographical regions have experienced distinct trends driven by changing climatic conditions, socio-economic factors and human activities. This section provides an overview of key trends in the seven major biogeographical regions.

4.1 The Arctic Ocean

In the Arctic Ocean, the rapid retreat of sea ice due to increasing temperatures has significantly impacted intertidal habitats (Assis et al., 2022). Rising sea levels and storm frequency have led to coastal erosion, altering sediment patterns and affecting species reliant on stable intertidal environments (Jones et al., 2009). The northward expansion of subarctic species has displaced native Arctic organisms, challenging Iindigenous Ppeoples and communities that depend on intertidal resources (Stafford et al., 2022). Increased commercial shipping traffic due to receding sea ice has led to higher pollution levels, including oil spills and noise pollution, disrupting intertidal ecosystems and wildlife (Ghosh & Rubly, 2015).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

The North Atlantic, Baltic Sea, Black Sea, Mediterranean and North Sea regions have shown varied trends. The North Atlantic and North Sea face extreme weather events, increased frequencies and severities of floods and erosion (Mendez-Tejeda et al., 2020), while warming in the Mediterranean has facilitated invasive species, challenging native communities (Yeruham et al., 2020). Coastal urbanisation in the Baltic (Vigouroux et al., 2021) and Black Seas (Akkoyunlu, 2018) has led to eutrophication, decreasing water quality.

4.3 The South Atlantic Ocean and the Wider Caribbean

In the South Atlantic and wider Caribbean, coastal development [Chapter S5A.C9], especially in urban areas, has fragmented mangrove and seagrass habitats (Blanco-Libreros & Ramírez-Ruiz, 2021). Tourism infrastructure expansion has further contributed to habitat loss (Tuholske et al., 2017).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf face intense socio-economic and anthropogenic environmental pressures. Mangrove forests have been

negatively affected by coastal squeeze (Milani, 2018), and increased temperatures have impacted intertidal ecosystems (Rajalakshmi & Achyuthan 2021).

4.5 The North Pacific Ocean

In the North Pacific, warming waters have shifted species distributions, facilitating invasive species (Liu et al., 2022). Coastal urbanisation (Momota & Hosokawa, 2021), anthropogenic activities (Yap et al., 2020) and increased storm activity pose threats (Kuwano-Yoshida et al., 2022), leading to habitat fragmentation and highlighting the need for resilient construction practices (Bulleri & Chapman 2010).

4.6 The South Pacific Ocean

The South Pacific, including many island nations and SIDS (small island developing states), has been affected by rising sea levels, leading to the loss of critical habitats and ecosystems like mangrove forests (Zhu et al., 2021) that are vital for communities dependent on small-scale fisheries (Flores-Verdugo et al., 2014). Pressures from urban expansion, pollution and habitat loss have caused the degradation of salt marshes and coastal wetlands, impacting both coastal biodiversity and the livelihoods of artisanal fishers (Gaete et al., 2017).

4.7 The Southern Ocean

The Southern Ocean has seen less direct human influence (Murphy et al., 2021), but climate change remains a major driver of environmental and ecological change and degradation of intertidal habitats and ecosystems, as increased temperatures have altered species distributions in Antarctica (Chelchowski et al., 2021).

5 Remaining key knowledge and capacity changes and any new gaps

The ongoing trends in anthropogenic impacts, such as coastal development [Chapter S5A.C9], pollution [Chapter S4.C6.sub5] or resource extraction, continue to degrade intertidal habitats (Stamp et al., 2022). Simultaneously, opportunities exist for (re-)establishment of intertidal ecosystems in degraded and newly emerged habitats. (Re-)establishment efforts, however, must address the balance between species richness, functional diversity, and species distinctiveness to ensure these ecosystems remain ecologically robust and contribute effectively to biodiversity, ecosystem processes and coastal resilience (Lester et al., 2020; Rahman et al., 2021, 2024).

Intertidal ecosystems exhibit a decline in native species richness (Cappelatti et al., 2020), and functional diversity and distinctiveness are increasingly impacted by the proliferation of invasive species (Pires-Teixeira et al., 2021) [Chapter S4.C6.sub1]. As species composition changes, the dynamic equilibrium of these ecosystems (Krohs & Zimmer, 2023) is at risk, potentially undermining their ability to provide essential services such as shoreline stabilisation, nutrient-cycling, and carbon sequestration (Pinto et al., 2014). The success of measures against invasive species will depend on increased awareness of the threats posed by them and on adequate training of staff in the responsible authorities (Roussos et al., 2021).

Conventional restoration methods, which focus on returning ecosystems to their original state, may be insufficient in the face of accelerating climate change and ongoing anthropogenic pressures (Capon & Pettit, 2018). High-intervention approaches, such as Ecosystem Co-Design (Zimmer, 2018; Zimmer et al., 2022), are gaining traction. These methods aim to create resilient socio-ecological systems that mitigate, and adapt to, the effects of climate change while serving human needs. Such strategies integrate natural and artificial components to bolster ecosystem services (Westphal et al., 2022).

Ultimately, the outlook for intertidal ecosystems depends on policy integration and effective management practices that combine conservation, (re-)establishment and adaptive approaches (Baskent, 2020). Stakeholder engagement, particularly involving local actors and communities, and incorporating ~~I~~indigenous Peoples' knowledge, will be crucial for developing strategies that sustain these vulnerable, yet vital, ecosystems amidst ongoing environmental challenges (Ndonye et al., 2021).

Key knowledge gaps for the intertidal zone revolve around the need for improved models and scenarios that project the future state of protected and (re-)established areas under ongoing climate change effects (Garner et al., 2023). Such models must incorporate both physical and biological variables to predict how (re-)establishment actions will fare against accelerating sea level-rise and shifting climatic conditions. Reliable projections are crucial for ensuring the long-term sustainability of intertidal conservation efforts and for informing adaptive management strategies (Judge et al., 2018).

A significant capacity gap is the lack of widespread, standardised monitoring of biodiversity loss and species distribution shifts. Implementation of advanced techniques, such as molecular taxonomy and environmental DNA (eDNA) approaches, is essential to fill this gap. These methods allow for non-invasive, accurate monitoring of species composition and help detect changes, especially in response to climate-induced shifts in distribution, providing critical information for conservation planning (Thomsen & Willerslev, 2015). Actions against future coastal squeeze, such as strategic spatial planning for coastal vegetated ecosystems, require further research and

implementation (Lester et al., 2020). Learning from examples like New Orleans, where proactive spatial planning has designated areas for future coastal vegetated ecosystems, can help mitigate habitat compression (de Mutsert et al., 2021). Such strategies must be adapted to regional contexts to ensure the preservation and resilience of intertidal habitats (Chambers et al., 2019).

Addressing these gaps requires coordinated international and regional efforts (Cavallo et al., 2016), increased funding for technological advances and capacity-development initiatives (Clark et al. 2018) to empower local communities and stakeholders in utilising modern tools and approaches for effective intertidal ecosystem management (Goodspeed et al., 2016).

6 References

Agardy T, MacIntosh K. 2023. Gray leads to green in the blue: building infrastructure to enhance coastal habitat. Coastal Engineering Proceedings 37: https://icce-ojs-tamu.tdl.org/icce/article/view/13051

Aiken CM, Mulloy R, Dwane G, Jackson EL. 2021. Working with nature approaches for the creation of soft intertidal habitats. Front Ecol Evol 9: https://doi.org/10.3389/fevo.2021.682349

Akkoyunlu A. 2018. Land-based pollution of the Black Sea along the Turkish shoreline. J Mar Sci Res Devel 8: https://doi.org/10.4172/2155-9910.1000248

Alsaleh M, Wang X, Nan Z, Liu R, Sun Q. 2023. Impact of coastal tourism demand on fisheries industry sustainability: A suggested framework for blue growth. Natural Resources Forum: 1–27. https://doi.org/10.1111/1477-8947.12332

Andriolo U, Gonçalves G. 2023. Impacts of a massive beach music festival on a coastal ecosystem — A showcase in Portugal. Science of the Total Environment 861: 1–8 https://doi.org/10.1016/j.scitotenv.2022.160733

Arguello-Pérez MA, Mendoza-Pérez JA, Tintos-Gómez A, Ramírez-Ayala E, Godínez-Domíngez E, de Asis Silva Bátiz F. 2019. Ecotoxicological analysis of emerging contaminants from wastewater discharges in the coastal zone of Cihuatlán (Jalisco, Mexico). Water 11: https://doi.org/10.3390/w11071386

Assis J, Serrão EA, Duarte CM, Fragkopoulou E, Krause-Jensen D. 2022. Major expansion of marine forests in a warmer Arctic. Front Mar Sci 9: https://doi.org/10.3389/fmars.2022.850368

Barrington K, Ridler N, Chopin T, Robinson S, Robinson B. 2008. Social aspects of the sustainability of integrated multi-trophic aquaculture. Aquaculture International 18: 201-211.

Baskent EZ. 2020. A framework for characterizing and regulating ecosystem services in a management planning context. Forests 11: https://doi.org/10.3390/f11010102

Blanco-Libreros JF, Ramírez-Ruiz K. 2021. Threatened mangroves in the Anthropocene: habitat fragmentation in urban coastalscapes of *Pelliciera* spp. (Tetrameristaceae) in Northern South America. Front Mar Sci 8: https://doi.org/10.3389/fmars.2021.670354

Braat L, Leuven JRFW, Lokhorst IR, Kleinhans MG. 2018. Effects of estuarine mudflat formation on tidal prism and large-scale morphology in experiments. Earth Surf Proc Landf 44: https://doi.org/10.1002/esp.4504

Bulleri F, Chapman MG. 2010. The introduction of coastal infrastructure as a driver of change in marine environments. J Appl Ecol 47: https://doi.org/10.1111/j.1365-2664.2009.01751.x

Burcharth HF, Zanuttigh B, Andersen TL, Lara JL, Steendam GJ, Ruol P, Sergent P, Ostrowski R Silva R, Martinelli L, Nørgaard JQH, Mendoza E, Simmonds D, Ohle N, Kappenberg J, Pan S, Nguyen DK, Toorman EA, Prinos Panayotis, Hoggart S, Chen Z, Piotrowska D, Pruszak Z, Schönhofer J, Skaja M, Stmytkiewicz P, Smytkiewicz M, Leont'yev I, Angelelli E, Formentin SM, Smaoui H, Bi Q, Sothmann J, Schuster D, Li M, Ge J, Lendzion J, Koftis T, Kuznetsov S, Puente A, Echavarri B, Medina R, Díaz-Simal P, Rodriguez IL, Maza M, Higuera P. 2015. Innovative engineering solutions and best practices ot mitigate coastal risk. In: Zanuttigh B, Nicholls R, Vanderlinden JP, Burcharth HF, Thompson RC (eds). Coastal risk management in a changing climate. 55-170: https://doi.org/10.1016/B978-0-12-397310-8.00003-8

Buzzi NS, Menéndez MC, Truchet DM, Delgado AL, Severini MDF. 2022. An overview on metal pollution on touristic sandy beaches: Is the COVID-19 pandemic an opportunity to improve coastal management? Marine Pollution Bulletin 174: https://doi.org/10.1016/j.marpolbul.2021.113275

Cai F, Cao C, Qi H, Su X, Lei G, Liu J, Zhao S, Liu G, Zhu K. 2022. Rapid migration of mainland China's coastal erosion vulnerability due to anthropogenic changes. Journal of Environmental Management 319: 115632.

Capon SJ, Pettit NE. 2018. Turquoise is the new green: Restoring and enhancing riparian function in the Anthropocene. Ecol Manag Rest 19: 44-53. https://doi.org/10.1111/emr.12326

Cappelatti L, Mauffrey ARL, Griffin JN. 2020. Functional diversity of habitat formers declines scale-dependently across an environmental stress gradient. Oecologia 194: 135-149. https://doi.org/10.1007/s00442-020-04746-1

Carranza A, zu Ermgassen PSE. 2020. A Global Overview of Restorative Shellfish Mariculture. Front Mar Sci 7: https://doi.org/10.3389/fmars.2020.00722

Cavallo M, Elliott M, Touza J, Quintino V. 2016. The ability of regional coordination and policy integration to produce coherent marine management: Implementing the Marine Strategy Framework Directive in the North-East Atlantic. Marine Policy 68: 108-116. https://doi.org/10.1016/j.marpol.2016.02.013

Chambers JC, Allen CR, Cushman SA. 2019. Operationalizing Ecological Resilience Concepts for Managing Species and Ecosystems at Risk. Front Ecol Evol 7: https://doi.org/10.3389/fevo.2019.00241

Chee SY, Othman AG, Sim YK, Adam ANM, Firth LB. 2017. Land reclamation and artificial islands: Walking the tightrope between development and conservation. Glob Ecol Cons 12: 80-95. https://doi.org/10.1016/j.gecco.2017.08.005

Chelchowski M, Balazy P, Grzelak K, Grzelak L, Kedra M, Legenzynska J, Kuklinski P. 2021. Vertical zonation of benthic invertebrates in the intertidal zone of Antarctica (Admiralty Bay, King George Island). Antarct Sci 34: 29-44. doi:10.1017/S095410202100047X

Chen Q, Zhao H, Liu Y, Jin L, Peng R. 2023. Factors Affecting the Adsorption of Heavy Metals by Microplastics and Their Toxic Effects on Fish. Toxics 11: 490. https://doi.org/10.3390/toxics11060490

Clark R, Reed J, Sunderland T. 2018. Bridging funding gaps for climate and sustainable development: Pitfalls, progress and potential of private finance. Land Use Policy 71: 335-346. https://doi.org/10.1016/j.landusepol.2017.12.013

de Mutsert K, Lewis KA, White ED, Buszowski J. 2021. End-to-End Modeling Reveals Species-Specific Effects of Large-Scale Coastal Restoration on Living Resources Facing Climate Change. Front Mar Sci 8: https://doi.org/10.3389/fmars.2021.624532

Du X, Song D, Wang H, Yang J, Liu H, Huo T. 2023. The combined effects of filter-feeding bivalves (*Cristaria plicata*) and submerged macrophytes (*Hydrilla verticillate*) on phytoplankton assemblages in nutrient-enriched freshwater mesocosms. Front Plant Sci 14: https://doi.org/10.3389/fpls.2023.1069593

Engle CR, van Senten J. 2022. Resilience of Communities and Sustainable Aquaculture: Governance and Regulatory Effects. Fishes 7: 268. https://doi.org/10.3390/fishes7050268

Evelpidou N, Spyrou E. 2024. Coastal areas and wetlands: Suggestions for sustainable mitigation and management strategies. In: Beylich AA, et al. (eds). Climate and Anthropogenic Impacts on Earth Surface Processes in the Anthropocene. Elsevier, Amsterdam. pp. 313–322.

Evelpidou N, Tzouxaniot M, Liaskos A. 2022. Coastal erosion: The future of sandy beaches. Proceedings of the European Academy of Sciences & Arts 1: 1-16. https://doi.org/10.5281/zenodo.7298431

Flores-Verdugo F, Amazcua F, Kovacs JM, Serrano D, Blanco-Correa M. 2014. Changes in the Hydrological Regime of Coastal Lagoons Affect Mangroves and Small Scale Fisheries: The Case of the Mangrove-Estuarine Complex of Marismas Nacionales (Pacific Coast of Mexico). 81-91. In: Amezcua F, Bellgraph B (eds). Fisheries Management of Mexican and Central American Estuaries. Estuaries of the World. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-8917-2_6

Friess DA, Howard J, Huxham M, Macreadie PI, Ross F. 2022. Capitalizing on the global financial interest in blue carbon. PLoS Climate PLOS Clim 1(8): e0000061. https://doi.org/10.1371/journal.pclm.0000061

Gaete H, Álvarez M, Lobos G, Soto E, Jara-Gutiérrez C. 2017. Assessment of oxidative stress and bioaccumulation of the metals Cu, Fe, Zn, Pb, Cd in the polychaete *Perinereis gualpensis* from estuaries of central Chile. Ecotoxicology and Environmental Safety 145: 653-658. https://doi.org/10.1016/j.ecoenv.2017.07.073

Galappaththi EK, Falardeau M, Harris LN, Rocha JC, Moore J-S, Berkes F. 2022. Resilience-based steps for adaptive co-management of Arctic small-scale fisheries. Environ Res Lett 17: 10.1088/1748-9326/ac7b37

Garner AJ, Sosa SE, Tan F, Tan CWJ, Garner GG, Horton BP. 2023. Evaluating Knowledge Gaps in Sea-Level Rise Assessments From the United States. Earth's Future 11: https://doi.org/10.1029/2022EF003187

Ghosh S, Rubly C. 2015. The emergence of Arctic shipping: issues, threats, costs, and risk-mitigating strategies of the Polar Code. Australian Journal of Maritime & Ocean Affairs 7: 171-182. http://dx.doi.org/10.1080/18366503.2015.1093695

Goodspeed R, Riseng C, Wehrly K, Yin W, Mason W, Schoenfeldt B. 2016. Applying design thinking methods to ecosystem management tools: Creating the Great Lakes Aquatic Habitat Explorer. Marine Policy 69: 134-145. https://doi.org/10.1016/j.marpol.2016.04.017

Habary A, Johansen JL, Nay TJ, Steffenson JF, Rummer JL. 2017. Adapt, move or die - how will tropical coral reef fishes cope with ocean warming? Glob Change Biol 23: 566-577: https://doi.org/10.1111/gcb.13488

Harahab N, Riniwati H, Utami TN, Abidin Z, Wati LA. 2021. Sustainability Analysis of Marine Ecotourism Management for Preserving Natural Resources and Coastal Ecosystem Functions. Env Res Eng Manag 77: https://doi.org/10.5755/j01.erem.77.2.28670

Heimhuber V, Raoult V, Glamore WC, Taylor MD, Gaston TF. 2023. Restoring blue carbon ecosystems unlocks fisheries' potential. Rest Ecol 32: e14052. https://doi.org/10.1111/rec.14052

Hoggart SPG, Hanley ME, Parker DJ, Simmonds DJ, Bilton DT, Filipova-Marinova M, Franklin EL, Kotsev I, Penning-Rowsell EC, Rundle SD, Trifonova E, Vergiev S, White AC, Thompson RC. 2014. The consequences of doing nothing: The effects of seawater flooding on coastal zones. Coast Eng 87: 169-182. https://doi.org/10.1016/j.coastaleng.2013.12.001

Hossain A, Senff P, Glaser M. 2022. Lessons for Coastal Applications of IMTA as a Way towards Sustainable Development: A Review. *Appl Sci* 12: 11920. https://doi.org/10.3390/app122311920

Idris NH, Munadi MHF. 2022. Recent progress on sea-level rise over the marginal seas in Southeast Asia. Proc. SPIE 12263, Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions 2022, 1226304. https://doi.org/10.1117/12.2639437

Johnston WG, Cooper JAG, Olynik J. 2023. Shoreline change on a tropical island beach, Seven Mile Beach, Grand Cayman: The influence of beachrock and shore protection structures. Mar Geol 45: 107006. https://doi.org/10.1016/j.margeo.2023.107006

Jones BM, Arp CD, Jorgenson MT, Hinkel KM, Schmutz JA, Flint PL. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophys Res Lett 36: https://doi.org/10.1029/2008GL036205

Judge R, Choi F, Helmuth B. 2018. Recent advances in data logging for intertidal ecology. Front Ecol Evol 6: https://doi.org/10.3389/fevo.2018.00213

Katsanevakis S, Coll M, Fraschetti S, Giakoumi S, Goldsborough D, Macic V, Mackelworth P, Rilov G, Stelzenmüller V, Albano PG, Bates AE, Bevilacqua S, Gissi E, Hermoso V, Mazaris AD, Pita C, Rossi V, Teff-Seker Y, Yates K. 2020. Twelve Recommendations for Advancing Marine Conservation in European and Contiguous Seas. Front Mar Sci 7: https:/doi.org/10.3389/fmars.2020.565968

Krohs U, Zimmer M. 2023. Do ecosystems have functions? Ecol Evol 13: e10458. https://doi.org/10.1002/ece3.10458

Kuwano-Yoshida A, Okajima S, Nakamura H. 2022. Rapid Increase of Explosive Cyclone Activity over the Midwinter North Pacific in the Late 1980s. J Clim 35: 1113-1133. https://doi.org/10.1175/JCLI-D-21-0287.1

Lima L, Oliveira FJM, Giocomini HC, Lima-Junior DP. 2018. Expansion of aquaculture parks and the increasing risk of non-native species invasions in Brazil. Rev Aquacult 10: 111-122. https://doi.org/10.1111/raq.12150

Lester SE, Dubel AK, Hernán G, McHenry J, Rassweiler A. 2020. Spatial planning principles for marine ecosystem restoration. Front Mar Sci 7: https://doi.org/10.3389/fmars.2020.00328

Liu Y-L, Zhong K-L, Jueterbock A, Satoshi S, Choi H-G, Weinberger F, Assis J, Hu Z-M. 2022. The invasive alga *Gracillaria vermiculophylla* in the native Northwest Pacific under ocean warming: Southern genetic consequence and Northern range expansion. Front Mar Sci 9: https://doi.org/10.3389/fmars.2022.983685

Lukoseviciute G, Panagopoulos T. 2021. Management priorities from tourists' perspectives and beach quality assessment as tools to support sustainable coastal tourism. Ocean & Coast Manag 208: 105646. https://doi.org/10.1016/j.ocecoaman.2021.105646

Mahmudi M, Musa M, Bunga A, Wati NA, Arsad S, Lusiana ED. 2022. A Water Quality Evaluation of Integrated Mangrove Aquaculture System for Water Treatment in Super-Intensive White Leg Shrimp Pond. J Ecol Eng: 23: 287-296. https://doi.org/10.12911/22998993/146746

Mendez-Tejeda R, Pérez-Valentín KA, Barreto-Orta M. 2020. Impact of extreme weather events on the beaches of Puerto Rico: The case of ocean park, San Juan. American Journal of Marine Science 8: 1-5. https://doi.org/10.12691/marine-8-1-1

Mieszkowska N, Burrows MT, Hawkins SJ, Sugden H. 2021. Impacts of pervasive climate change and extreme events on rocky intertidal communities: evidence from long-term data. Front Mar Sci 8: https://doi.org/10.3389/fmars.2021.642764.

Milani AS. 2018. Mangrove forests of the Persian Gulf and the Gulf of Oman. In: Makowski C, Finkl CW (eds). *Threats to Mangrove Forests: Hazards, Vulnerability and Management*. Springer: 53-75.

Moazampour SR, Nabavi SMB, Roozbahani MM, Khodadai M. 2021. Determination of total petroleum hydrocarbons and selected heavy metals (Pb, Co, V, Ni) concentration levels in surficial sediments of the Arvand River estuary and their impact on benthic macroinvertebrate assemblages. Intl J Env Anal Chem 103: 2841-2857. https://doi.org/10.1080/03067319.2021.1900143

Momota K, Hosokawa S. 2021. Potential impacts of marine urbanization on benthic macrofaunal diversity. Sci Rep 11: 4028. https://doi.org/10.1038/s41598-021-83597-z

Murphy EJ, Johnston NM, Hofmann EE, Phillips RA, Jackson JA, Constable AJ, Henley SF, Melbourne-Thomas J, Trebilco R, Cavanagh RD, Tarling GA, Saunders RA, Barnes DKA, Costa DP, Corney SP, Fraser CI, Höfer J, Hughes KA, Sands CJ, Thorpe SE, Trathan PN, Xavier JC. 2021. Global connectivity of Southern ocean ecosystems. Front Mar Sci 9: https://doi.org/10.3389/fevo.2021.624451

Ndonye HN, Mulwa A, Ndunge Kyalo D. 2021. Stakeholder engagement and performance of community based conservation projects: A case of Laikipia conservation region conservancies. J Econ Sust Devel 21: https://doi.org/10.7176/JESD/12-4-07

Nguyen HM, Yadav NS, Barak S, Lima FP, Sapir Y, Winters G. 2020. Responses of invasive and native populations of the seagrass *Halophila stipulacea* to simulated climate change. Front Mar Sci 6: https://doi.org/10.3389/fmars.2019.00812

NOAA. 2024. Is sea level rising? oceanservice.noaa.gov/facts/sealevel.html

O'Shaughnessy KA, Hawkins SJ, Yunnie ALE, Hanley ME, Lunt P, Thompson RC, Firth LB. 2020. Occurrence and assemblage composition of intertidal non-native species may be influenced by shipping patterns and artificial structures. Mar Poll Bull 154: 111082. https://doi.org/10.1016/j.marpolbul.2020.111082

~~Kuwano-Yoshida A, Okajima S, Nakamura H. 2022. Rapid Increase of Explosive Cyclone Activity over the Midwinter North Pacific in the Late 1980s. J Clim 35: 1113-1133. https://doi.org/10.1175/JCLI-D-21-0287.1~~

Phang VXH, Chou LM, Friess DA. 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. Earth Surf Proc Landf 40: 1387-1400. https://doi.org/10.1002/esp.3745

Pinto P, de Jonge VN, Marques JC. 2014. Linking biodiversity indicators, ecosystem functioning, provision of services and human well-being in estuarine systems: Application of a conceptual framework. Ecol Ind 36: 644-655. https://doi.org/10.1016/j.ecolind.2013.09.015

Pires-Teixeira LM, Neres-Lima V, Creed JC. 2021. How Do Biological and Functional Diversity Change in Invaded Tropical Marine Rocky Reef Communities? Diversity 13: 353. https://doi.org/10.3390/d13080353

Rahman MM, Zimmer M, Ahmed I, Donato D, Kanzaki M, Xu M. 2021. Co-benefits of protecting mangroves for biodiversity conservation and carbon storage. Nature Comm 12: 3875. https://doi.org/10.1038/s41467-021-24207-4

Rahman MM, Zimmer M, Donato D, Ahmed I, Xu M, Wu J. 2024. Functional composition outweighs taxonomic and functional diversity in maintaining ecosystem properties and processes of mangrove forests. Glob Change Biol 30: e17152 https://doi.org/10.1111/gcb.17152

Rahmanpour S, Ghorghani NF, Lotfi Ashtiyani SM. 2014. Heavy metal in water and aquatic organisms from different intertidal ecosystems, Persian Gulf. Environ Monit Assess 186: 5401-5409. https://doi.org/10.1007/s10661-014-3788-4

Rajalakshmi PR, Achyuthan H. 2021. Climate change as observed in the Bay of Bengal. J Clim Change 7: 69-82. https://doi.org/10.3233/JCC210020

Rilov G, David N, Guy-Haim T, Golomb D, Arav R, Filin S. 2021. Sea level rise can severely reduce biodiversity and community net production on rocky shores. Sci Total Env 791: 148377 https://doi.org/10.1016/j.scitotenv.2021.148377

Román M, Román S, Vázquez E, Troncoso J, Olabarria C. 2020. Heatwaves during low tide are critical for the physiological performance of intertidal macroalgae under global warming scenarios. Sci Rep 10: 21408. https://doi.org/10.1038/s41598-020-78526-5

Roussos O, Kapetanopoulou C, Petza D. 2021. ACTION PLAN 2021-2023: INVALIS - Protecting European Biodiversity from Invasive Alien Species. Natural Environment and Climate Change Agency. Athens, Greece.

Saitis G. 2022. Geomorphological-Geoenvironmental Investigation of Natural and Artificial Beachrocks Formation Mechanism and their potential as a soft engineering method against coastal hazards. Comparative studies from the Eastern Mediterranean and southern Japan. Ph.D. thesis, Department of Geology & Geo-Environment, National and Kapodistrian University of Athens.

Sedano F, Pavón-Paneque A, Navarro-Barranco C, Guerra-García JM, Digenis M, Sempere-Valverde J, Espinosa F. 2021. Coastal armouring affects intertidal biodiversity across the Alboran Sea (Western Mediterranean Sea). Mar Env Res 171: 105475. https://doi.org/10.1016/j.marenvres.2021.105475

Stafford KM, Farley EV, Ferguson M, Kuletz KJ, Levine R. 2022. Northward range expansion of subarctic upper trophic level animals into the Pacific Arctic region. Oceanography 35: 158-166. https://doi.org/10.5670/oceanog.2022.101

Stamp T, West E, Robbins T, Plenty S, Sheehan E. 2022. Large-scale historic habitat loss in estuaries and its implications for commercial and recreational fin fisheries, *ICES J Mar* Sci 79: 1981-1991. https://doi.org/10.1093/icesjms/fsac141

Tetelepta JMS, Abrahamsz J, Mamesah JAB, Pattikawa JA, Wawo M, Al Hamid F. 2023. The local wisdom knowledge applied in the management of coastal resources at Ilili Village, Westerm Seram District, Indonesia. IOP Conf Ser: Earth Environ Sci 1207: 012023. https://doi.org/10.1088/1755-1315/1207/1/012023

Thinh NA, Thanh NN, Tuyen LT, Hens L. 2019. Tourism and beach erosion: valuing the damage of beach erosion for tourism in the Hoi An World Heritage site, Vietnam. Environ Dev Sustain 21: 2113-2124. https://doi.org/10.1007/s10668-018-0126-y

Thomsen PF, Willerslev E. 2015. Environmental DNA – An emerging tool in conservation for monitoring past and present biodiversity. Biol Cons 183: 4-18. https://doi.org/10.1016/j.biocon.2014.11.019

Tuholske C, Tane Z, López-Carr D, Roberts D, Cassels S. 2017. Thirty years of land use/cover change in the Caribbean: Assessing the relationship between urbanization and mangrove loss in Roatán, Honduras. Appl Geogr 88: 84-93. https://doi.org/10.1016/j.apgeog.2017.08.018

Tuholske C, Halpern BS, Blasco G, Villasenor JC, Frazier M, Caylor K. 2021. Mapping global inputs and impacts from human sewage in coastal ecosystems. PLoS ONE: https://doi.org/10.1371/journal.pone.0258898

United Nations. 2017. The First Global Integrated Marine Assessment: World Ocean Assessment I. Cambridge: Cambridge University Press.

United Nations. 2021. The Second World Ocean Assessment: WORLD OCEAN ASSESSMENT II, Volume I.

Van Coppenolle R, Schwarz C, Temmerman S. 2018. Contribution of Mangroves and Salt Marshes to Nature-Based Mitigation of Coastal Flood Risks in Major Deltas of the World. Est Coasts 41: 1699-1711. https://link.springer.com/article/10.1007/s12237-018-0394-7

Van Dam B, Helfer V, Kaiser D, Sinemus E, Staneva J, Zimmer M. 2024. Towards a fair, reliable, and practical verification framework for Blue Carbon-based CDR. Environ Res Lett 19: 081004. https://doi.org/10.1088/1748-9326/ad5fa3

Van der Meulen F, IJff S, van Zetten R. 2023. Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nordic J Bot: https://doi.org/10.1111/njb.03290

Vigouroux G, Kari E, Beltrán-Abaunza JM, Uotila P, Yuan D, Destouni G. 2021. Trend correlations for coastal eutrophication and its main local and whole-sea drivers – Application to the Baltic Sea. Sci Total Environ 779: 146367. https://doi.org/10.1016/j.scitotenv.2021.146367

von Hellfeld R, Zarzuelo M, Zaldibar B, Cajaraville MP, Orbea A. 2022. Accumulation, Depuration, and Biological Effects of Polystyrene Microplastic Spheres and Adsorbed Cadmium and Benzo(a)pyrene on the Mussel *Mytilus galloprovincialis*. Toxics 10: 18. https://doi.org/10.3390/toxics10010018

Wang YP, Gao S, Jia J, Thompson CEL, Gao J, Yang Y. 2012. Sediment transport over an accretional intertidal flat with influences of reclamation, Jiangsu coast, China. Mar Geol 291–294: 147-161. https://doi.org/10.1016/j.margeo.2011.01.004

Waryszak P, Gavoille A, Whitt AA, Kelvin J, Macreadie PI. 2021. Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. Coast Eng J 63: 335-350. https://doi.org/10.1080/21664250.2021.1920278

Westphal H, Murphy GN, Doo SS, Mann T, Petrovic A, Schmidt C, Stuhr M. 2022. Ecosystem design as an avenue for improving services provided by carbonate producing marine ecosystems. PeerJ: https://doi.org/10.7717/peerj.12785

Yap CK, Leow CS, Peng SHT, Ismail MS. 2020. Human interaction with the environmental ecosystem: A review, some notes and insights. J Aquat Pollut Toxicol 4: 26. https://doi.org/10.37532/2581-804X/4.1.26

Yeruham E, Shpigel M, Abelson A, Rilov G. 2020. Ocean warming and tropical invaders erode the performance of a key herbivore. Ecology 101: e02925. https://doi.org/10.1002/ecy.2925

Zhu B, Bai Y, He X, Chen X, Li T, Gong F. 2021. Long-Term Changes in the Land–Ocean Ecological Environment in Small Island Countries in the South Pacific: A Fiji Vision. *Remote Sensing* 13: 3740. https://doi.org/10.3390/rs13183740

Zimmer M. 2018. Ecosystem Design: when mangrove ecology meets human needs. In: Makowski C, Finkl CW (eds). *Threats to Mangrove Forests: Hazards, Vulnerability and Management*. Springer: 367-376.

Zimmer M, Ajonina GN, Amir AA, Cragg S, Crooks S, Dahdouh-Guebas F, Duke N, Fratini S, Friess DA, Helfer V, Huxham M, Kathiresan K, Kodikara KAS, Koedam N, Lee SY, Mangora MM, Primavera J, Satyanarayana B, Yong JWH, Wodehouse D. 2022. When nature needs a helping hand: different levels of human intervention for mangrove (re-)establishment. *Front Forests Glob Change* 5: 784322 https://doi.org/10.3389/ffgc.2022.784322

Section 4

Sub-chapter 5b: Biogenic reefs and sandy, muddy and rocky shore substrates

Lead Member of the Group of Experts: Roberto de Pinho

Co-Lead Member of the Group of Experts: Felicia Mogo

Coordinating author: Ronaldo Christofoletti

Authors: Omar Defeo, Moisés A Aguilera, Stuart Jenkins, Gray A Williams, Rebecca Morris, Barbara Pinheiro, Maria Gabriela Palomo, Dahai Liu, Corrine Almeida, Juliet Karisa, Kira Krumhansl,

Keynote points

- Coastal habitats such as sandy, muddy, and rocky shores and biogenic reefs are crucial for biodiversity and ecosystem services, supporting economic activities and protecting coastlines.
- Coastal habitats are interconnected by ocean currents conforming to a meta-ecosystem, where energy and organisms can move across boundaries, enhancing ecosystem resilience. As such, Integrated management approaches are needed.
- These habitats face intense pressures from climate change and human activity, with warming temperatures and heat waves, rising sea levels, coastal hardening, and pollution impacting biodiversity and ecosystem functions.
- The loss and degradation of coastal habitats threaten human well-being, from increased flooding risks to loss of livelihoods in tourism and fisheries.
- Addressing these challenges demands robust governance, scientific innovation, strong partnerships and enhanced ocean literacy to promote and conserve resilient, sustainable coastal ecosystems.

1. Introduction and context

This chapter focuses on four critical coastal habitats: sandy, muddy, and rocky shores, and biogenic reefs, highlighting their ecological and economic importance. These environmental systems support diverse species that contribute to water filtration, and nutrient cycling and play an important role in the coastal food chain. In addition, biogenic reefs, formed by organisms like corals, oysters, and mussels, provide natural barriers against coastal erosion. As home to invaluable natural resources, these coastal habitats are essential for tourism, fisheries, and recreation, underscoring their economic, social, cultural and ecological significance.

Understanding these habitats requires recognizing their interconnectedness that is known as a meta-ecosystem, where energy, materials, and organisms move across habitats, shaping their resilience and health. This spatial connectivity emphasizes the need for collective management rather than isolated approaches to ensure their persistence and functionality (Vozzo et al. 2023).

However, these coastal habitats face a multitude of stressors, primarily driven by local human activity and climate change. Urban expansion, pollution, and climate-induced impacts such as rising sea levels, and heatwaves are degrading biodiversity and ecosystem functions (IOC-UNESCO, 2024). These cumulative stressors pose significant challenges to the resilience, conservation and sustainability of these ecosystems.

This chapter provides an updated assessment of biogenic reefs, sandy, muddy, and rocky shores, focusing on the changes observed since WOAII, emphasizing the need for integrated coastal management to support biodiversity functions and sustainable use of marine resources, which includes guaranteeing equitable access to coastal resources.

2. Changes in the State of Biogenic Reefs, Sandy, Muddy, and Rocky Shore Substrates

In the last decade, biogenic reefs, sandy, muddy, and rocky shores are undergoing increased transformations of its landscape due to a mix of environmental and anthropogenic pressures. Climate change and local anthropogenic impacts are driving transformations that threaten the stability and functionality of natural habitats (Hatje et al. 2024). Bivalve-based biogenic reefs illustrate this point; oyster reefs faced centuries of extraction and estimates suggest 85% of oyster reefs have been lost globally with impacts on the socio-ecological systems (Beck et al 2011; Thurstan et al. 2020) whereas mussel reefs have faced similar historical declines due to overharvesting, replacement by invasive species and more recently climate change, leading to recent scientific efforts for mussel reefs restoration (Petraitis and Dudgeon 2020; Roberts et al. 2023; Buschbaum et al. 2024). These reefs play a vital role in coastal ecosystems by filtering water, attenuating waves, stabilizing sediments, and providing habitat for a variety of species. However, rising sea, increasing air, and water temperatures, along with increased pollution and nutrient runoff, lead to hypoxic conditions that weaken reef structures and reduce biodiversity. The harvesting of oysters and mussels, if unmanaged, further diminishes reef resilience, leading to long-term declines in water quality and biodiversity (Ponti et al. 2021; Gianni et al. 2023).

Urbanization stressors, including population density, tourism, nocturnal light, urban infrastructure, vegetation changes, and some beach nourishment practices, significantly reduce species richness and biomass on sandy and muddy shores (Orlando et al., 2020; Corte et al., 2022; De Schipper et al., 2024) and also can impact on nesting areas for migratory animals, as turtles. Artificial light at night disrupts key ecological processes and impacts biodiversity, including circadian rhythms, feeding, reproduction, and migration, increasing the vulnerability of species and altering predator-prey dynamics (Marangoni et al., 2022). In addition, recent studies showed that coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by the end of the century, compromising resilience to sea-level rise (Vousdoukas et al. 2020, Nawarat et al., 2024). Combined pressures from sea-level rise and urbanization shrink intertidal zones, affecting dependent species and reducing vital ecosystem services, such as coastal protection, recreation, and habitat for shorebirds (Defeo et al., 2021; Lansu et al., 2024). Conserving natural areas and applying nature-based solutions can reduce infrastructure impacts by up to sevenfold (Lansu et al., 2024; Nawarat et al., 2024).

Muddy shores, found in sheltered areas like estuaries and bays, are vital as nursery habitats for fish, feeding grounds for migratory birds, and sites of high nutrient cycling. However, they are highly vulnerable to sedimentation changes caused by natural events (e.g., storms) and human activities (e.g., dredging, coastal construction). Increased sedimentation can smother benthic communities, disrupt nutrient dynamics, and degrade habitat quality. Large-scale infrastructure, like hydropower stations and reservoirs, reduces sediment and water flow, leading to seawater backflow, salinization, and declines in marine biodiversity (Yi et al., 2023). Pollution from agricultural runoff and urban waste introduces nutrients and toxins, creating hypoxic zones that further harm biodiversity (Daramola et al., 2022; Popoola, 2022). Additionally, urban infrastructure such as seawalls and breakwaters replaces natural habitats with hard substrates, which can facilitate biological invasions and species range expansions (Airoldi et al., 2015; Dong et al., 2016; Wang et al., 2020)

Sea-level rise significantly impacts rocky shores and biogenic reefs by submerging intertidal areas, resulting in less biodiverse submerged communities and diminished ecosystem services such as net production and biodiversity (Rilov et al., 2021). Changes in wave energy further affect these ecosystems, for example high-energy environments reduce oyster density and surface area, decreasing species diversity (Vozzo et al., 2021). Climate change is also altering community composition on rocky shores, with warming waters shifting the range of intertidal and subtidal species (Sanford et al., 2019; Smale et al., 2019, Krumhansl et al.2024). Extreme events like heatwaves cause mortality in temperature-sensitive species such as forest-forming kelps, transitioning communities to- low-lying macroalgal turfs or filter-feeders, and increasing the abundance of warm-tolerant species (Filbee-Dexter & Wernberg 2018, Smith et al. 2021, Weitzman et al., 2021). Seasonal species loss can also occur in tropical monsoonal areas-. These shifts reduce ecological resilience, increasing vulnerability to disturbances and facilitating invasive species establishment under heat stress (Diez et al., 2012; Rilov et al., 2021; Weitzman et al., 2021).

These soft and hard-bottom interconnected habitats are influenced by the exchange of energy, nutrients, and organisms across their boundaries, forming what is known as a 'meta-ecosystem´ (Loreau et al. 200314). However, it is still uncertain how changes in one habitat type, such as a decline in biogenic reefs, can have cascading effects on adjacent habitats, like sandy and muddy shores, altering nutrient flows and larval supply. This interdependence emphasizes the need for integrated management approaches that consider the connectivity of natural habitats and the cumulative anthropogenic impacts on coastal ecosystems, especially in face of the increasing global warming, as 2023 and 2024 reached records of air and ocean temperature (IOC-UNESCO, 2024).

3. Consequences of the changes on human population, economies, and well-being

The degradation of biogenic reefs, and sandy, muddy, and rocky shores has direct and indirect implications for human well-being. Natural habitats are crucial in providing multiple ecosystem services like coastal protection, supporting commercial fisheries and coastallivelihoods, and offering opportunities to enhance local ecological knowledge and cultural values. As natural buffers, biogenic reefs protect coastal areas from wave action and storm surges, mitigate eutrophication through nitrogen removal, and sequester significant amounts of carbon (Krause-Jensen & Duarte 2016, Eger et al. 2023). Ecosystem services from kelp forests globally have been valued at $500 billion USD (Eger et al. 2023). With the weakening of these reefs due to human impacts and habitat fragmentation, communities face increased vulnerability to coastal hazards, resulting in higher costs for flood defense infrastructure and disaster recovery (Ponti et al. 2021; Giglio et al. 2024), and losses of kelp forests are associated with significant declines in fisheries revenues (Rogers-Bennett et al. 2019). Losses of macrophytes in soft-sediment and rocky habitats reduces their capacity to sequester carbon, and sediment disturbance causes carbon emissions.

Sandy beaches attract millions of visitors annually, generating substantial revenue for local economies. However, the uncontrolled development of tourism and urbanization presents an increasing impact on the habitats. For example, the impacts of artificial light on coastal habitats require immediate attention, as it reduces biodiversity and associated ecosystem services, such as sustainable fisheries and coastal protection. Indirect economic impacts include decreased fishery productivity and degradation of tourism habitats (Marangoni et al., 2022). Also, the loss of beach areas due to coastal squeeze and erosion reduces their appeal, leading to declines in tourism revenue and job losses in the service sector, that the total revenue loss could reach €140,400/m² per year (Alexandrakis et al., 2015). Moreover, increased litter, pollution, and habitat degradation on popular beaches lowers their recreational value, affecting both the living happiness of residents and the travel willingness of tourists (Harris and Defeo, 2022; Bozzeda et al. 2023).

For traditional communities and Iindigenous ~~communities~~Peoples, muddy and rocky shores provide critical resources, such as shellfish and seaweed, and hold cultural and spiritual significance. The degradation of these habitats threatens not only food security but also cultural heritage. Threats to the recreational gathering of intertidal resources can also impact well-being (—Morris-Webb 2021). In many coastal regions, these communities are also at the frontline of climate change impacts, experiencing increased flooding, loss of land, and displacement. This loss of traditional livelihoods and connection to natural landscapes can lead to psychosocial stress and loss of cultural identity, impacting overall community well-being (Biedenweg et al. 2016; Bennett et al. 2023).

Human health may also be impacted as coastal degradation leads to increased exposure to pollutants and pathogens, particularly in urbanized areas where urban infrastructure enhances the presence of anthropogenic litter and synanthropic species (e.g., rats) which are vectors of different pathogens (Aguilera et al. 2023). For instance, the decline in oyster reefs reduces water filtration capacity, increasing the concentration of harmful bacteria and pollutants in coastal waters. This compromises water quality which is essential for activities like swimming, fishing, and shellfish harvesting, posing health risks to local populations (Fanini et al. 2020; Vousdoukas et al. 2020).

4. Key region-specific changes and consequences

From global to local drivers, climate change and anthropogenic impacts are influencing habitats worldwide. In this section, we will present examples of such impacts based on their geographic, climatic, and socio-economic context considering recent updates (2018-2024 period).

Increased wave energy and extreme weather in the North-West Atlantic and North Sea intensify erosion and sediment transport, reducing biodiversity and habitat resilience in sandy and rocky shores. Coastal urban expansion worsens these impacts by increasing pollution and weakening natural defenses. In the UK, marine heatwaves significantly reduced cold-water species, while winter storms damaged habitats, including mussel and algae loss. Despite some recovery, climate change drove shifts towards warm-affinity species (Mieszkowska et al., 2021). In the Gulf of Maine and eastern Canada, warming temperatures and heat waves, overfishing, and interactions with invasive species are causing declines in kelp abundances and shifts from cold to warm-tolerant species (Suskiewicz et al. 2024, Krumhansl et al. 2024). Similarly, the 2014–2017 Gulf of Alaska heatwave transitioned rocky intertidal habitats from macroalgae to barnacle- and mussel-dominated communities, reducing diversity and ecosystem complexity with lasting effects on productivity and trophic interactions (Weitzman et al., 2021).

The South Atlantic shows increased knowledge in its western region, particularly in Argentina and Brazil, but remains less studied on the east coast. The West faces significant coastal erosion, habitat alteration, and ecological imbalances due to storms, cold fronts, and disasters like oil spills and mine tailing discharges (Gutierrez et al., 2023; Escobar, 2019; Soares et al., 2020). These disturbances impact tourism, fisheries, and biogenic reefs with long-term socio-economic effects. Key environmental drivers, such as ocean temperature, wave exposure, and freshwater inputs, shape intertidal communities, altering species abundance and marine trophic chains, trends increasingly influenced by climate change (Pardal et al., 2021, 2022, 2023; Cordeiro et al., 2024). Excessive fishing of herbivores, such as fish and sea urchins, has caused biodiversity loss and macroalgal overgrowth, while urban pollution and eutrophication promote opportunistic species, further degrading benthic ecosystems (Martinez and Altvater, 2024).

In the Indian Ocean region, rapid coastal development, including artificial island construction, disrupts natural sediment flows, harming coastal habitats. In regions like the Maldives, these modifications have altered fish migration routes and reduced access to traditional fishing grounds, affecting food security and local economies. Plastic pollution, illegal waste dumping from these developments further degrades water quality, impacting biodiversity and human health (Honorato-Zimmer et al. 2022, McCabe 2023,). Marine heat waves on top of regional warming are causing widespread tropicalization of kelp forests (Zarxo-Perello et al. 2017). The Eastern and South Eastern Pacific coasts are strongly influenced by climate-driven upwelling systems critical for nutrient supply to sandy and rocky shores (Thiel et al., 2007). Shifts in wind patterns affecting upwelling intensity disrupt ecosystem productivity, impacting fisheries and biodiversity. The region is also vulnerable to oceanographic events such as El Niño, which exacerbate coastal erosion, flooding, seawater encroachment, and ecosystem changes, leading to long-term socio-economic challenges (Xiu et al., 2018; Gelcich et al., 2019). During the 2015–2017 El Niño event, species turnover was significant, with some migrating southward due to temperature anomalies (i.e. changes in temperature related to expected temperatures in the region), although latitudinal community structure remained largely stable (Valqui et al., 2021).

Arctic coastal erosion, driven by permafrost thaw and increased wave action from sea ice loss, is expected to accelerate significantly by the 21st century, especially under high-emission scenarios (Nielsen et al., 2022). This process threatens sandy and muddy shores by displacing sediments, altering nutrient dynamics, and degrading habitat quality. It also releases significant amounts of organic carbon, contributing to greenhouse gas emissions, while jeopardizing infrastructure, biodiversity, and ecosystem services, with erosion rates doubling in some warming scenarios. Productivity of macroalgae on rocky shores in the Arctic may increase with climate change due to reduced ice cover and increasing climate suitability for some species (Filbee-Dexter et al. 2019), though declines in some cold-adapted macroalgal species are expected at their southern range extent (Li et al. 2024) or where turbidity increases due to ice melt (Filbee-Dexter et al. 2019).

5. Outlook and remaining key knowledge and capacity changes and any new gaps

Biogenic reefs and sandy, muddy, and rocky shores face increasing pressures from climate change, urbanization, and human exploitation, threatening their biodiversity and ecosystem services. Coastal population growth, land reclamation, and infrastructure development disrupt natural processes, accelerate biodiversity loss, and alter sediment dynamics (Vousdoukas et al. 2020; Luijendijk et al. 2018). Emergent threats like plastic pollution and artificial light at night further strain these environments requiring target research and mitigation strategies (Marangoni et al. 2022; Ford et al. 2022).

Innovative approaches such as blue engineering utilizing eco-friendly materials in coastal defenses, show promise for sustainable urban development that respects ecological integrity (Bugnot et al. 2018, Pinardi et al., 2024). However, further research is necessary to understand the long-term impacts of these approaches on meta-ecosystems reducing biotic homogenization, and improving the interconnectedness of natural coastal habitats with consequences for ecosystem resilience and biodiversity (Firth et al. 2024).

Incorporating traditional and ~~l~~Indigenous Peoples' ecological knowledge into governance frameworks is vital, offering place-based insights for sustainable management and restoration (Strain et al., 2018; Stori et al., 2019, Haugan et al 2024). However, significant knowledge gaps persist, particularly regarding the cumulative impacts of multiple stressors, including terrestrial influences, on marine ecosystems. Improved monitoring systems, capacity building, and interdisciplinary research are crucial, especially in under-researched biodiversity hotspots like the South Atlantic, Wider Caribbean, and Southeast Asia (Coleman et al. 2019, Cruz Motta et al., 2020, Muller-Karger et al. 2024). A socio-ecological approach integrating natural and social sciences is essential for holistic coastal management and conservation (Arbic et al., 2024).

Promoting ocean literacy and raising public awareness through education, communication, and cultural aspects including all knowledge systems (Glithero et al. ~~(~~2024) about the socio-economic importance of these coastal habitats are key steps to enhancing stakeholder engagement in conservation. Multilevel governance structures that include all national and community stakeholders can foster collaboration and ensure that policies reflect local realities. This participatory approach requires financial investment in capacity building and technical training, enabling communities to actively manage and monitor their ecosystems.

For effective conservation and restoration, countries must develop equitable, inclusive, and adaptive policies that prioritize sustainable management of coastal habitats (Waltham et al. 2020) based on the understanding of their structural and functional connectivity. This includes securing long-term funding for monitoring and restoring natural habitats, greening artificial infrastructures for biodiversity, and utilizing nature-based solutions (Morris et al. 2018; Aguilera et al. 2020). By empowering communities and fostering resilience in these habitats allows countries to enhance the resilience of their coastal communities against climate change impacts, ensuring the protection of coastlines, conservation of biodiversity and sustainability of livelihoods (Sabine et al. 2024).

Safeguarding coastal habitats demands robust governance that integrates diverse knowledge systems and encourages participatory decision-making. Innovative and extensive research is needed in tropical and subtropical regions, where data gaps persist while addressing disparities in coastal management between high- and middle-income countries (Nawarat et al., 2024). Coordinated, well-financed strategies aligned with global initiatives like the 2030 Agenda and the UN Ocean Decade are essential to ensuring the resilience and sustainability of these ecosystems for future generations. Continued monitoring, research, local management and international cooperation are essential to adapt to the evolving challenges and safeguard these invaluable natural resources.

References

- Aguilera, M. A., Rojas, A., Bulleri, F., and Thiel, M. Breakwaters as habitats for synanthropes: Spatial associations of vertebrates and vegetation with anthropogenic litter. Science of The Total Environment, vol. 862, art. 160753, 2023.
- Aguilera, M. A., Tapia, J., Gallardo, C., and others. Loss of coastal ecosystem spatial connectivity and services by urbanization: Natural-to-urban integration for bay management. Journal of Environmental Management, vol. 276, art. 111297, 2020.
- Airoldi, Laura, and others. Corridors for aliens but not for natives: Effects of marine urban sprawl at a regional scale. Diversity and Distributions, vol. 21, No. 7, pp. 755–768, 2015.
- Alexandrakis, George, Constantine Manasakis, and Nikolaos A. Kampanis. Valuating the effects of beach erosion to tourism revenue: A management perspective. Ocean & Coastal Management, vol. 111, pp. 1–11, 2015.
- Arbic, Brian K., and others. Skills, knowledge, technology, and participatory decision-making for all. Ocean Decade Vision 2030 White Papers, Challenge 9. Paris: UNESCO-IOC, 2024, 95 pp.
- Beck, Michael W., Brumbaugh, Robert D., Airoldi, Laura, Carranza, Alvar, Coen, Loren D., Crawford, Christine, and others. Oyster reefs at risk and recommendations for conservation, restoration, and management. BioScience, vol. 61, No. 2, pp. 107–116, 2011. DOI: 10.1525/bio.2011.61.2.5.

- Bennett, Nathan J. , Juan José Alava, Caroline E. Ferguson, Jessica Blythe, Elisa Morgera, David Boyd, Isabelle M. Côté, Environmental (in)justice in the Anthropocene ocean, Marine Policy, Volume 147, 2023, 105383, ISSN 0308-597X, https://doi.org/10.1016/j.marpol.2022.105383.
- Biedenweg, Kelly, and others (2016). A holistic framework for identifying human wellbeing indicators for marine policy. Marine Policy, vol. 64, pp. 31–37.
- Bozzeda, F., Ortega, L., Costa, L. L., and others. Global patterns in sandy beach erosion: Unraveling the roles of anthropogenic, climatic, and morphodynamic factors. Frontiers in Marine Science, vol. 10, art. 1270490, 2023.
- Bugnot, A. B., Mayer-Pinto, M., Johnston, E. L., Schaefer, N., and Dafforn, K. A. Learning from nature to enhance blue engineering of marine infrastructure. Ecological Engineering, vol. 120, pp. 611–621, 2018.
- Buschbaum, C., Shama, L.N.S., Amorim, F.L.L. et al. Climate change impacts on a sedimentary coast—a regional synthesis from genes to ecosystems. Mar. Biodivers. 54, 64 (2024). https://doi.org/10.1007/s12526-024-01453-5
- Coleman, J. L., Ascher, J. S., Bickford, D., Buchori, D., Cabanban, A., Chisholm, R. A., ... & Carrasco, L. R. (2019). Top 100 research questions for biodiversity conservation in Southeast Asia. Biological Conservation, 234, 211-220.
- Cordeiro, C. A. A. M., Pardal, A., Giménez, L., Ciotti, A. M., Jenkins, S. R., Burrows, M. T., Williams, G. A., Christofoletti, R. A. Environmental factors have stronger effects than biotic processes in patterns of intertidal populations along the Southeast coast of Brazil. Marine Environmental Research, 2024.
- Corte, Guilherme N., and others. Evaluation of the effects of urbanization and environmental features on sandy beach macrobenthos highlights the importance of submerged zones. Marine Pollution Bulletin, vol. 182, art. 113962, 2022.
- Cruz-Motta, J. J., Miloslavich, P., Guerra-Castro, E., Hernández-Agreda, A., Herrera, C., Barros, F., and others. Latitudinal patterns of species diversity on South American rocky shores: Local processes lead to contrasting trends in regional and local species diversity. Journal of Biogeography, vol. 47, No. 9, pp. 1966–1979, 2020.
- Daramola, S., Li, H., Omonigbehin, O., Faruwa, A., Gong, Z. Recent retreat and flood dominant areas along the muddy Mahin coastline of Ilaje, Nigeria. Regional Studies in Marine Science, vol. 52, art. 102272, 2022.
- De Schipper, Matthieu A., Ludka, Bonnie C., Raubenheimer, Britt, Luijendijk, Arjen P., and Schlacher, Thomas A. Beach nourishment has complex implications for the future of sandy shores. Nature Reviews Earth & Environment, vol. 15, No. 1, 2024.
- Defeo, O., McLachlan, A., Armitage, D., and others. Sandy beach social-ecological systems at risk: Regime shifts, collapses, and governance challenges. Frontiers in Ecology and Environment, vol. 19, pp. 564–573, 2021.
- Diez, J. M., D'Antonio, C. M., Dukes, J. S., Grosholz, E. D., Olden, J. D., Sorte, C. J., and others. Will extreme climatic events facilitate biological invasions? Frontiers in Ecology and the Environment, vol. 10, No. 5, pp. 249–257, 2012. https://doi.org/10.1890/110137.
- Dong, Yun-Wei, and others. The marine 'Great Wall' of China: Local- and broad-scale ecological impacts of coastal infrastructure on intertidal macrobenthic communities. Diversity and Distributions, vol. 22, No. 7, pp. 731–744, 2016.
- Escobar, Herton. Mystery oil spill threatens marine sanctuary in Brazil. Science, vol. 366, No. 6466, pp. 672–672, 2019. DOI: 10.1126/science.366.6466.672.
- Fanini, Lucia, Defeo, Omar, Elliott, Michael. Advances in sandy beach research – Local and global perspectives. Estuarine, Coastal and Shelf Science, vol. 234, art. 106646, 2020.

- Firth, L. B., Bone, J., Bartholomew, A., Bishop, M. J., Bugnot, A., Bulleri, F., and others. Coastal greening of grey infrastructure: An update on the state of the art. Proceedings of the Institution of Civil Engineers-Maritime Engineering, 2024.
- Ford, H. V., Jones, N. H., Davies, A. J., Godley, B. J., Jambeck, J. R., Napper, I. E., and Koldewey, H. J. The fundamental links between climate change and marine plastic pollution. Science of the Total Environment, vol. 806, art. 150392, 2022.
- Gelcich, S., Martínez-Harms, M. J., Tapia-Lewin, S., Vasquez-Lavin, F., and Ruano-Chamorro, C. Comanagement of small-scale fisheries and ecosystem services. Conservation Letters, vol. 12, No. 2, art. e12637, 2019.
- Gianni, F., Turicchia, E., Abbiati, M., and others. Spatial patterns and drivers of benthic community structure on the northern Adriatic biogenic reefs. Biodiversity and Conservation, vol. 32, pp. 3283–3306, 2023. https://doi.org/10.1007/s10531-023-02654-3.
- Giglio, V. J., Aued, A. W., Cordeiro, C. A. M. M., and others. A global systematic literature review of ecosystem services in reef environments. Environmental Management, vol. 73, pp. 634–645, 2024. https://doi.org/10.1007/s00267-023-01912-y.
- Glithero, Diz, and others. Restoring society's relationship with the ocean. Ocean Decade Vision 2030 White Papers, Challenge 10. Paris: UNESCO-IOC, 2024, 125 pp.
- Gutierrez, J. L., Bagur, M., Lorenzo, R. A., and Palomo, M. G. A facultative mutualism between habitat-forming species enhances the resistance of rocky shore communities to heat waves. Frontiers in Ecology and Evolution, vol. 11, art. 1278762, 2023.
- Harris, Linda R., and Defeo, Omar. Sandy shore ecosystem services, ecological infrastructure, and bundles: New insights and perspectives. Ecosystem Services, vol. 57, art. 101477, 2022.
- Hatje, Vanessa, and others. Understand and beat marine pollution. Ocean Decade Vision 2030 White Papers, Challenge 1. Paris: UNESCO-IOC, 2024, 88 pp.
- Haugan, Peter, and others. Develop a sustainable and equitable ocean economy. Ocean Decade Vision 2030 White Papers, Challenge 4. Paris: UNESCO-IOC, 2024, 97 pp.
- Honorato-Zimmer, D., Weideman, E. A., Ryan, P. G., & Thiel, M. (2022). Amounts, sources, fates and ecological impacts of marine litter and microplastics in the Western Indian Ocean region: a review and recommendations for actions. Oceanography and Marine Biology, 533-589.
- IOC-UNESCO. State of the Ocean Report 2024. Paris: IOC-UNESCO, 2024. (IOC Technical Series, 190). https://doi.org/10.25607/4wbg-d349.
- Lansu, E. M., Reijers, V. C., Höfer, S., and others. A global analysis of how human infrastructure squeezes sandy coasts. Nature Communications, vol. 15, No. 1, art. 432, 2024.
- Loreau, M., Mouquet, N. and Holt, R.D. (2003), Meta-ecosystems: a theoretical framework for a spatial ecosystem ecology. Ecology Letters, 6: 673-679. https://doi.org/10.1046/j.1461-0248.2003.00483.x
- Luijendijk, A., Hagenaars, G., Ranasinghe, R., and others. The state of the world's beaches. Scientific Reports, vol. 8, art. 6641, 2018. https://doi.org/10.1038/s41598-018-24630-6.
- McCabe, Robert (2023) Environmental drivers of maritime insecurity: governance, enforcement and resilience in the western Indian Ocean, Conflict, Security & Development, 23:3, 237-265, DOI: 10.1080/14678802.2023.2256251
- Marangoni, L. F., Davies, T., Smyth, T., and others. Impacts of artificial light at night in marine ecosystems—A review. Global Change Biology, vol. 28, No. 18, pp. 5346–5367, 2022.
- Martinez, A.S., Altvater, L. (2024). Anthropogenic Stressors on Shallow Coastal Rocky Reefs. In: Coutinho, R., Christofoletti, R.A. (eds) Brazilian Rocky Shores. Brazilian Marine Biodiversity . Springer, Cham. https://doi.org/10.1007/978-3-031-67206-4_6

- Mieszkowska, Nova, and others. Impacts of pervasive climate change and extreme events on rocky intertidal communities: Evidence from long-term data. Frontiers in Marine Science, vol. 8, art. 642764, 2021.
- Morris-Webb. An interdisciplinary understanding of coastal resource collection in Wales. PhD thesis, Bangor University, 2021.
- Morris, R. L., Konlechner, T. M., Ghisalberti, M., and Swearer, S. E. From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. Global Change Biology, vol. 24, No. 5, pp. 1827–1842, 2018.
- Muller-Karger, Frank E., and others. Protect and restore ecosystems and biodiversity. Ocean Decade Vision 2030 White Papers, Challenge 2. Paris: UNESCO-IOC, 2024, 112 pp.
- Nawarat, K., Reyns, J., Vousdoukas, M. I., and others. Coastal hardening and what it means for the world's sandy beaches. Nature Communications, vol. 15, art. 10626, 2024. https://doi.org/10.1038/s41467-024-54952-1.
- Nielsen, David M., and others. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change, vol. 12, pp. 263–270, 2022.
- Orlando, L., Ortega, L., and Defeo, O. Urbanization effects on sandy beach macrofauna along an estuarine gradient. Ecological Indicators, vol. 111, art. 106036, 2020.
- Pardal, A., Cordeiro, C.A.A.M., Ciotti, A.M., Jenkins, S.R., Giménez, L., Burrows, M.T., Christofoletti, R.A. Influence of environmental variables over multiple spatial scales on the population structure of a key marine invertebrate. Marine Environmental Research, vol. 170, art. 105410, 2021.
- Pardal, A., Jenkins, S. R., Christofoletti, R. A. Local and large-scale spatial variation in a marine predator-prey interaction in the southwestern Atlantic. Oecologia, vol. 199, No. 3, pp. 685–698, 2022.
- Pardal, A., Martinez, A.S., Ciotti, A.M., Christofoletti, R.A., Cordeiro, C.A.A.M. Macroecology of rocky intertidal benthic communities along the southwestern Atlantic: Patterns of spatial variation and associations with natural and anthropogenic variables. Marine Environmental Research, vol. 190, art. 106099, 2023.
- Petraitis, P.S., Dudgeon, S.R. Declines over the last two decades of five intertidal invertebrate species in the western North Atlantic. Communications Biology, vol. 3, art. 591, 2020. DOI: 10.1038/s42003-020-01326-0.
- Pinardi, Nadia, and others. Increase community resilience to ocean hazards. Ocean Decade Vision 2030 White Papers, Challenge 6. Paris: UNESCO-IOC, 2024, 120 pp.
- Ponti, M., Linares, C., Cerrano, C., Rodolfo-Metalpa, R., and Hoeksema, B.W. Editorial: Biogenic Reefs at Risk: Facing Globally Widespread Local Threats and Their Interaction With Climate Change. Frontiers in Marine Science, vol. 8, art. 793038, 2021. DOI: 10.3389/fmars.2021.793038.
- Popoola, O.O. Spatio-Temporal Assessment of Shoreline Changes and Management of the Transgressive Mud Coast, Nigeria. European Scientific Journal, vol. 18, No. 20, pp. 99, 2022. DOI: 10.19044/esj.2022.v18n20p99.
- Rahman, Serina. Johor's Forest City Faces Critical Challenges. Trends in Southeast Asia 3. ISEAS Yusof Ishak Institute, 2017a.
- Rahman, Serina. The Socio-Cultural Impacts of Forest City. ISEAS Yusof Ishak Institute, 2017b. Disponível em: http://hdl.handle.net/11540/7217.
- Rilov, Gil, and others. Sea level rise can severely reduce biodiversity and community net production on rocky shores. Science of the Total Environment, vol. 791, art. 148377, 2021.
- Roberts, Sophie M. , Simon E. Reeves, Andrew Bossie, Alan Cottingham, Andrew Jeffs, Jenny R. Hillman, Determining mussel restoration success: An Australasian case study, Biological

Conservation, Volume 285, 2023, 110235, ISSN 0006-3207, https://doi.org/10.1016/j.biocon.2023.110235.

- Sabine, Christopher, and others. Unlock ocean-based solutions to climate change. Ocean Decade Vision 2030 White Papers, Challenge 5. Paris: UNESCO-IOC, 2024, 77 pp.
- Sanford, E., Sones, J. L., García-Reyes, M., Goddard, J. H., and Largier, J. L. Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. Scientific Reports, vol. 9, No. 1, art. 4216, 2019.
- Smale, D. A., Wernberg, T., Oliver, E. C., Thomsen, M., Harvey, B. P., Straub, S. C., ... and Moore, P. J. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, vol. 9, No. 4, pp. 306–312, 2019.
- Soares, Marcelo de Oliveira, and others. Oil spill in South Atlantic (Brazil): Environmental and governmental disaster. Marine Policy, vol. 115, art. 103879, 2020.
- Stori, Fernanda Terra, and others. Traditional ecological knowledge supports ecosystem-based management in disturbed coastal marine social-ecological systems. Frontiers in Marine Science, vol. 6, art. 571, 2019. https://doi.org/10.3389/fmars.2019.00571.
- Strain, Elisabeth M. A., and others. Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? Journal of Applied Ecology, vol. 55, No. 1, pp. 426–441, 2018. https://doi.org/10.1111/1365-2664.12961.
- Thiel, M., Macaya, E. C., Acuña, E., Arntz, W. E., Bastias, H., Brokordt, K., ... & Vega, J. M. The Humboldt Current System of Northern and Central Chile: oceanographic processes, ecological interactions and socioeconomic feedback. Oceanography and Marine Biology: An Annual Review. 195-344, 2007.
- Thurstan, Ruth H. , Ben K. Diggles, Chris L. Gillies, Michael K. Strong, Ray Kerkhove, Sarah M. Buckley, Robert A. King, Vince Smythe, Gideon Heller-Wagner, Rebecca Weeks, Fred Palin, Ian McLeod, Charting two centuries of transformation in a coastal social-ecological system: A mixed methods approach, Global Environmental Change, Volume 61, 2020, 102058, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2020.102058.Valqui, Juan, and others. Changes in rocky intertidal communities after the 2015 and 2017 El Niño events along the Peruvian coast. Estuarine, Coastal and Shelf Science, vol. 250, art. 107142, 2021.
- Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L., Plomaritis, T.A., Athanasiou, P., Luijendijk, A., Feyen, L. Sandy coastlines under threat of erosion. Nature Climate Change, vol. 10, pp. 260–263, 2020. DOI: 10.1038/s41558-020-0697-0.
- Vozzo, M.L., Cumbo, V.R., Crosswell, J.R. and Bishop, M.J. (2021), Wave energy alters biodiversity by shaping intraspecific traits of a habitat-forming species. Oikos, 130: 52-65. https://doi.org/10.1111/oik.07590
- M.L. Vozzo, C. Doropoulos, B.R. Silliman, A. Steven, S.E. Reeves, R. ter Hofstede, M. van Koningsveld, J. van de Koppel, T. McPherson, M. Ronan, & M.I. Saunders, To restore coastal marine areas, we need to work across multiple habitats simultaneously, Proc. Natl. Acad. Sci. U.S.A. 120 (26) e2300546120, https://doi.org/10.1073/pnas.2300546120 (2023).
- Zarco-Perello, S., Wernberg, T., Langlois, T. J., & Vanderklift, M. A. (2017). Tropicalization strengthens consumer pressure on habitat-forming seaweeds. Scientific Reports, 7(1), 820.
- Waltham, N. J., Elliott, M., Lee, S. Y., Lovelock, C., Duarte, C. M., Buelow, C., ... & Sheaves, M. UN decade on ecosystem restoration 2021–2030—what chance for success in restoring coastal ecosystems? Frontiers in Marine Science, 7, 71, 2020.
- Wang, Wei, and others. Global warming and artificial shorelines reshape seashore biogeography. Global Ecology and Biogeography, vol. 29, No. 2, pp. 220–231, 2020.

- Weitzman, Benjamin, and others. Changes in rocky intertidal community structure during a marine heatwave in the Northern Gulf of Alaska. Frontiers in Marine Science, vol. 8, art. 556820, 2021.
- Xiu, Peng, and others. Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. Scientific Reports, vol. 8, No. 1, art. 2866, 2018.
- Yi, Y.J., Gao, Y.N., Wu, X.F., and others. Modeling the effect of artificial flow and sediment flux on the environment and plankton of an estuary. International Journal of Sediment Research, vol. 38, No. 3, pp. 335–348, 2023.

Section 4

Sub-chapter 5c: Atolls, their Lagoons and Islands

Luigi Jovane[1], Fiona Whitaker[2], André W. Droxler[3], Alessio Rovere[4,5], Miguel Mies[1,6], Antonia Correia[7,8], Shiham M. Adam[9], Jody M. Webster[6]

1-Universidade de São Paulo, São Paulo, Brazil
2-University of Bristol, Bristol, UK
3-Rice University, Houston, US
4-Ca' Foscari University of Venice, Venezia, Italy
5-MARUM, Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany
6- Instituto Coral Vivo, Bahia, Brazil
7- Universidade de Algarve, Faro, Portugal
8- Associação Kipt Inovação e Turismo, Laboratório Colaborativo, Portugal
9- Maldives Marine Research Institute, Malé, Maldives
10-University of Sydney, Sydney, Australia

1 Keynotes

- New "Antecedent Karst Theory" for origin of atolls and atoll islands as an alternative to Darwin's "Subsidence Theory"
- New concepts on the hydrogeology of atolls and atoll islands
- Updated perspective on atolls and lagoons and tourism
- Production of carbonate sands and sediment transport during anomalous storm events can maintain the sediment supply atoll islands
- Global and local stressors are increasingly altering the functioning of critical ecological processes in atolls.

- Conservation measures for atoll ecosystems should focus on reducing CO_2 emissions, enforcing MPAs, promoting sustainable use, engaging communities, and supporting research.

2 Introduction

Atolls are ring-shaped coral reefs encircling lagoons, commonly found in tropical and subtropical seas (Figure 1). Atoll islands are morphologically coherent wave-built accumulations of bioclastic sediment, located on atoll rims or on patch reefs within atoll lagoons, and emergent at all stages of the tide. Distant from continental influence, atolls are usually surrounded by abyssal depths, although their reef crests rise close to mean sea level and enclose lagoons that range from a few to 70 meters deep (Purdy and Winterer, 2001). At a broader scale, the diameter of atolls typically spans from a few to several dozen kilometers. Worldwide, there are some 268 atolls, with a further 171 subtidal atoll reefs with little or no island development (Goldberg, 2016). Lagoons are often euhaline, with exchange of ocean water through reef passages or via indirect mechanisms, but many atolls in the central Pacific have isolated lagoons that range from hypersaline to brackish or fresh. Atolls serve as habitats of global significance for tropical biodiversity, including seabirds, marine turtles, and other keystone island species, whilst inhabited "atoll nations" serve as home to Iindigenous Ppeoples and cultures (Steibl et al., 2024a,b).

3 Environmental change since WOAII

Further baseline information on atolls, their lagoons and islands can be found in the Supplementary Materials and WOA I (Chapter 7) and WOAII (Chapter 7C). Darwin's "Subsidence Theory" suggests that atolls form as volcanic islands gradually sink, with coral growth keeping pace, creating a reef-ringed lagoon (Darwin, 1842; Davis, 1928). The "Antecedent Karst Theory" (DoxlerDroxler and Jorry, 2021) argues instead that atolls develop from preexisting limestone karst topography, where dissolution and erosion shape the reef structure before submersion. Essentially, the former emphasizes vertical subsidence, while the latter highlights preformed karst landscapes as the foundation for

atoll formation. “Antecedent Karst Theory” is introduced as an alternative to Darwin’s “Subsidence Theory” as a new concept in this WOA III compared to the previous WOAs. We also provide an updated perspective on the hydrogeology of atolls and atoll islands and the impact of tourism on Atolls and Lagoons. Further novel topics addressed in WOA III are the vulnerability of atolls and their fauna to sea-level and climate change, along with response strategies and the role of ecosystem services, restoration, conservation, mitigation, and adaptation.

3.1 The unique ecological functioning of atolls

Their isolation from continental influence means that reef ecosystems of atolls function differently from coastal reefs located on continental shelves. The absence of river discharges and the typical remoteness limit nutrient availability, making atolls highly oligotrophic (Hatcher, 1990; Ke et al., 2018). Primary production is thus more dependent on the photosynthesis performed by coral-associated Symbiodiniaceae dinoflagellates. Symbiodiniaceans are hosted intracellularly by corals and dependent primarily on nutrients provided by the host metabolism instead of the surrounding water (Davy et al., 2012). The remoteness of atolls also limits connectivity processes, as fewer nearby source populations exist compared to coastal reefs, making recruitment and population replenishment reliant on self-seeding and long-distance larval transport (Underwood et al., 2012). Likewise, the isolation and the lower sediment input amplify the impact of bioerosive processes by organisms such as sponges, bivalves, and urchins, which perforate the reef carbonate framework produced by hermatypic corals (Pari et al., 2002). These processes operate in atolls mean that the availability of sediment, nutrients, and larval propagules is limited compared to that in coastal areas, making atolls more vulnerable to natural and anthropogenic disturbance

3.2 Atoll vulnerability to anthropogenic stressors including sea-level rise and climate change

Habitability is dependent upon availability of safe land freshwater and food, and access to safe settlements and infrastructure and to sustainable economic activities (Duvat et al., 2020, 2021). Multiple anthropogenic stressors affect atolls as a result of human activities or environmental changes at both local and global scales. Local-scale stressors include overfishing, unregulated tourism, and coastal development (Knowlton and Jackson, 2008; McMichael et al. 2023). Overfishing is common as local populations heavily rely on fisheries resources, and can quickly deplete fish stocks (Newton et al., 2007; Wolanski et al., 2020). Unregulated tourism often results in trampling and anchoring on the reef, which also damages the carbonate reef framework, whilst coastal and infrastructure development often results in habitat destruction and reef pollution (Hawkins and Roberts, 1993; Allemand and Osborn, 2019; Rios et al., 2021; UNEP, 2022). Increased waste discharge from residential and industrial activities leads to organic and inorganic contamination, plastic pollution, and nutrient enrichment, promoting algal overgrowth and coral mortality across the reef (Sheppard et al., 2020).

Besides local-scale stressors, atolls and reef ecosystems in general are highly vulnerable to the two major global-scale stressors that impact environments worldwide - global warming and ocean acidification - both of which are a consequence of increased CO_2 concentrations in the atmosphere and ocean. Increasing sea-surface temperatures and more frequent and intense marine heatwaves are by far the greatest threat to atolls and reef ecosystems. Corals under thermal stress undergo bleaching, which produce extensive coral mortality (Hughes et al., 2020). Ocean acidification, on the other hand, greatly intensifies erosive processes in the atoll framework (Hoegh-Gudlberg et al., 2007). In addition, with an increasingly energetic atmosphere, atolls are subject to intense wave action that threatens their structural integrity (McLean and Kench, 2015; Hynes et al., 2025).

3.3 Impacts on organisms, functional roles, and ecological processes

Global warming, the main threat to reef environments, disrupts the coral–dinoflagellate symbiosis in a phenomenon called “bleaching” (Glynn, 1996). Thermal stress triggers the

excessive production of reactive oxygen species (ROS) by the dinoflagellates (Lesser, 2006). As ROS accumulation overwhelms the coral antioxidant defenses, it leads to cellular damage. Eventually corals expel their symbiotic dinoflagellates, and the white calcareous skeleton becomes visible under the translucent tissue. Consequently, the absence of the photosynthetically-derived carbon provided by the dinoflagellates leads to an energetic deficit, causing coral mortality (Anthony et al., 2007). Once corals perish, their bare skeleton is subject to erosion, further undermining the reef integrity (Braz et al., 2022). Since 2018, numerous atolls worldwide, including those in Hawaii, Chagos Archipelago, French Polynesia, and the Maldives, among others, have experienced severe coral cover declines of up to 76% due to bleaching (Sheppard et al., 2020; Speare et al., 2022; Winston et al., 2022). The most vulnerable species are branching corals, especially *Acropora* spp., which play a key role in supporting biodiversity by providing habitat complexity (Richardson et al., 2017).

Ocean acidification is slowly producing its first impacts on coral reefs. Its main consequence is impairing the calcification process in corals, giant clams, and other calcifying reef organisms. The CO_2 absorbed by the ocean reacts with water to form H_2CO_3 (carbonic acid), which dissociates and releases a proton (H^+), thus lowering the pH. This proton binds with CO_3^{-2} (carbonate ions) and reduces its availability, thus inhibiting the production of $CaCO_3$ skeletons (Hoegh-Guldberg et al., 2007). This makes corals more susceptible to erosion from waves and boring organisms, ultimately reducing habitat complexity. Recent projections have shown that atolls in the Western and Central Pacific are among the most vulnerable regions (Duvat et al., 2021).

Overfishing has also had a major impact on the functioning of atolls. One of the main symptoms of overfishing is the reduction in catch per unit effort, which is declining globally in reef environments (Eddy et al., 2021). Following suit, keystone species like sharks, groupers, and parrotfishes have been recently experiencing significant decline in atolls in the Maldives, Belize, and Solomon Islands (Hughes et al., 2020; McClanahan and Muthiga, 2020; Skinner et al., 2020). Some of these species play critical roles in maintaining reef resilience – for example, herbivorous parrotfish consume large amounts of

turf algae, which are the main competitors of corals (Holbrook et al., 2016). Parrotfish removal contributes to the occurrence of phase shifts, where reefs transition from a coral-dominated to an algae-dominated state (Hughes et al., 2007). Likewise, the loss of higher trophic levels such as predators often leads to trophic cascades. Therefore, global and local stressors are altering the functioning of critical processes in atolls, including calcification, photosynthesis, competition, and trophic interactions.

4 Region-specific changes

4.1 The Arctic Ocean and 4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

The Arctic Ocean and the North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea do not have Atolls.

4.3 The South Atlantic Ocean and the Wider Caribbean,4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf, 4.5 The North Pacific Ocean, and 4.6 The South Pacific Ocean

Atolls are present across World's ocean basins at low latitudes, but the vast majority (96%) of the lie in the Indian and Pacific Oceans (56 and 367 atolls respectively, Goldberg, 2016). Reef provinces are generally divided into three macroregions based on their biogeographic patterns: Indo-Pacific, Caribbean and South Atlantic. However, exposure and vulnerability to global environmental change are determined by a combination of biological factors with contrasting atoll and island physical geomorphologies and degrees of socioeconomic development – from uninhabited and rural to urban islands (Duvat et al., 2017). All climate scenarios project a global increase in cyclone intensity, and frequency of intense ENSO and Indian Ocean Dipole events (IPCC 2019) that will impact atolls in all ocean basins. However, there are important spatial variations in exposure to climate risk, with atolls in the Western Pacific subject to a more rapid increase in risk compared to those in the Central Pacific and Indian Ocean (Duvat et al., 2021).

The responses and resilience to these stressors vary significantly among reef provinces (Roff and Mumby, 2012, Duvat et al., 2021). Coral bleaching disparities have been observed, with South Atlantic reefs, typically dominated by massive, stress-tolerant corals, experiencing less bleaching compared to those in the Indo-Pacific and Caribbean (Mies et al., 2020). The Rocas Atoll, the only atoll in the South Atlantic, experienced minimal coral mortality despite record-breaking thermal stress in 2019 (Gaspar et al., 2021). In the Indian Ocean reefs on the remote atolls of the Chagos Archipelago recovered to net accretion within 2–6 years after mass bleaching episodes associated with the El Niño Southern-Oscillation (ENSO) (Lange et al., 2023). Conversely, densely populated atolls of the Maldives took approximately 15 years to reach a similar degree of recovery and accretion (Carruthers et al., 2024). This underlines the need for a holistic and spatial planning-based approach to improve coral reef recovery in atolls because each one will respond in a unique way.

Increasing seawater temperature and acidification, coupled with rapid rates of sea-level rise, may alter the oceanographic dynamics and biological functioning of atolls. This may enhance erosive processes and lead to the inundation of low-lying islands, resulting in multiple territorial and social challenges for island nation communities. Atoll islands are subject to changes in their size and position due to both anthropogenic and natural causes and one of the most pressing questions is whether they are currently gaining or losing land. A recent study of land area changes in 221 atolls in the Indo-Pacific between 2000 and 2017 on showed a net land mass gain (Holdaway et al., 2021). However, these ~~positive changes~~increases, which are more common on atolls located in the South China Sea and the Maldives, resulted mostly from land reclamation rather than natural processes. McLean and Kench (2015), Kench et al. (2022) and Kench (2024) investigated shoreline change on 244 islands in the last 30 years during which sea level rose at an average of 3 mm $year^{-1}$. Contrary to the prevailing narrative of inundation, erosion, and out-migration (Dickinson, 2009; McMichael et al., 2023; Weatherill, 2023; ~~Ticolf~~Tierolf et al., 2023), evidence shows that island area generally expands due to sediment accretion.

Critical to the future preservation of atoll islands is the maintenance of sediment supply (Tuck et al., 2021), both *in situ* through the production of carbonate sands and by sediment transport during anomalous storm events through reef crest-sediment apron pathways. Sediment consolidation and binding are regulated by vegetation and soil development, influenced by rainfall patterns, wind exposure (Steibl et al., 2024a,b), and the aeolian supply of non-carbonate material and guano, which enhance soil productivity (Browning et al., 2023; McTainsh and Strong, 2007; D'Amico et al., 2023) (Figure 2).

Rising sea levels will also give rise to lateral intrusion of saltwater. On islands with a dense human population this stress is superimposed on salinization from over-abstraction of groundwater and aquifer contamination (Ferguson and Gleeson, 2012; Werner et al., 2013; Michael et al., 2017; Sawyer et al., 2016). In some areas, for example in the western part of the Micronesian group of islands, the effects of sea-level rise may be mitigated in part by increased freshwater recharge due to higher rainfall in the coming decades, but other islands will experience increasing drought influenced by natural climatic cycles, such as the El Niño and La Niña phases of the ENSO (van Der Velde et al., 2006; Bailey et al., 2021). Changes in tidal and wave energy and morphological changes due to coastal erosion during storm surges will also negatively impact the volume of fresh groundwater (Briggs et al., 2021; Stanic et al., 2024).

In addition to a rise in mean sea-level, the freshwater lens is vulnerable to salinization due to seawater inundation during extreme storms. Saltwater can infiltrate through the vadose zone as well as through open boreholes, trenches and/or karst shafts which provide direct access to the aquifer and can continue after the storm surge, sourced from seawater ponded in surface depressions (Holding and Allen, 2015). Numerical simulations suggest that the degree of aquifer salinization due to overwash is largely determined by vadose zone thickness, but it is the recharge rate that determines recovery times (Holding and Allen, 2015). These range from 1 to 19 years after a single overwash event. The non-linear interactions between wave-driven flooding and sea-level rise will lead, by the mid-21st century, to annual overwash of most atoll islands causing widespread erosion and loss of potable water (Storlazzi et al., 2018). Combined with the effects of tidal

fluctuations on mixing of an increasingly thin freshwater lens with underlying seawater, inundation will detrimentally impact the ecological sustainability, agricultural productivity, and human habitation of atoll islands.

Another critical issue is the appeal of atoll islands to tourists, which arises in part from the perception of lagoons as pristine and tranquil destinations. For instance, surveys conducted in the Maldives revealed that 65% of tourists consider environmental quality a critical factor in their choice of lagoon destinations (UNEP, 2022). However, environmental degradation and overcrowding can tarnish this image, diminishing their attractiveness to future visitors. Maintaining a positive destination image requires balancing tourism development with conservation efforts to ensure that lagoons retain their natural beauty and ecological health. Nonetheless, lagoons remain highly attractive destinations, often creating a trade-off between preservation and visitation.

Tourism-related activities commonly exert pressure on lagoon ecosystems. Infrastructure development, such as hotels, restaurants, and marinas, can lead to habitat destruction and fragmentation. For instance, the construction of coastal resorts often involves dredging and land reclamation, which disrupt lagoon hydrodynamics and sedimentation patterns (Pinto et al., 2020). Data indicate that over 50% of mangroves in some lagoon regions have been lost to tourism infrastructure (Gómez et al., 2018). Additionally, direct tourism activities such as diving, snorkeling, boat anchoring, and trampling promote additional erosion and also interfere with trophic interactions from the lagoon to the reef (Diedrich, 2007; Renfro and Chadwick, 2017). Pollution is another critical concern. The influx of tourists can result in elevated levels of solid waste and wastewater, often exceeding the natural assimilative capacity of lagoons. This can lead to eutrophication, characterized by algal blooms, oxygen depletion, and fish kills (Martínez et al., 2019).

While tourism can boost local economies by creating jobs and generating revenue, it can also lead to socio-cultural changes (Everett et al., 2018). However, the commercialization of lagoon areas may marginalize local communities, who often depend on these ecosystems for traditional livelihoods like fishing and aquaculture. Furthermore,

overcrowding during peak tourist seasons can strain local infrastructure and reduce the quality of life for residents.

~~4.5 The North Pacific Ocean, 4.6 The South Pacific Ocean~~ and 4.7 The Southern Ocean

The ~~North Pacific Ocean, the South Pacific Ocean and~~ Southern Ocean does not have atolls.

5 Remaining key knowledge and capacity changes and any new gaps

5.1 Response strategies and the role of ecosystem services

Although reducing greenhouse gas emissions is essential, the magnitude of physical and chemical changes already embedded in climate and ocean systems indicates that the proper implementation of adaptation strategies to enhance resilience is crucial to ensuring the survival of atoll islands. Anomalous storm events can have a positive effect on the sediment balance of an atoll island, where shoreward sediment transport leads to coastal accretion, and bleaching events can result in periods of enhanced sediment generation (Perry et al., 2020; 2023). However, more often storm-driven coastal erosion and sediment export has a negative (and potentially catastrophic) effect (Storlazzi et al., 2018; Georgiou et al., 2024). Superimposed on these effects are the negative environmental and social impacts of tourism that must be balanced against the economic benefits that it can bring. Such strategies, including the establishment of effective marine protected areas (MPAs) and no-take zones, and promoting eco-tourism practices that minimize environmental footprints (UNEP, 2022) should be adopted.

Construction of engineered barriers such as cut-off walls and subsurface dams that physically limit the hydraulic connectivity between the aquifer beneath the island and the saline aquifer offshore is being attempted to control seawater intrusion along some continental margins (Chang et al., 2022, Zheng et al., 2022, Fang et al., 2023). This is likely an impractical solution for most low-lying atoll islands, but comparable impoundment of freshwater within a Pleistocene karstified island aquifer has been shown to result from a

coastal mantle of lower permeability Holocene grainstone (Whitaker and Smart, 2004). This highlights the risks of construction and dredging that threaten the integrity of such natural barriers, especially for islands growing by lateral accretion. The focus should be directed towards developing approaches to minimize the effects of washover on the freshwater lens.

The effectiveness of responses to climate-driven challenges in atoll water supply depends on abundance and demand. Traditional rainwater storage tanks can support low demand but quickly become depleted, especially during droughts (Wallace et al., 2015). Enhanced aquifer recharge and underground storage schemes are generally preferable to more high-cost options such as seawater desalination, especially for smaller communities, but remain vulnerable to seawater inundation and contamination. However, atoll island cities and tourist developments can more readily benefit from the technological advances that mean potable water can be supplied at increasingly low cost (Shokri and Fard, 2023).

Whilst climatic factors cannot be controlled locally, retention of sediment on the islands can be supported by ecological interventions such as reforestation, forest diversification, and removal of invasive species, as well as appropriate management of agricultural activity and human infrastructure engineering (Duvat et al., 2017; Steibl et al., 2024a,b). Coastal ecosystems such as mangrove swamps and seagrass beds have high organic carbon storage in biomass and soil (Macreadie et al., 2021). There is a need to preserve and to enhance this “blue carbon” storage, as well as to restore biodiversity and other ecosystem services benefits of coastal and shallow marine ecosystems (Twomey et al., 2024; Hagger et al., 2024). Nature-based solutions are more sustainable and widely applicable for the wide range of challenges facing non-urbanised atolls. It has been strongly suggested that the key to unlocking these solutions is linking ecosystem-based interventions that span marine and terrestrial zones with processes of sediment production and accretion of atoll islands (Steibl et al. 2024a,b). The success of such a program depends heavily on prior planning and design, effective monitoring, evaluation and reporting, and post-implementation maintenance (Standards Reference Group SERA,

2018). However, in urbanized atolls like Malé and Majuro, the timescales involved render nature-based solutions largely unviable. Rising of atolls and the constructions of coastal defenses are the type of interventions currently being implemented in capitals such as Funafuti and Majuro (Esteban et al., 2019a,b). Moreover, adaptation by communities using limited means can be successful, using a combination of creativity, low-level construction techniques and some nature-based solutions (Jamero et al., 2017, 2018; Narayan et al., 2020).

One of the largest sources of uncertainty in monitoring, modelling, and managing such low-lying islands is the limited availability of accurate high-resolution bathymetric and topography data (Pacheco et al., 2015) to examine changes in coastal morphology over a larger spatial scale and at higher temporal frequency (Hamylton 2017; Vitousek et al. 2023). Satellite remote sensing, airborne LiDAR, and drone photogrammetry should be employed to obtain high-resolution bathymetric and topographic data, assess vegetation cover, and analyze recharge and evapotranspiration on atoll islands (Andréfouët and Paul, 2023; Hamylton et al., 2020; Casella et al., 2017; Collin et al., 2017).

Recently, more attention has been directed towards the resilience of atoll freshwater lenses to natural and demographic changes (Ketabchi et al., 2016). Despite the resource-intensive nature of hydrogeological investigations of atoll islands, there are a few long-established monitoring networks such as on Bonriki (Kiribati) or Cocos (Keeling) Islands. More high-quality investigations are needed to encompass the full range of island sizes and environmental conditions so that they are better able to inform groundwater management and mitigation strategies for any individual atoll island (Werner et al., 2017). Even in well-studied atoll islands, our understanding of the flow paths within the lens and mixing zone is surprisingly poor. Additionally, a better understanding of the effects of tides in karstified island aquifers is needed, not least to reconcile discrepancies between mixing zones simulated using numerical models and those measured in the field (Martin et al., 2012; Ghassemi et al., 2000; Collignon et al., 2020). Groundwater resources on atoll islands are particularly vulnerable due to a combination of high permeability soils and thin

vadose zone but, aside from aquifer salinization, relatively little attention has been given to biological and chemical contamination.

Numerical models can simulate a wide range of physical, chemical, and biological processes, provide a quantitative understanding of the interactions between different processes, and offer a route for predicting responses to changes in environmental conditions and/or management practices. Two challenges common to computer simulations of any system are difficulties in model parameterization and a paucity of field data for validation (Splinter and Coco, 2021; Twomey et al., 2024). Moreover, quantification of model uncertainty requires a suite of simulations to be run (Lui et al., 2022; Herrera et al., 2021). The potential use of the output as training datasets for machine learning algorithms (Reichstein et al., 2019; Papacharalampous and Tyralis, 2022) offers a powerful route to address these challenges. It is critical to match modelling methods to project objectives, budget, and available data. Relatively simple algebraic models can be rapid to implement. For example, Bailey et al. (2021; 2022) and Sangupta et al., (2021) calculate the future groundwater resources of 91 atoll islands in Micronesia from mean annual recharge, island width, Holocene thickness and hydraulic conductivity. Finally, although quantitative models are essential to describe risks and reduce uncertainty in resource management and climate change response projects, conceptual models may suffice for project managers to make informed decisions (Larsen et al., 2016; Twomey et al., 2024).

5.2 Restoration, conservation, mitigation, and adaptation

The health of active coral reefs along the atoll rims is one of the key properties that may mitigate the adverse effects of sea-level rise and increased tempestuousness. Reef crests act as natural breakwaters and dissipate incoming wave energy by wave breaking and bottom friction (Carlot et al., 2023; Huang et al., 2024), providing the ecosystem service of coastal protection. Sea-level rise rates exceeding coral growth and reef crest accretion have a negative effect on wave dissipation exerted by coral reefs (Baldock et al., 2014; Quartaet et al, 2015; Toth., 2023). Rising sea-levels may also increase seawater circulation across the reef, moderating diurnal temperature extremes (and thus coral bleaching), as

well as affecting lagoon flushing times, calcification rates, and many other physically linked biological processes that affect the health and resilience of coral reef communities and those within the lagoon (Gruber et al., 2019; Lowe et al., 2016)

Many conservation measures have been proposed for the protection of atolls, ranging from passive to active initiatives. Active coral restoration projects have been developed across the planet, but so far have failed to restore species or ecosystem functioning at a relevant scale. This is largely because the restoration performed is often undone by bleaching episodes associated with heatwaves and global warming (Hughes et al., 2023). In fact, this has caused some governments to refrain from funding any further active restoration practices. However, creating marine protected areas and neutralizing local-scale impacts (*e.g.*, pollution, unregulated fisheries and tourism) has occasionally proven effective in reducing the global-scale impacts (Graham et al., 2008). On the other hand, marine protected areas must be adequately designed, anticipating local oceanographic and biological factors, such as (larval) connectivity, which is critical for sustaining genetic and species diversity in atolls, which are often remote.

Adoption of hazard mitigation and adaptation strategies for atoll nations, as with all coastal communities, is critically contingent on communication of impacts to policy-makers and users. Communities receive more effectively the message when sea-level and climate metrics are referenced to risk of local scale societal impacts, for example to facilities such as hospitals and airports, both for more frequent and for rarer extreme sea-level events (Rasmussen et al., 2022). The survival of atoll nations, with the exception of urbanized atolls, depends on the development of cross-disciplinary collaboration to protect and restore exchanges of sediment, water, and nutrients between the atoll islands, lagoons, and coral reefs. For urbanized and densely populated atolls this is not valid because several engineering solutions are available (Yamamoto and Esteban, 2014).

Within this context, given the ecological uniqueness and vulnerability of atoll ecosystems, conservation measures must be tailored to their specific needs. These include (i) reducing CO_2 emissions to halt global warming and ocean acidification, (ii) establishing and enforcing MPAs to limit local stressors, (iii) implementing sustainable use

programs, (iv) engaging local communities in conservation through education, awareness, and sustainable livelihoods, and (v) supporting research and long-term monitoring programs to address knowledge gaps and evaluate conservation efforts.

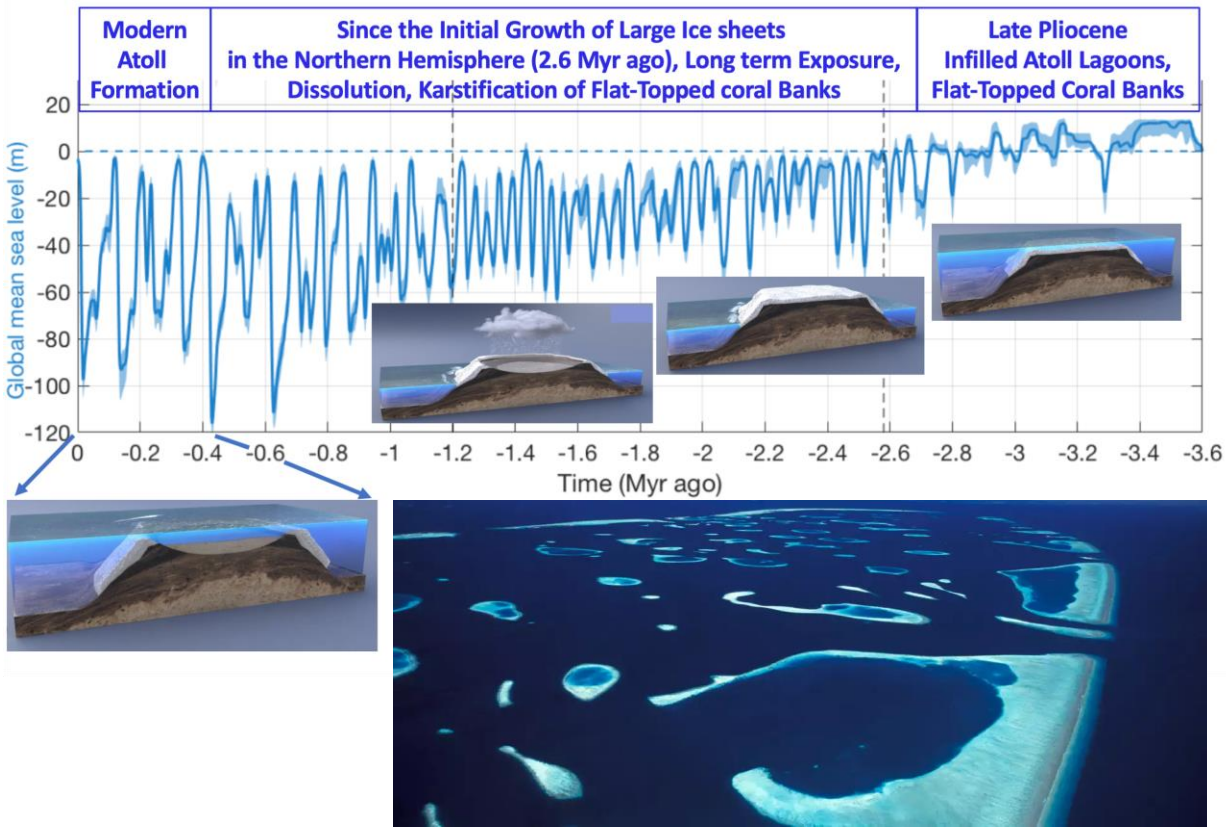


Figure 1-

Example of an atoll in the Maldives, with a coralgal rim enclosing a lagoon including a series of patch reefs, both displayed in light blue. B. Sea level fluctuations over the last 3.6 million years (Berends et al., 2021), framework to explain the modern atoll origin by the newly published "Improved Antecedent Karst Theory" (Droxler and Jorry, 2021), with schematic figures (from a video produced by Ifremer) of the evolution of a Late Pliocene flat-topped Bank, through its long term exposure during the Quaternary forming a karstic~~karsic~~ morphology characteristic of a central depression bounded by a raised rim, which becomes preferentially colonized by coral reefs during their deglacial and highstand reflooding in the last 450,000 years.

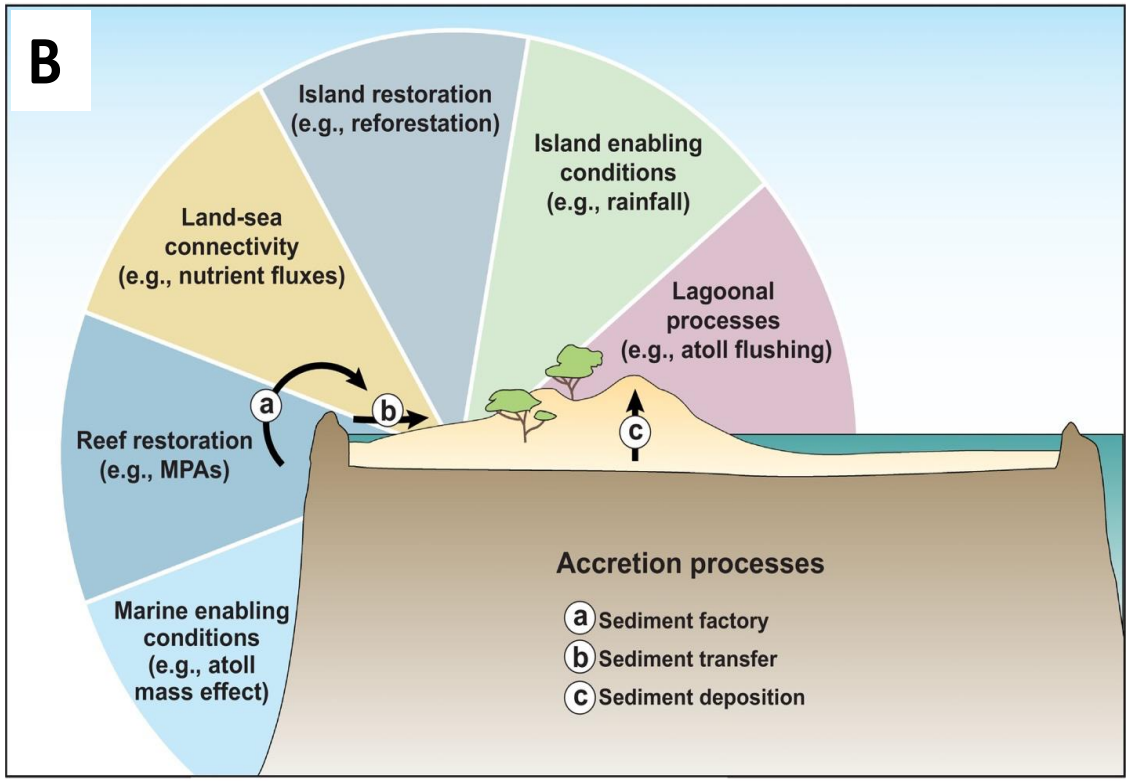


Figure 2.

Identifying bio-geosphere links critical for atoll island protection~~protetion~~ and restoration. Abbreviation MPA: Marine Protected Areas (Steibl et al., 2024b).

References

Agassiz, A. E. R. (1903). On the formation of barrier beefs and of the different types of atolls. *Proceedings of the Royal Society of London*, *71*(467-476), 412-414.

Allemand, D., & Osborn, D. (2019). Ocean acidification impacts on coral reefs: From sciences to solutions. *Regional Studies in Marine Science, 28*. DOI:10.1016/j.rsma.2019.100558

Andréfouët, S., & Paul, M. (2023). Atolls of the world: A reappraisal from an optical remote sensing and global mapping perspective. *Marine Pollution Bulletin, 194*, 115400. DOI:10.1016/j.marpolbul.2023.115400

Anthony, K. R., Connolly, S. R., & Hoegh-Guldberg, O. (2007). Bleaching, energetics, and coral mortality risk: Effects of temperature, light, and sediment regime. *Limnology and Oceanography, 52*(2), 716–726. DOI:10.4319/lo.2007.52.2.0716

Aubert, O., & Droxler, A. (1996). Seismic stratigraphy and depositional signatures of the Maldive carbonate system (Indian Ocean). *Marine and Petroleum Geology*, *13*(5), 503-536. DOI:10.1016/j.scitotenv.2024.169881

Bailey, R. T., Bieger, K., Flores, L., & Tomer, M. (2022). Evaluating the contribution of subsurface ENdrainage to watershed water yield using SWAT+ with groundwater modeling. *Science of The Total Environment, 802*, 149962. DOI:10.1016/j.scitotenv.2021.149962

Bailey, R. T., Tasdighi, A., Park, S., Tavakoli-Kivi, S., Abitew, T., Jeong, J., & Worqlul, A. W. (2021). APEX-MODFLOW: A new integrated model to simulate hydrological processes in watershed systems. *Environmental Modelling & Software, 143*, 105093. DOI:10.1016/j.envsoft.2021.105093

Baldock, T. E., Golshani, A., Callaghan, D. P., Saunders, M. I., & Mumby, P. J. (2014). Impact of sea-level rise and coral mortality on the wave dynamics and wave forces on barrier reefs. *Marine Pollution Bulletin, 83*(1), 155–164. DOI:10.1016/j.marpolbul.2014.03.058

Belopolsky, A. V., & Droxler, A. W. (2004). Seismic expressions of prograding carbonate bank margins: Middle Miocene, Maldives, Indian Ocean. DOI:10.1306/M81928C12

Belopolsky, A., & Droxler, A. (2003). Imaging Tertiary carbonate system—the Maldives, Indian Ocean: insights into carbonate sequence interpretation. *The Leading Edge*, *22*(7), 646-652. DOI:10.1190/1.1599690

Berends, K. D., Gensen, M. R., Warmink, J. J., & Hulscher, S. J. (2021). Multidecadal analysis of an engineered river system reveals challenges for model-based design of human interventions. *CivilEng, 2*(3), 580–598. DOI:10.3390/civileng2030032

Blanchon, P. (2011). Geomorphic zonation. In *Encyclopedia of modern coral reefs* (pp. 469-486). Springer, Dordrecht.

Braz, G. B., Lacerda, C. H., Evangelista, H., Güth, A. Z., Rumbelsperger, A. M., Capel, K. C., & Mies, M. (2022). Unprecedented erosion of *Mussismilia harttii*, a major reef-building species in the Southwestern Atlantic, after the 2019 bleaching event. *Coral Reefs, 41*(5), 1537–1548. DOI:10.1007/s00338-022-02283-9

Briggs, M. A., Cantelon, J. A., Kurylyk, B. L., Kulongoski, J. T., Mills, A., & Lane, J. W. (2021). Small atoll fresh groundwater lenses respond to a combination of natural climatic cycles and human modified geology. *Science of the Total Environment, 756*, 143838. DOI:10.1016/j.scitotenv.2020.143838

Browning, T., Achterberg, E. P., Bogner, B., von Keitz, T. E., Hu, Z., Melzer, H., & Stelzner, M. (2023). CLOCKS: Northern Cascadia: Extent of locked zone, prism deformation, slip-to-toe, and the edge of subduction, and CASCADIA CO_2: Seismic multi-parameter study at a possible site for CO_2 storage in basalt in the Cascadia Basin utilizing shear wave events (secondary user). *ReSEAt*, Cruise No. SO294, 13.09.2022–27.10.2022, Vancouver (Canada)–Port Hueneme (USA).

Camoin, G. F., Ebren, P., Eisenhauer, A., Bard, E., & Faure, G. (2001). A 300 000-yr coral reef record of sea level changes, Mururoa atoll (Tuamotu archipelago, French Polynesia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *175*(1-4), 325-341. DOI:10.1016/S0031-0182(01)00378-9

Carlot, J., Vousdoukas, M., Rovere, A., Karambas, T., Lenihan, H. S., Kayal, M., & Parravicini, V. (2023). Coral reef structural complexity loss exposes coastlines to waves. *Scientific Reports, 13*(1), 1683. DOI:10.1038/s41598-023-28945-x

Carruthers, L., Ersek, V., Maher, D., Sanders, C., Tait, D., Soares, J., & Sippo, J. Z. (2024). Sea-level rise and extreme Indian Ocean Dipole explain mangrove dieback in the Maldives. *Scientific Reports, 14*(1), 27012. DOI:10.1038/s41598-024-73776-z

Casella, E., Collin, A., Harris, D., et al. (2017). Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs, 36*, 269–275.

Chang, Q., Zheng, T., Gao, C., Zheng, X., & Walther, M. (2022). How to cope with downstream groundwater deterioration induced by cutoff walls in coastal aquifers. *Journal of Hydrology, 610*, 127804. DOI:10.1016/j.jhydrol.2022.127804

Collignon, B. (2019). Earth tide effect in karstic and non-karstic aquifers in the Guinea Gulf. In *Eurokarst 2018, Besançon: Advances in the Hydrogeology of Karst and Carbonate Reservoirs* (pp. 233–242). Springer International Publishing. DOI:10.13140/RG.2.2.30206.28483

Collin, A., Duvat, V., Pillet, V., Salvat, B., & James, D. (2018). Understanding interactions between shoreline changes and reef outer slope morphometry on Takapoto Atoll (French Polynesia). *Journal of Coastal Research, (85)*, 496–500. DOI:10.2112/SI85-100.1

D'Amico, A., De Boni, A., Palmisano, G. O., Acciani, C., & Roma, R. (2023). Environmental analysis of soilless tomato production in a high-tech greenhouse. *Cleaner Environmental Systems, 11*, 100137. DOI:10.1016/j.cesys.2023.100137

Darwin, C. (1842). *The structure and distribution of coral reefs*. Smith, Elder and Co.

Davis, W. M. (1928). *The coral reef problem*. American Geographical Society.

Davy, S. K., Allemand, D., & Weis, V. M. (2012). Cell biology of cnidarian-dinoflagellate symbiosis. *Microbiology and Molecular Biology Reviews, 76*(2), 229–261. DOI:10.1128/MMBR.05014-11

Der Velde, I. R., van der Werf, G. R., Houweling, S., Maasakkers, J. D., Borsdorff, T., Landgraf, J., ... & Aben, I. (2021). Vast CO_2 release from Australian fires in 2019–2020 constrained by satellite. *Nature, 597*(7876), 366–369. DOI:10.1038/s41586-021-03712-y

Der Velde, M., Javaux, M., Vanclooster, M., & Clothier, B. E. (2006). El Niño–Southern Oscillation determines the salinity of the freshwater lens under a coral atoll in the Pacific Ocean. *Geophysical Research Letters, 33*(21). DOI:10.1029/2006GL027748

Dickinson, W. R. (2009). Pacific atoll living: How long already and until when. *GSA Today, 19*(3), 4–10. DOI:10.1130/GSATG35A.1

Diedrich, A. (2007). The impacts of tourism on coral reef conservation awareness and support in coastal communities in Belize. *Coral Reefs, 26*(4), 985–996. DOI:10.1007/s00338-007-0224-z

DOI:10.1007/s00338-016-1522-0

Droxler, A. W., & Jorry, S. J. (2021). The origin of modern atolls: Challenging Darwin's deeply ingrained theory. *Annual Review of Marine Science, 13*(1), 537–573. DOI:10.1146/annurev-marine-122414-034137

Duvat, V. K. (2020). Human-driven atoll island expansion in the Maldives. *Anthropocene, 32*, 100265. DOI:10.1016/j.ancene.2020.100265

Duvat, V. K., Magnan, A. K., Perry, C. T., Spencer, T., Bell, J. D., Wabnitz, C. C., ... & Le Cozannet, G. (2021). Risks to future atoll habitability from climate-driven environmental changes. *Wiley Interdisciplinary Reviews: Climate Change, 12*(3), e700. DOI:10.1002/wcc.700

Duvat, V. K., Magnan, A. K., Wise, R. M., Hay, J. E., Fazey, I., Hinkel, J., ... & Ballu, V. (2017). Trajectories of exposure and vulnerability of small islands to climate change. *Wiley Interdisciplinary Reviews: Climate Change, 8*(6). DOI:10.1002/wcc.478

Eddy, T. D., Lam, V. W., Reygondeau, G., Cisneros-Montemayor, A. M., Greer, K., Palomares, M. L. D., ... & Cheung, W. W. (2021). Global decline in capacity of coral reefs to provide ecosystem services. *One Earth, 4*(9), 1278–1285. DOI:10.1016/j.oneear.2021.08.016

Esteban, M., Laurice Jamero, M., Nurse, L., Yamamoto, L., Takagi, H., Nguyen, T. D., et al. (2019). Adaptation to sea level rise on low coral islands: Lessons from recent events. *Ocean & Coastal Management*. DOI:10.1016/j.ocecoaman.2018.10.031

Everett, H., Simpson, D., & Wayne, S. (2018). *Tourism as a driver of growth in the Pacific: A pathway to growth and prosperity for Pacific Island countries* (Issues in Pacific Development No. 2). Asian Development Bank – Pacific Private Sector Development Initiative.

Fang, Y., Qian, J., Zheng, T., Wang, H., Zheng, X., & Walther, M. (2023). Submarine groundwater discharge in response to the construction of subsurface physical barriers in coastal aquifers. *Journal of Hydrology, 617*. DOI:10.1016/j.jhydrol.2022.129010

Ferguson, G., & Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change, 2*(5), 342–345. DOI:10.1038/nclimate1413

Gaspar, T. L., Quimbayo, J. P., Ozekoski, R., Nunes, L. T., Aued, A. W., Mendes, T. C., ... & Segal, B. (2021). Severe coral bleaching of *Siderastrea stellata* at the only atoll in the South Atlantic driven by sequential marine heatwaves. *Biota Neotropica, 21*(2). DOI:10.1590/1676-0611-bn-2020-1131

Georgiou, I. Y., FitzGerald, D. M., & Hanegan, K. C. (2024). Storm and tidal interactions control sediment exchange in mixed-energy coastal systems. *PNAS Nexus, 3*(2). DOI:10.1093/pnasnexus/pgae042

Ghassemi, F., Alam, K., & Howard, K. W. F. (2000). Fresh-water lenses and practical limitations for their three-dimensional simulation. *Hydrogeology Journal, 8*(5), 521–537. DOI:10.1007/s100400000087

Gischler, E., & Oschmann, W. (2005). Historical climate variation in Belize (Central America) as recorded in scleractinian coral skeletons. *Palaios*, *20*(2), 159-174. DOI:10.2210/palo.2004.p04-09

Glynn, P. W. (1996). Coral reef bleaching: Facts, hypotheses and implications. *Global Change Biology, 2*(6), 495–509. DOI:10.1111/j.1365-2486.1996.tb00063.x

Goldberg, W. M. (2016). Atolls of the world: Revisiting the original checklist. *Atoll Research Bulletin, 610*, 1–47. DOI:10.5479/si.0077-5630.610

Gómez-Vega, M., & Herrero-Prieto, L. C. (2018). Achieving tourist destination competitiveness: Evidence from Latin-American and Caribbean countries. *International Journal of Tourism Research, 20*(6), 782–795. DOI:10.1002/jtr.2231

Graham, N. A. J., McClanahan, T. R., MacNeil, M. A., Wilson, S. K., Polunin, N. V. C., Jennings, S., Chabanet, P., Clark, S., Spalding, M. D., Letourneur, Y., Bigot, L., Galzin, R., Öhman, M. C., Garpe, K. C., Edwards, A. J.,

& Sheppard, C. R. C. (2008). Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS ONE, 3*(8). DOI:10.1371/journal.pone.0003039

Green, J. A. M., Molloy, J. L., Davies, H. S., & Duarte, J. C. (2018). Is there a tectonically driven supertidal cycle?. *Geophysical Research Letters*, *45*(8), 3568-3576. DOI:10.1002/2017gl076695

Grimaldi, C. M., Lowe, R. J., Benthuysen, J. A., Green, R. H., Reyns, J., Kernkamp, H., & Gilmour, J. (2022). Wave and tidally driven flow dynamics within a coral reef atoll off northwestern Australia. *Journal of Geophysical Research: Oceans*, *127*(3), e2021JC017583. DOI:10.1029/2021JC017583

Grossmann, M., Nielsen, S. N., Rivadeneira, M. M., & Valdivia, N. (2023). The latitudinal gradient of functional diversity of Miocene marine mollusks from Chile. Ecography, 2023(2). DOI: 10.1111/ecog.06344

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Key, R. M., Kozyr, A., Lauvset, S. K., Lo Monaco, C., Mathis, J. T., Murata, A., Olsen, A., Pérez, F. F., Sabine, C. L., Tanhua, T., & Wanninkhof, R. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science, 363*(6432), 1193–1199. DOI:10.1126/science.aau5153

Hagger, V., Stewart-Sinclair, P., Rossini, R. A., Adame, M. F., Glamore, W., Lavery, P., ... & Lovelock, C. E. (2024). Lessons learned on the feasibility of coastal wetland restoration for blue carbon and co-benefits in Australia. *Journal of Environmental Management, 369*, 122287. DOI:10.1016/j.jenvman.2024.122287

Hamylton, S. M. (2017). Mapping coral reef environments: A review of historical methods, recent advances and future opportunities. *Progress in Physical Geography, 41*(6), 803–833. DOI:10.1177/0309133317744998

Hamylton, S. M., Morris, R. H., Carvalho, R. C., Roder, N., Barlow, P., Mills, K., & Wang, L. (2020). Evaluating techniques for mapping island vegetation from unmanned aerial vehicle (UAV) images: Pixel classification, visual interpretation and machine learning approaches. *International Journal of Applied Earth Observation and Geoinformation, 89*. DOI:10.1016/j.jag.2020.102085

Hatcher, B. G. (1990). Coral reef primary productivity: A hierarchy of pattern and process. *Trends in Ecology & Evolution, 5*(5), 149–155. DOI:10.1016/0169-5347(90)90221-X

Hawkins, J. P., & Roberts, C. M. (1993). Effects of recreational scuba diving on coral reefs: Trampling on reef-flat communities. *Journal of Applied Ecology*, 25–30. DOI:10.2307/2404267

Herrera, P. A., Marazuela, M. A., & Hofmann, T. (2022). Parameter estimation and uncertainty analysis in hydrological modeling. *Wiley Interdisciplinary Reviews: Water, 9*(1), e1569. DOI:10.1002/wat2.1569

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., ... & Hatziolos, M. E. (2007). Coral reefs under rapid climate change and ocean acidification. *Science, 318*(5857), 1737–1742. DOI:10.1126/science.1152509

Hoffmeister, J. E., & Ladd, H. S. (1944). The antecedent-platform theory. *The Journal of Geology, 52*(6), 388–402.

Holbrook, S. J., Schmitt, R. J., Adam, T. C., & Brooks, A. J. (2016). Coral reef resilience, tipping points and the strength of herbivory. *Scientific Reports, 6*, 35817.DOI:10.1038/srep35817

Holdaway, A., Ford, M., & Owen, S. (2021). Global-scale changes in the area of atoll islands during the 21st century. *Anthropocene, 33*. DOI:10.1016/j.ancene.2021.100282

Holding, S., & Allen, D. M. (2015). Wave overwash impact on small islands: Generalised observations of freshwater lens response and recovery for multiple hydrogeological settings. *Journal of Hydrology, 529*, 1324–1335. DOI:10.1016/j.jhydrol.2015.08.052

Huang, X., Tang, J., & Shen, Y. (2024). Long time series of ocean wave prediction based on PatchTST model. *Ocean Engineering, 301*. *DOI:10.1016/j.oceaneng.2024.117572*

Hughes, A. C., & Grumbine, R. E. (2023). The Kunming-Montreal Global Biodiversity Framework: What it does and does not do, and how to improve it. *Frontiers in Environmental Science, 11*. DOI:10.3389/fenvs.2023.1281536

Hughes, A. T., Hamilton, R. J., Choat, J. H., & Rhodes, K. L. (2020). Declining grouper spawning aggregations in Western Province, Solomon Islands, signal the need for a modified management approach. *PLoS One, 15*(3), DOI:10.1371/journal.pone.0230485

Hughes, T. P., Rodrigues, M. J., Bellwood, D. R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M. S., Steneck, R. S., & Willis, B. (2007). Phase shifts, herbivory, and the

resilience of coral reefs to climate change. *Current Biology, 17*(4), 360–365. DOI:10.1016/j.cub.2006.12.049

Hynes, M. G., Masdar, H., Parenden, D., de Voogd, N. J., Stuut, J. B. W., Jompa, J., ... & Renema, W. (2025). Impact of Holocene relative sea-level changes on patch reef-island development in the Spermonde Archipelago, South Sulawesi, Indonesia. *The Holocene, 35*(5), 556–570. DOI:10.1177/09596836251313628

Jamero, M. L., Onuki, M., Esteban, M., & Tan, N. (2018). Community-based adaptation in low-lying islands in the Philippines: Challenges and lessons learned. *Regional Environmental Change, 18*(8), 2249–2260. DOI:10.1007/s10113-018-1353-0

Jamero, M., Onuki, M., Esteban, M., Billones-Sensano, X. K., Tan, N., Nellas, A., ... & Valenzuela, V. P. (2017). Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change, 7*(8), 581–586. DOI:10.1038/nclimate3344

Jorry, S., Jouet, G., Prat, S., Courgeon, S., Le Roy, P., Camoin, G., & Caline, B. (2014, December). A modern analog for carbonate source-to-sink sedimentary systems: the Glorieuses archipelago and adjacent basin (SW Indian Ocean). In *AGU Fall Meeting Abstracts* (Vol. 2014, pp. EP21C-3553).

Ke, Z., Tan, Y., Huang, L., Liu, H., Liu, J., Jiang, X., & Wang, J. (2018). Spatial distribution patterns of phytoplankton biomass and primary productivity in six coral atolls in the central South China Sea. *Coral Reefs, 37*(3), 919–927. DOI:10.1007/s00338-018-1717-7

Kench, P. S., Sengupta, M., Ford, M. R., & Owen, S. D. (2024). Island change framework defines dominant modes of atoll island dynamics in response to environmental change. *Communications Earth & Environment, 5*(1), 585. DOI:10.1038/s43247-024-01757-1

Kench, P. S., Liang, C., Ford, M. R., Owen, S. D., Aslam, M., Ryan, E. J., ... & McLean, R. F. (2023). Reef islands have continually adjusted to environmental change over the past two millennia. *Nature communications*, *14*(1), 508. DOI:10.1038/s41467-023-36171-2

Kench, P. S., Beetham, E. P., Turner, T., Morgan, K. M., Owen, S. D., & McLean, R. F. (2022). Sustained coral reef growth in the critical wave dissipation zone of a Maldivian atoll. *Communications Earth & Environment, 3*(1), 9. DOI:10.1038/s43247-021-00338-w

Kench, P. S., McLean, R. F., & Nichol, S. L. (2005). New model of reef-island evolution: Maldives, Indian Ocean. *Geology*, *33*(2), 145-148. DOI:10.1130/G21066.1

Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. *Journal of Hydrology, 535*, 235–255. DOI:10.1016/j.jhydrol.2016.01.063

Khanna, P., Droxler, A. W., Nittrouer, J. A., Tunnell Jr, J. W., & Shirley, T. C. (2017). Coralgal reef morphology records punctuated sea-level rise during the last deglaciation. *Nature communications*, *8*(1), 1046. DOI:10.1038/s41467-017-00966-x

Knowlton, N., & Jackson, J. B. C. (2008). Shifting baselines, local impacts, and global change on coral reefs. *PLoS Biology, 6*(2), e54. DOI:10.1371/journal.pbio.0060054

Kuenen, P. H., 1933, Geology of coral reefs, Snellius Exped., 5, Part 2, 125pp.

Lange, I. D., Perry, C. T., & Stuhr, M. (2023). Recovery trends of reef carbonate budgets at remote coral atolls 6 years post-bleaching. *Limnology and Oceanography, 68*(S8), S8–S22. DOI:10.1002/lno.12066

Larsen, M. A., Christensen, J. H., Drews, M., Butts, M. B., & Refsgaard, J. C. (2016). Local control on precipitation in a fully coupled climate-hydrology model. *Scientific Reports, 6*(1), 22927. DOI:10.1038/srep22927

Lesser, M. P. (2006). Oxidative stress in marine environments: Biochemistry and physiological ecology. *Annual Review of Physiology, 68*, 253–278. DOI:10.1146/annurev.physiol.68.040104.11000

Lino, Y. Pranjal, K., Priyansh, S., Jagath, C., Udayashankar, H.N., Babu, D.S.S., Balakrishna, K., 2023. Submarine Groundwater Discharge (SGD): Impacts, challenges, limitations, and management recommendations, Groundwater for Sustainable Development: 21, 100903. DOI:10.1016/j.gsd.2023.100903.

Liu, J., Webster, J. M., Salles, T., Wang, S., Ma, Y., Xu, W., Li, G., & Yan, W. (2022). The formation of atolls: New insights from numerical simulations. *Journal of Geophysical Research: Earth Surface, 127*(8), DOI:10.1029/2022JF006812

Lowe, R. J., Pivan, X., Falter, J., Symonds, G., & Gruber, R. (2016). Rising sea levels will reduce extreme temperature variations in tide-dominated reef habitats. *Science Advances, 2*(8), DOI:10.1126/sciadv.1600825

MacNeil, F. S. (1954). The shape of atolls; an inheritance from subaerial erosion forms. *American Journal of Science, 252*(7), 402–427. DOI:10.1016/0025-3227(65)90025-3

Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment, 2*(12), 826–839. DOI:10.1038/s43017-021-00224-1

Martin, J. B., Gulley, J., & Spellman, P. (2012). Tidal pumping of water between Bahamian blue holes, aquifers, and the ocean. *Journal of Hydrology, 416–417*, 28–38. DOI:10.1016/j.jhydrol.2011.11.033

Martínez, M., Pérez, A., & Torres, R. (2019). Eutrophication in Mediterranean lagoons: Drivers and management strategies. *Environmental Management, 63*(2), 234–245. DOI:10.1007/s00267-018-1120-3

McClanahan, T. R., & Muthiga, N. A. (2020). Change in fish and benthic communities in Belizean patch reefs in and outside of a marine reserve, across a parrotfish capture ban. *Marine Ecology Progress Series, 645*, 25–40. DOI:10.3354/meps13357

McLean, R., & Kench, P. (2015). Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change, 6*(5), 445–463. DOI:10.1002/wcc.350

McMichael, C. (2023). Climatic and environmental change, migration, and health. *Annual Review of Public Health, 44*(1), 171–191. DOI:10.1146/annurev-publhealth-071421-045148

McTainsh, G., & Strong, C. (2007). The role of aeolian dust in ecosystems. *Geomorphology, 89*(1–2), 39–54. DOI:10.1016/j.geomorph.2006.07.028

Michael, H. A., Post, V. E., Wilson, A. M., & Werner, A. D. (2017). Science, society, and the coastal groundwater squeeze. *Water Resources Research, 53*(4), 2610–2617. DOI:10.1002/2017WR020851

Mies, M., Francini-Filho, R. B., Zilberberg, C., Garrido, A. G., Longo, G. O., Laurentino, E., Güth, A. Z., Sumida, P. Y. G., & Banha, T. N. S. (2020). South Atlantic coral reefs are major global warming refugia and less susceptible to bleaching. *Frontiers in Marine Science, 7*, 514. DOI:10.3389/fmars.2020.00514

Miller, K. G., Schmelz, W. J., Browning, J. V., Kopp, R. E., Mountain, G. S., & Wright, J. D. (2020). Ancient sea level. *Oceanography*, *33*(2), 32-41. DOI:10.5670/oceanog.2020.224

Montaggioni, L. F., Borgomano, J., Fournier, F., & Granjeon, D. (2015). Quaternary atoll development: New insights from the two-dimensional stratigraphic forward modelling of Mururoa Island (Central Pacific Ocean). *Sedimentology, 62*(2), 466–500. DOI: 10.1111/sed.12175

Narayan, S., Esteban, M., Albert, S., Jamero, M. L., Crichton, R., Heerlien, J., Goby, G., & Jupiter, S. (2020). Local adaptation responses to coastal hazards in small island coastal communities: Insights from four Pacific island nations. *Environmental Science & Policy, 104*, 199–207. DOI:10.1016/j.envsci.2019.11.006

Newton, K., Côté, I. M., Pilling, G. M., Jennings, S., & Dulvy, N. K. (2007). Current and future sustainability of island coral reef fisheries. *Current Biology, 17*(7), 655–658. DOI:10.1016/j.cub.2007.02.054

Nunn, P. D. (2016). Sea levels, shorelines and settlements on Pacific reef islands. *Archaeology in Oceania*, *51*(2), 91-98. DOI:10.1002/arco.5082

Oberle, F. K. J., Cheriton, O. M., Swarzenski, P. W., Brown, E. K., & Storlazzi, C. D. (2023). Physicochemical coastal groundwater dynamics between Kauhakō Crater Lake and Kalaupapa settlement, Moloka‘i, Hawai‘i. *Marine Pollution Bulletin, 187*, 114509. DOI:10.1016/j.marpolbul.2022.114509

Ohde, S., Greaves, M., Masuzawa, T., Buckley, H. A., Van Woesik, R., Wilson, P. A., ... & Elderfield, H. (2002). The chronology of Funafuti Atoll: revisiting an old friend. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, *458*. DOI: 10.1098/rspa.2002.0978

Pacheco, A., Horta, J., Loureiro, C., & Ferreira, Ó. (2015). Retrieval of nearshore bathymetry from Landsat 8 images: A tool for coastal monitoring in shallow waters. *Remote Sensing of Environment, 159*, 102–116. DOI:10.1016/J.RSE.2014.12.004

Papacharalampous, G., & Tyralis, H. (2022). A review of machine learning concepts and methods for addressing challenges in probabilistic hydrological post-processing and forecasting. *Frontiers in Water, 4*, DOI:10.3389/frwa.2022.961954

Pari, N., Peyrot-Clausade, M., & Hutchings, P. A. (2002). Bioerosion of experimental substrates on high islands and atoll lagoons (French Polynesia) during 5 years of exposure. *Journal of Experimental Marine Biology and Ecology, 276*(1–2), 109–127. DOI:10.1016/S0022-0981(02)00243-5

Pérez-Ceballos, R., Zaldívar-Jiménez, A., Canales-Delgadillo, J., López-Adame, H., López-Portillo, J., & Merino-Ibarra, M. (2020). Determining hydrological flow paths to enhance restoration in impaired mangrove wetlands. *PloS one,* 15(1), DOI: 10.1371/journal.pone.0227665

Perry, C. T., Lange, I. D., & Stuhr, M. (2023). Quantifying reef-derived sediment generation: Introducing the SedBudget methodology to support tropical coastline and island vulnerability studies. *Cambridge Prisms: Coastal Futures, 1*, e26. DOI:10.1017/cft.2023.14

Perry, C. T., Morgan, K. M., Lange, I. D., & Yarlett, R. T. (2020). Bleaching-driven reef community shifts drive pulses of increased reef sediment generation. *Royal Society Open Science, 7*(9), 192153. DOI:10.1098/rsos.192153

Pinto, C. A., Silveira, T. M., & Teixeira, S. B. (2020). Beach nourishment practice in mainland Portugal (1950–2017): Overview and retrospective. *Ocean & Coastal Management, 192*, 105211. DOI:10.1016/j.ocecoaman.2020.105211

Purdy, E. G., (1974), Reef Configurations: Cause and Effect, Reefs in Time and Space: Selected Examples from the Recent and Ancient, Léo F. Laporte

Purdy, E. G., & Winterer, E. L. (2001). Origin of atoll lagoons. *Geological Society of America Bulletin, 113*(7), 837–854. DOI:10.1130/0016-7606(2001)113<0837:OOAL>2.0.CO;2

Purdy, E. G., & Winterer, E. L. (2006). Contradicting barrier reef relationships for Darwin's evolution of reef types. *International Journal of Earth Sciences*, *95*(1), 143-167. DOI:10.1007/s00531-005-0511-2

Quataert, E., Storlazzi, C., Van Rooijen, A., Cheriton, O., & Van Dongeren, A. (2015). The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophysical Research Letters, 42*(15), 6407–6415. DOI:10.1002/2015GL064861

Quinn, P. F. B. J., Beven, K., Chevallier, P., & Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological processes*, 5(1), 59-79.

Rasmussen, D.J., Kulp, S., Kopp, R.E. *et al*. Popular extreme sea level metrics can better communicate impacts. *Climatic Change* 170, 30 (2022). DOI:10.1007/s10584-021-03288-6

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat, F. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature, 566*(7743), 195–204. DOI:10.1038/s41586-019-0912-1

Renfro, B., & Chadwick, N. E. (2017). Benthic community structure on coral reefs exposed to intensive recreational snorkeling. *PLoS One, 12*(9). DOI:10.1371/journal.pone.0184175

Richardson, L.E., Graham, N.A.J., Pratchett, M.S. *et al.* Structural complexity mediates functional structure of reef fish assemblages among coral habitats. *Environ Biol Fish* 100, 193–207 (2017). DOI:10.1007/s10641-016-0571-0

Ríos, J., Almeida, S., & Cruz, L. (2021). Socio-economic impacts of tourism on lagoon communities. *Sustainable Development, 29*(1), 12–23. DOI:10.1590/1809-4422ASOC137111V1942016

Roff, G., & Mumby, P. J. (2012). Global disparity in the resilience of coral reefs. *Trends in Ecology & Evolution, 27*(7), 404–413. DOI:10.1016/j.tree.2012.04.007

Rougerie, F., & Wauthy, B. (1993). The endo-upwelling concept: from geothermal convection to reef construction. *Coral reefs*, *12*(1), 19-30. DOI:10.1007/BF00303781

Rovere, A., Khanna, P., Bianchi, C. N., Droxler, A. W., Morri, C., & Naar, D. F. (2018). Submerged reef terraces in the Maldivian archipelago (Indian Ocean). *Geomorphology*, *317*, 218-232. DOI:10.1016/j.geomorph.2018.05.026

Sawyer, A. H., Michael, H. A., & Schroth, A. W. (2016). From soil to sea: The role of groundwater in coastal critical zone processes. *Wiley Interdisciplinary Reviews: Water, 3*(5), 706–726. DOI:10.1002/wat2.1157

Schlager, W., & Purkis, S. J. (2013). Bucket structure in carbonate accumulations of the Maldive, Chagos and Laccadive archipelagos. *International Journal of Earth Sciences*, *102*(8), 2225-2238. DOI:10.1007/s00531-013-0913-5

Sengupta, D., Mukherjee, P.K., Mukhopadhyay, B. *et al*. Multivariate statistics on groundwater geochemical data to identify arsenic release mechanism and related microenvironments: a case study from West Bengal, India. *Environ Earth Sci* 81, 439 (2022). DOI:10.1007/s12665-022-10571-x

Sheppard, C., Sheppard, A., & Fenner, D. (2020). Coral mass mortalities in the Chagos Archipelago over 40 years: Regional species and assemblage extinctions and indications of positive feedbacks. *Marine pollution bulletin*, *154*. DOI:10.1016/j.marpolbul.2020.111075

Shokri, A., & Fard, M. S. (2023). Techno-economic assessment of water desalination: Future outlooks and challenges. *Process Safety and Environmental Protection, 169*, 564–578. DOI:10.1016/j.psep.2022.11.007

Skinner, C., Mill, A.C., Newman, S.P. *et al*. The importance of oceanic atoll lagoons for coral reef predators. *Mar Biol* 167, 19 (2020). DOI:10.1007/s00227-019-3634-x

Speare, K. E., Adam, T. C., Winslow, E. M., Lenihan, H. S., & Burkepile, D. E. (2022). Size-dependent mortality of corals during marine heatwave erodes recovery capacity of a coral reef. *Global change biology*, *28*(4), 1342–1358. DOI:10.1111/gcb.16000

Splinter, K. D., & Coco, G. (2021). Challenges and opportunities in coastal shoreline prediction. *Frontiers in Marine Science, 8*, 788657. DOI:10.3389/fmars.2021.788657

Spratt, R. M., & Lisiecki, L. E. (2016). A Late Pleistocene sea level stack. *Climate of the Past*, *12*(4), 1079-1092. DOI:10.5194/cp-12-1079-2016, 2016.

Stanic, S., LeRoux, N. K., Paldor, A., Mohammed, A. A., Michael, H. A., & Kurylyk, B. L. (2024). Saltwater intrusion into a confined island aquifer driven by erosion, changing recharge, sea-level rise, and coastal flooding. *Water Resources Research, 60*(1). DOI:10.1029/2023WR036394

Steibl, S., Bunbury, N., Young, H. S., & Russell, J. C. (2024). A renaissance of atoll ecology. *Annual Review of Ecology, Evolution, and Systematics, 55*(1), 301–322. DOI:10.1146/annurev-ecolsys-102722-013447

Storlazzi, C. D., Gingerich, S. B., van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., Voss, C. I., & McCall, R. (2018). Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances, 4*(4), eaap9741. DOI:10.1126/sciadv.aap9741

Tierolf, L., Haer, T., Botzen, W., & Aerts, J. (2023, May). Coastal adaptation dynamics under future shoreline changes. In *EGU General Assembly Conference Abstracts* (pp. EGU-16808). DOI:10.1016/j.scitotenv.2024.170239

Toomey, M. R., Woodruff, J. D., Donnelly, J. P., Ashton, A. D., & Perron, J. T. (2016). Seismic evidence of glacial-age river incision into the Tahaa barrier reef, French Polynesia. *Marine Geology*, *380*, 284-289. DOI:10.1016/j.margeo.2016.04.008

Toth, G., Velli, M., & van der Holst, B. (2023). Theory of magnetic switchbacks fully supported by Parker Solar Probe observations. *The Astrophysical Journal, 957*(2), 95. DOI:10.3847/1538-4357/acfd91

Tuck, M. E., Ford, M. R., Kench, P. S., & Masselink, G. (2021). Sediment supply dampens the erosive effects of sea-level rise on reef islands. *Scientific Reports, 11*(1), 5523. DOI:10.1038/s41598-021-85076-x

Twomey, A. J., Nunez, K., Carr, J. A., Crooks, S., Friess, D. A., Glamore, W., Orr, M., Reef, R., Rogers, K., Waltham, N. J., & Lovelock, C. E. (2024). Planning hydrological restoration of coastal wetlands: Key model considerations and solutions. *Science of the Total Environment, 915*, 169881. DOI:10.1016/j.scitotenv.2024.169881

Twomey, A. J., Nunez, K., Carr, J. A., Crooks, S., Friess, D. A., Glamore, W., ... & Lovelock, C. E. (2024). Planning hydrological restoration of coastal wetlands: Key model considerations and solutions. *Science of the Total Environment*, *915*. DOI:10.1016/j.scitotenv.2024.169881

Tyralis, H., & Papacharalampous, G. (2023). Hydrological post-processing for predicting extreme quantiles. *Journal of Hydrology*, 617, 129082. DOI: /10.1016/j.jhydrol.2023.129082

Underwood, J. N., Travers, M. J., & Gilmour, J. P. (2012). Subtle genetic structure reveals restricted connectivity among populations of a coral reef fish inhabiting remote atolls. *Ecology and Evolution, 2*(3), 666–679. DOI:10.1002/ece3.80

UNEP. (2022). *Integrated coastal zone management: Guidelines for sustainable tourism*. Nairobi: United Nations Environment Programme.

Vitousek, S., Vos, K., Splinter, K. D., Erikson, L., & Barnard, P. L. (2023). A model integrating satellite-derived shoreline observations for predicting fine-scale shoreline response to waves and sea-level rise across large coastal regions. *Journal of Geophysical Research: Earth Surface, 128*(7). DOI:10.1029/2022JF006936

Wallace, C. D., & Bailey, R. T. (2015). Sustainable rainwater catchment systems for Micronesian atoll communities. *JAWRA Journal of the American Water Resources Association, 51*(1), 185–199. DOI:10.1111/jawr.12244

Weatherill, C. K. (2023). *Vulnerability and resistance: Islanding climate change politics* [Doctoral dissertation, The University of Manchester (United Kingdom)]. DOI:10.4324/9781849774895

Werner, A. D., Sharp, H. K., Galvis, S. C., Post, V. E., & Sinclair, P. (2017). Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. *Journal of Hydrology, 551*, 819–844. DOI:10.1016/j.jhydrol.2017.02.047

Werner, A.D., Zhang, Q., Xue, L. *et al*. An Initial Inventory and Indexation of Groundwater Mega-Depletion Cases. *Water Resour Manage* 27, 507–533 (2013). DOI:10.1007/s11269-012-0199-6

Whitaker, F., & Frazer, M. (2018). Process-based Modelling of Syn-depositional Diagenesis. *Reactive Transport Modeling: Applications in Subsurface Energy and Environmental Problems*, 107-155. DOI:10.1002/9781119060031.ch3

Whitaker, F. F., & Smart, P. L. (2004). Hydrogeology of the Bahamian archipelago. In H. L. Vacher & T. M. Quinn (Eds.), *Developments in Sedimentology* (Vol. 54, pp. 183–216). Elsevier. DOI:10.1016/S0070-4571(04)80026-8

White, I., & Falkland, T. (2010). Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, *18*(1), 227-246. DOI:10.1007/s10040-009-0525-0

Winston, M., Oliver, T., Couch, C., Donovan, M. K., Asner, G. P., Conklin, E., Fuller, K., Grady, B. W., Huntington, B., Kageyama, K., & Kindinger, T. L. (2022). Coral taxonomy and local stressors drive bleaching prevalence across the Hawaiian Archipelago in 2019. *PLoS ONE, 17*(9). DOI:10.1371/journal.pone.0269068

Wolanski, E., Choukroun, S., & Nhan, N. H. (2020). Island building and overfishing in the Spratly Islands archipelago are predicted to decrease larval flow and impact the whole system. *Estuarine, Coastal and Shelf Science, 233*. DOI:10.1016/j.ecss.2019.106545

Yamamoto, L., & Esteban, M. (2017). Migration as an adaptation strategy for atoll island states. *International Migration, 55*(2), 144–158. DOI:10.1111/imig.12318

Yıldırım, D. Ç., Yıldırım, S., Bostancı, S. H., & Turan, T. (2022). The nexus between human development and fishing footprint among mediterranean countries. *Marine pollution bulletin*, 176, 113426. https://doi.org/10.1016/j.marpolbul.2022.113426

Zheng, T., Gao, M., Chang, Q., Zheng, X., & Walther, M. (2022). Dynamic desalination of intruding seawater after construction of cut-off walls in a coastal unconfined aquifer. *Frontiers in Marine Science, 9*. DOI:10.3389/fmars.2022.857807

Section 4

Sub-chapter 5d: Tropical and Subtropical Coral Reefs.

Sweet, Michael[1], Beger, Maria[2]; Camp, Emma F[3]; del Campo, Javier[4]; Dobson, Kerri[5]; Galvis, Nohora[6]; Goby, Gillian[7]; Harding, Simon[8]; Huang, Danwei[9]; Mcleod, Elizabeth[10]; van der Meij, Sancia ET[11]; Precht, William[12]; Razak, Tries[13]; Richards, Zoe[14]; Rinkevich, Buki[15]; Schläppy, Marie-Lise[16]; Storlazzi, Curt D[17]; Tavakoli-Kolour, Parviz[18]; Ivanenko, Viatchelav[19]; Voolstra, Christian R[20]; Walker, Brian K[21]

1 Nature-based Solutions Research Centre, Aquatic Research Facility, University of Derby, U.K.

2 School of Biology, Faculty of Biological Sciences, University of Leeds, LS2 9JT, U.K. & Centre for Biodiversity and Conservation Science, School of the Environment, University of Queensland, QLD 4072 Australia

3 Climate Change Cluster (C3), University of Technology Sydney, Ultimo, NSW 2007, Australia

4 Institut de Biologia Evolutiva (CSIC - Universitat Pompeu Fabra), Barcelona, Catalonia, Spain

5 School of Ocean & Earth Sciences, University of Southampton, U.K.

6 International Coral Reef Observatory @ICR_Observatory, Columbia

7 MCC Sustainable Futures, Perth, WA 6000, Australia.

8 Institute of Marine Resources, The University of the South Pacific, Suva, Fiji

9 Lee Kong Chian Natural History Museum, National University of Singapore, Singapore

10 The Nature Conservancy, U.S.A.

11 GELIFES, University of Groningen, Nijenborgh 7, 9747 AG Groningen, The Netherlands

12 Coastal & Marine Sciences, Bio-Tech Consulting, Miami, Florida U.S.A.

13 Department of Marine Science & Technology, Faculty of Fisheries & MarineScience, IPB University, Bogor, Indonesia

14 Coral Conservation & Research Group, Curtin University, Bentley, Australia & Western Australian Museum, Welshpool, Australia

15 Israel Oceanographic & Limnological Research, National Institute of Oceanography, POB 9753, Tel Shikmona 3109701, Haifa, Israel

16.Ocean Graduate School, University of Western Australia, Australia

17 U.S. Geological Survey, Pacific Coastal and Marine Science Center, 2885 Mission Street, Santa Cruz, CA 95060, U.S.A

18 Sesoko Marine Research Station, Tropical Biosphere Research Center, University of the Ryukyus, Okinawa, Japan

19 Shenzhen MSU -BIT University, China & Lomonosov Moscow State University, Russia

20 Department of Biology, University of Konstanz, Konstanz, Germany

21 GIS & Spatial Ecology Lab, Department of Marine and Environmental Sciences, Nova Southeastern University, Dania Beach, Florida, U.S.A.

1 Keynotes

1. Global declines in coral cover persist, owing to increasing ocean temperatures associated with climate change, continued coastal development, pollution, sedimentation, diseases, and destructive and over extraction of marine resources (fishing and coral harvesting). These stressors impact coral biodiversity, reef-associated fauna and the architectural complexity of reef frameworks, compromising the food security and livelihoods of millions of people dependent on these ecosystems (*virtually certain, well established*).
2. The frequency and severity of disturbances caused by heatwaves, disease outbreaks, and tropical storms have increased (*virtually certain, established but incomplete*), curtailing recovery time between such disturbances. This pattern is projected to continue its current trajectory (at best) or accelerate (*very likely*).
3. Ecosystem services provided by coral reefs are substantial, not only in terms of biodiversity, but also in terms of direct economic benefits (coastal protection, livelihoods for millions, nurseries for commercial species), as well as less tangible uses, such as cultural and aesthetic (intrinsic) value (*virtually certain, well established*).
4. Conservation/restoration/regeneration efforts are underway on a global scale, but few attract long-term sustainable implementations with socioeconomic considerations, i.e. livelihoods (*virtually certain, well established*). A wide range of approaches/tools are being developed, many attempting to mitigate or halt reef declines. Yet, these are often restricted to local reef wide projects with the potential for upscaling sometimes criticized (*unresolved*). Documented results are also almost always undermined by a clear disconnect between other policy decisions such as extraction and burning of fossil fuels and coastal development (*likely*). Regardless of scalability concerns, all programs need to be imbedded within a broader evidence-based conservation framework.
5. Global efforts are required to reduce emissions and ongoing climate change facilitating reef ecosystem survival and continued function (*virtually certain, established but incomplete*). The reefs of today will not be the reefs of tomorrow (*virtually certain*) and shifting baselines need to be considered when setting objectives in conservation, ~~and~~ restoration and/or regeneration (*virtually certain, established but incomplete*).

2 Introduction

Coral reefs stand as one of the planet's most valuable natural assets, supporting approximately 25% of marine life and providing some level of support for approximately one billion people across more than 100 nations (Fisher et al. 2015; Sing-Wong et al. 2022). For example, 70% of the protein intake among Pacific Islanders comes from reef-associated fisheries (Charlton et al. 2016), and reefs are heralded as the medicine chests of the 21st century (Blockley et al. 2017).

The value of goods and services provided by coral reefs is estimated at US$2.7 trillion. These include US$7 billion per year from food security and livelihoods, US$6 billion in shoreline protection, and US$36 billion to the global tourism industry (GCRMN Status of Coral Reefs of the World: 2020).

3 The environmental change since WOAII

3.1 Changes in the overall status

Global coral reef conditions continue to deteriorate since WOAII (2011859-e-woa-ii-vol-i.pdf), with multiple compounding threats intensifying across all major reef systems (**Figure 1**). Recent evidence demonstrates both accelerating decline and increasingly complex challenges to reef survival (Gutierrez et al. 2024).

Marine heatwaves between 2018-2025 have triggered widespread coral mortality through recurring global-scale coral bleaching events (Eakin et al. 2019; Moriarty et al. 2023). Due to local stressors, there remains uncertainty regarding coral recovery rates (Donovan et al. 2021; Brown et al. 2023; Walker et al. 2024). Scientific evidence demonstrates (with *high levels of certainty*) that global temperature rise should be constrained to no more than ~~1-1.5~~1.5-2°C above pre-industrial levels to avoid the most serious consequences of climate change on coral reefs (Global Tipping Points Report 2023). This threshold has been proposed by some to represent a critical biological limit, or 'tipping point', beyond which reef ecosystems face potentially irreversible consequences. However, others argue that the term 'tipping point' can sometimes confuse and even distract from urgent climate action needed (Kopp et al. 2025).

Regardless of the terminology, nearly all scientists agree that reefs will be impacted when even ~~if/when~~ 1.0~~-1.5~~°C above pre-industrial levels is exceeded and ~~. For example, Logan et al. (2021) suggest that limiting warming to less than 2°C will allow coral reefs to survive through to 2100 without drastic shifts in community composition. However, u~~under IPCC-AR5's RCP 6.0 and 8.5 scenarios, coral-dominated communities (as we know them today) will ~~are expected to~~ essentially disappear. Even under less severe warming scenarios (RCP 4.5) the outlook looks dire, with sharp declines in reef cover occurring, however some remain optimistic that recovery is possible with sufficient genetic variability persisting (McManus et al. ~~(~~2021) ~~predict that, in the Caribbean for example, a sharp decline in reef cover will occur, but they remain optimistic that recovery is possible with sufficient genetic variability persisting~~ under a less severe ~~warming scenario (RCP 4.5)~~ (*established, but incomplete*). ~~For example, Logan et al. (2021)~~ Indeed, ~~suggest that~~ limiting warming to ~~less than 2~~2°C or less may ~~will~~ allow coral reefs to survive through to 2100 without drastic shifts in community composition (Logan et al. 2021).

That said, and rather ~~A~~alarmingly, ~~according to~~ more ~~the most~~ current scientific assessments, suggest that even maintaining temperatures below 1.5°C presents substantial risks to reef ecosystem survival (*established, but incomplete*) (Dixon et al. 2022). There is ~~already~~ already evidence that some regions have approached or even crossed the upper end of this range and that global warming above 1.5°C ~~,~~ (on a global scale)~~ly~~, is expected by as early as 2034. Ocean warming above 2.7°C is further expected around 2100 (*likely, well established*). If realized, this exceeds even the optimistic thermal safety margins for coral survival.

Sadly, major regional shifts in reef ~~composition~~ composition and reef associated fish species are already being documented (Edmunds et al. 2014; Ceccarelli et al. 2024). This is ~~,~~ alongside ~~with~~ decreased habitat complexity (Edgar et al. 2023), increasing impacts from nutrient pollution (Nalley et al. 2023) and reduced recovery periods between stress events (Emslie et al. 2024)~~.~~. Hypoxic conditions are present on 84% of surveyed reefs, with 13% experiencing severe oxygen depletion (Pezner et al. 2023). Disease prevalence has reached unprecedented levels (Burke et al. 2023), and reefs are being exposed to intensifying ocean acidification (IPCC Ocean and Cryosphere report), shifting salinity patterns, and increasing freshwater flood impacts (Rothig et al. 2023) (**Figure 1**).

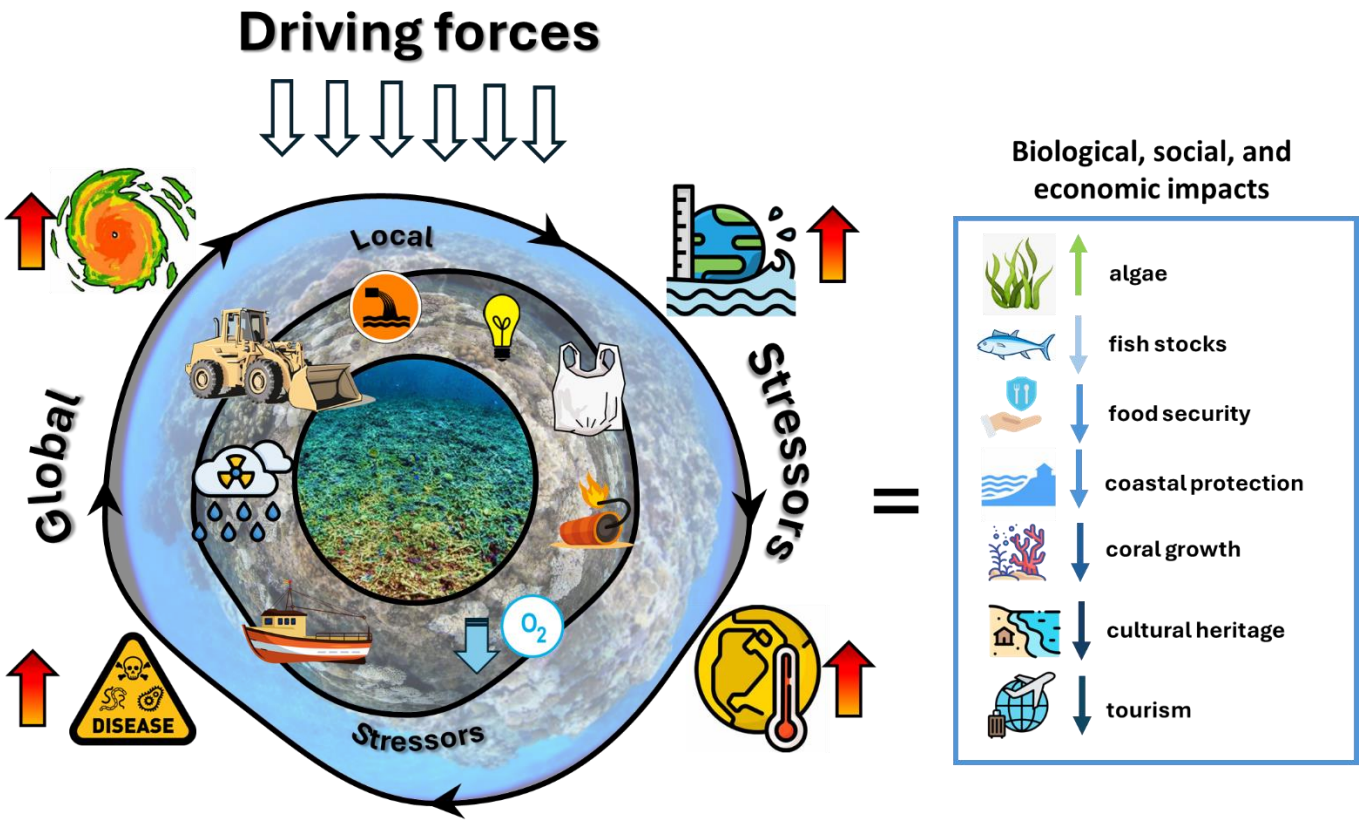


Figure 1. An infographic to highlight the main factors contributing to the changes observed to coral reefs: drivers, cumulative global and adaptive local stressors, current state of reefs, resulting impacts, and responses (DPSIR). **Driving forces** include ongoing human activities such as rapid economic growth, the linear economy, over-consumption, over-population, corruption, overexploitation of reef resources for short-term economic gain and insufficient investment in sustainable practices and conservation efforts. Stressors act at the global (outer circle) and local (inner circle) scales, and in many cases are cumulative/additive. **Local stressors** are region and site-specific, and occur in addition to **global stressors**, ultimately affecting how coral reefs respond to bleaching and disease. Reefs, in general, are experiencing decreased coral cover, habitat degradation, reduced biodiversity, disrupted food webs, and loss of foundation species and ecological functioning, which results in several **biological, social and economic impacts**. To save these ecosystems, urgent action must be taken to **reduce** the **carbon footprint**, **transition to a circular economy**, and **increase political support for conservation**. Of note, we have not indicated the scale of the stressors and instead focus on the cumulative impacts.

The notion of subtropical and temperate reef refuges is being refuted and earlier hopes for natural adaptation through poleward expansion or deep refugia have proven overly optimistic. Indeed, temperate coral reefs experience lower winter temperatures than tropical locations and this impacts the diversity and community of fish species that can become established (Booth 2020), coral bleaching and subsequent mortality events are higher in temperate locations (Lachs et al. 2021), and such reefs exhibit high coral endemicity (Mizerek et al. 2021), and high environmental stochasticity (Beger et al. 2014). Further, any apparent gains that do occur at subtropical locations are almost certainly *unlikely* to offset losses seen in the tropics (Adam et al. 2021). Even previously identified "bright spots" (where corals survive present day heat waves) (Cinner et al. 2016; Fox et al. 2021; Brown et al. 2023) have shown vulnerability to extreme events, as demonstrated in the South Atlantic. Once considered a refuge from bleaching events, this region suffered 80-90% mortality of dominant reef-building corals during a 50-day marine heatwave in 2019 (Duarte et al. 2020).

Despite isolated cases of recovery or even coral cover stability (Chan et al. 2023), the overall global trajectory indicates compromised reef resilience (**Figure 2**). Indeed, the increasing frequency of ~~disturbances,~~disturbances ~~leaves~~leave insufficient time for recovery between events (Emslie et al. 2024). This results in demographic shifts, homogenization of reef-associated communities, compromised resilience of the reef ecosystem at large, simplification in habitat structure and decreased structural complexity (Richardson et al. 2018; Magel et al. 2019; Sommer et al. 2024).

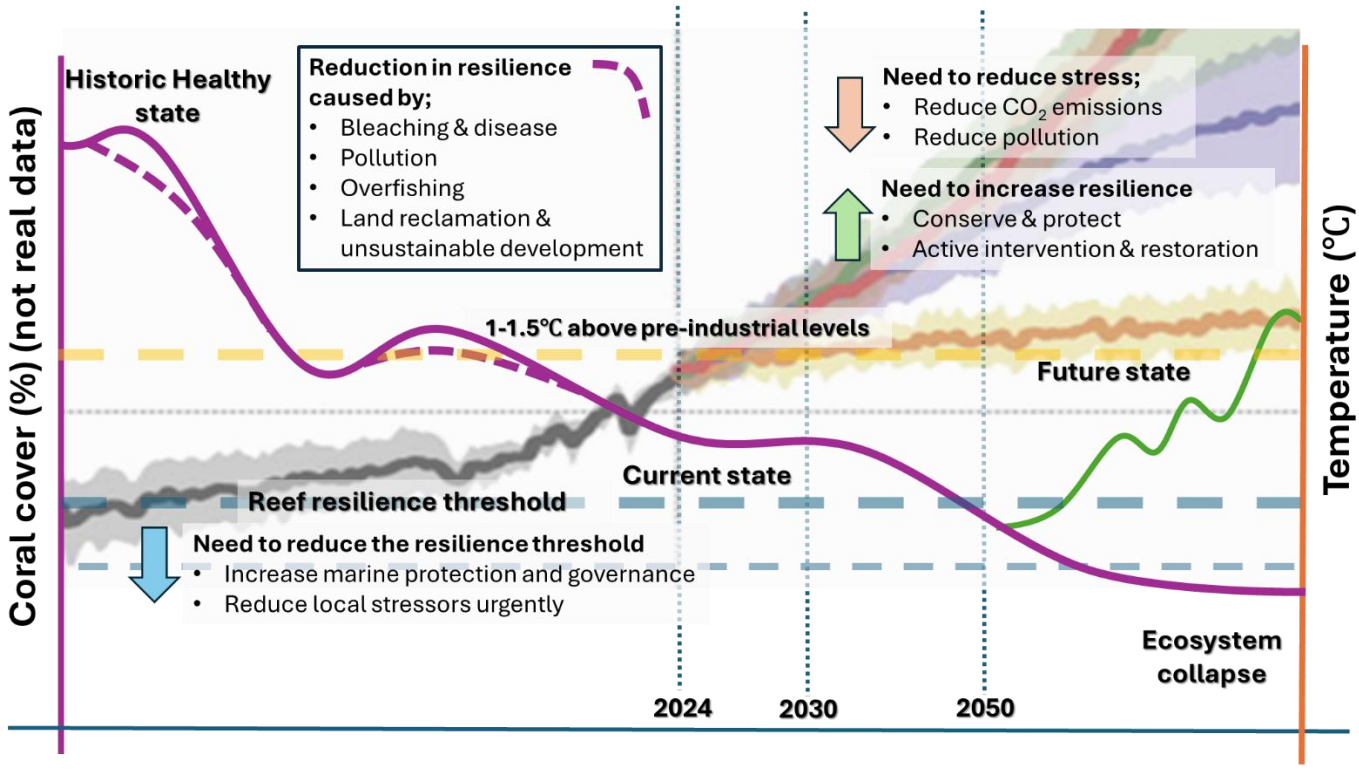


Figure 2.The overall trajectory of global coral reefs indicates **compromised resilience** and **decline in coral cover** (purple line). Note; coral cover lines are not based on real data and represent a generalized trend of what is occurring on a global scale. A further **reduction in reef resilience** is highlighted by the **dashed lines** indicating more rapid decline in some areas compared to others. There is an unarguable need to **reduce the stress** faced by reefs (namely reducing or reversing climate change (orange arrow), while simultaneously attempting to **increase resilience** (green arrow). This latter aspect can be undertaken in two key ways: **reducing reef resilience threshold** (**blue arrow** and **blue dashed lines**) and/or **increasing reef resilience** (green arrow). Average sea surface temperature (°C) increases (and possible scenarios of future change) are depicted by the graph. Data derived from IPCC AR6. The **critical 1-1.5°C threshold** should not be breached if we want functional coral reef ecosystems to remain. There is the very real possibility that **ecosystem collapse** may occur if significant action is not undertaken immediately. Reducing all stressors (where possible) and improving water quality in general (orange arrow), will likely result in many reefs around the world being restored or regenerated to a functional state (green line). Indeed, corals remain remarkably resilient and able to adapt to a degree of climate change.

4 Region-specific changes

4.2 The Northeast Atlantic Ocean, Mediterranean Sea

The Mediterranean presents an alarmingly unique case of accelerated warming, with rates three times the global average (Dayan et al. 2023, Copernicus 2024). The 2022 marine heatwave was particularly severe, with surface temperatures reaching 31°C and thermal anomalies extending to unprecedented depths, exceeding 27°C at 20 meters (Castellanos-Gallindo et al. 2020; Ozer et al. 2022). These intense warming events have triggered mass mortality events among sessile benthic species, particularly affecting octocoral populations (Capdevila et al. 2024).

4.3 The South Atlantic Ocean and the Wider Caribbean

The Caribbean region represents one of the most dramatic examples of long-term reef decline, with coral cover reduced by more than 80% since systematic monitoring began in the 1970s (Gardner et al. 2003, Schutte et al. 2010, Precht et al. 2020). Although this value has been queried in the more recent CGCRMN report (2020), the situation in this region has certainly been exacerbated by the 2023 thermal stress event, which began months earlier and sustained 2-3 times the heat stress of former events (Hoegh-Guldberg et al. 2023). In Little Cayman (for example), ~80% of corals either bleached or showed signs of mortality during this period, and after the final survey, 54% were found dead (Doherty et al. 2025). This catastrophic loss in coral is despite ~57% of the coastal environment being classified as no-take Marine Protected Areas.

Particularly ~~concerning~~ concerning in the Caribbean, is the shift in coral community composition from critical framework-building genera, such as *Acropora* and *Orbicella* (Toth et al. 2023), to more stress tolerant species, such as *Agaricia, Porites* and *Siderastrea* (Aronson et al. 2002, Green et al. 2008, Toth et al. 2019).

The emergence in 2014 of Stony Coral Tissue Loss Disease (SCTLD) has further impacted reefs in this region (Precht et al. 2016, Alvarez-Filip et al. 2022). The disease is persistent and has caused local extinctions of some species (Neely et al. 2021). While treatment efforts using antibiotics and probiotics have shown some success (Neely et al. 2020; Pitts et al. 2025), reinfection remains a significant challenge (Kozachuk 2024; Zummo 2024).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf, Strait of Malacca and the South China Sea

Recent bleaching events have shown marked variation in impact across sub-regions (Souter et al. 2021). For example, the reefs in the Mozambique channel and Southwest Madagascar show surprising resilience, whereas Kenya, Tanzania, and the Seychelles experienced severe degradation (Obura et al. 2022).

The reefs in the Persian Gulf and Red Sea were historically heralded for their thermal tolerance (Osman et al. 2018), however these are now also in decline (Anton et al. 2020). Coral cover in the Persian Gulf has dropped from 27% in 2019 to 12% in 2022 (Burt 2024), while some reefs in the Central and Southern Red Sea have seen declines of up to 45% (Anton et al. 2020). In the Red Sea, coral community responses do appear to be region specific, with communities in the south and central regions being more ~~promptly~~ commonly affected by mass bleaching events than those in the north~~ern and central regions~~ (Gonzalez et al. 2024). Coral cover has declined from >40% (2014) to <5% (2018) in locations such as Al Lith, Farasan Banks and Farasan Islands (Gonzalez et al. 2024). Coral cover in the eastern Arabian Sea also dropped significantly from 45% in 2014 to 20% in 2019 (De et al. 2023).

4.5 The Pacific Ocean

Studies appear contradictory and at odds regarding coral cover in this region. For example, some studies present reefs as having stable trends in cover over the last decade (Chan et al. 2023), whereas other studies report accelerating loss beyond previous projections (Souter et al. 2021).

There is certainly evidence to suggest that the consequential effects of climate warming are often delayed in certain regions, driven primarily by large interdecadal variations in the coral triangle area for example (Zinke et al. 2018).

In the East Asia region, more coral on average was reported in 2019 than in 1983 (Souter et al. 2021). However, in 2024, across Malaysia (for example), 50.7% of corals bleached, and this later resulted in 34.1% dying – although again regional variation was reported with the northeastern parts of the peninsular being more impacted (Szereday et al. 2025).

The Great Barrier Reef (GBR) also ~~had~~ showed a slight increase in reported regional hard coral cover in the early part of ~~(~~2024~~)~~ - compared to 2022 and 2023 (AIMS 2024). However, this preceded the 2024-2025 bleaching event where temperature anomalies in the GBR exceeded the 95th-percentile of pre-1900 baseline measurements (Henley et al. 2024). During 2024-2025, the southern GBR saw severe and widespread bleaching, to levels not previously recorded (Byrne et al. 2025). At One Tree Reef (for example), 80% of monitored coral colonies ~~were~~ bleached and 53% died shortly afterwards. Colony collapse occurred in 95% of the *Acroporas* assessed (Byrne et al. 2025). The protected status and offshore location of OTR did not protect the corals from heat stress bleaching and mortality.

Worryingly, many surveys which focus on similar small region-wide spatial scales have already begun to document local extinctions of coral and population depletions across multiple species (Richards et al. 2021). This indicates that although general trends in coral cover may well be stable (in parts), a fundamental shift in community composition is certainly occurring (Chan et al. 2024).

For more nearshore areas, cumulative pressures (such as sediment and nutrient run-off) have been highlighted as a particular concern in the region. ~~-~~Indeed, the reduction of pollutant loads has been slow due to only modest improvements in land management to date (Queensland Government - State of the Environment Report 2020).

5 Knowledge gaps, challenges and capacity changes

Although advances have been made to address the previously identified knowledge gaps in World Ocean Assessment II (2011859-e-woa-ii-vol-i.pdf), there are still key points that present significant challenges.

These include understanding barriers to political will, strengthening governance, and increasing our recognition of the habitats socioeconomic value (i.e. local nutrition and food security). Understanding how to enhance reef resilience, along with monitoring reef status and drivers of change are also key areas to focus on, ensuring we include cumulative global and local stressors and their resulting impact and responses (**Table 1**).

The future of coral reef ecosystems hinges on the ability to align global emissions policies with local protection efforts. Ramifications of not addressing these concerns will extend far beyond coastal communities, affecting food security, economic stability, and social justice worldwide.

As climate impacts on reefs intensify, there is an increase in understanding of the benefits (and limitations) of resilience-based tools and adaptive interventions that can be applied in coral conservation and regeneration efforts (Mcleod et al. 2019; Shaver et al. 2022).

The same can be said for our knowledge of ~~. Along with the~~ sustainable management of coral reef fisheries (Zamborain-Mason et al. 2023). Indeed, this latter study concludes that most reef fish stocks open to extraction are currently compromised – especially in the context of aiming for maximizing long term production.

~~The importance of coral reef fisheries should not be understated. They are indeed~~Reef fish are critically important for food and nutrition security and the livelihoods of ~~at large for~~ millions of the most vulnerable people in the world. In this context additional efforts in achieving sustainable management governance of these fisheries (through a multidimensional lens for example) ~~is~~are not only desirable but imperative (Basurto et al. 2025). It is also widely agreed that such management systems need to be suitable for the small-scale nature of most coral reef fisheries, which often occur in regions of the world with limited technical and institutional capacities (Cinner et al. 2020). Dimensions that need to be included consist of; catch, poverty eradication, shared governance, advancing gender equality and nutrient supply. This can be done by ensuring; (a) small-scale fisheries are built into trade statistics, (b) there is fair distribution of catch benefits with fishers' tenure rights secured, (c) enabling affordable and accessible aquatic foods for all. ~~These management systems need to be suitable for the small-scale nature of most coral reef fisheries, which often occur in regions of the world with limited technical and institutional capacities (Cinner et al. 2020).~~

Major capacity gaps that remain in this space include; insufficient policy support, lack of scalable restoration methodologies, and limited access and training on the ground for the most

advanced and promising monitoring technologies (Madin et al. 2019). Reef restoration practices that are self-sustaining (regarding their finances and funding) should be highlighted as examples of good practice if they exist already. -Regular and consistent monitoring should be integrated into all management strategies and practices (Voolstra et al. 2023), and there needs to be a general improvement in coordination for capacity development (Obura et al. 2019).

It must be acknowledged that future coral reefs will differ from historical baselines (**Figure 2**). Management and conservation practices should explore best practices enabling a transition to a best possible other state, ensuring a level of support for biodiversity and livelihoods/dependance of coast economics and people, as reef ranges shift. Critical assessment of any outcomes/impacts is not only essential but should now be mandatory. Protection of high-value genotypes in biobanks is likely to become a priority, aiming to conserve genetic diversity and even the survival of species. Actions to differentiate the environmental costs of destroying coral reefs for developmental purposes (benefiting a few), from the economic benefits of effective reef protection which benefits everyone must be clear and open.

Table 1. While advances have been made to address knowledge gaps reported in WOAII (including understanding the responses of reef communities to climate change, the socioeconomic value of coral reefs and the distribution and ecology of mesophotic coral reefs), there are still key gaps pertaining to the (i) enhancement of reef resilience in the face of climate change, (ii) strengthening reef governance and management, and (iii) recognizing the socio-economic value of coral reefs.

Knowledge Gaps and Suggested Action Points
Theme 1: Enhancement of Reef Resilience in the Face of Climate Change
· *Establish standardized ecological and socio-economic **International** or **National Coral Reef Monitoring and Restoration Networks** and support existing global programs. Track longer term trends and stress impacts such as climate impacts including storms and anoxic events, disease and invasive species outbreaks (Chapter 6), along with mapping newly discovered reefs and sentinel coral colonies.*
· *Identify climate resistant coral species and genotypes. Explore and up-scale (where possible) intervention strategies such as cryopreservation, biobanking, assisted evolution and assisted gene flow.*
· *Develop a centralized database integrating diverse reef-related data (photogrammetry, acoustics, diversity assessments, environmental parameters etc.). Creation of 'digital twins' for better informed decision making.*

· *Launch a comprehensive marine biodiversity assessment program that involves integrated taxonomic and molecular research to consider cryptic taxa and exploring the risk of silent extinctions of species and loss of genetic diversity.*
Theme 2: Strengthening Reef Governance and Management
· *Implement a framework for active reef interventions, ensuring local appropriateness and effectiveness. Participatory methods that include first nation peoples should be strongly encouraged.*
· *Increase members' capacity to collect, analyze and use data to inform fisheries management decisions and policies aimed at maximizing food production and livelihoods while maintaining the structure and functioning of the coral reef ecosystems.*
· *Develop and execute a **Reef Adaptation Strategy** linked to the Sustainable Oceans Plan addressing rapidly changing environmental conditions.*
· *Establish a **Coral Reef Community Empowerment Program** to increase local capacity for reef fisheries management. Listen to stakeholders and include them in decision making.*
· *Create national standards for reef-related Nature-based Solutions aligning with international best practice.*
· *Increase scientific studies on local, regional and global causation, relating transdisciplinary indicators from the anthropogenic impacts to the health state of coral reef organisms and ecosystems integrity worldwide.*
· *Improve the design and enforcement of existing Marine Protected Areas. Banning nets and spearguns on reefs for example, would increase global reef fish stocks by ~10.5% - essentially matching all conservation efforts to date (Caldwell et al. 2024).*
· *Implement policies minimizing land-based sources of pollution. Targeted EIAs should be undertaken to identify key point-sources of localized pollution. Turn lights off (especially around the coral spawning window), improve waste management, establish buffer zones along coastlines reducing sediment, nutrient, and contaminant inputs.*

Theme 3: Recognizing the Socio-economic Value of Coral Reefs
· *Commission a comprehensive economic valuation of national coral reef ecosystems. Differentiating environmental costs of destroying coral reefs for development, from the economic benefits of effective protection.*
· *Integrate reef value assessments into national infrastructure and development planning. Citizen science helps to involve communities to improve management effectiveness.*
· *Explore innovative pathways to protection, intervention or restoration. e.g. reef insurance - see SwissRE in collaboration with the Nature Conservancy. INTRODUCING CORAL REEF INSURANCE - Austbrokers Terrace Insurance | Adelaide | Melbourne (abterrace.com.au)*

In conclusion, if the planet's carbon footprint is not significantly lowered, coral reefs (as we know them today) will almost certainly cease to exist, and reefs of the future will be very different ecosystems, likely less complex, harboring lower biodiversity and offering reduced ecosystem services.

This unfolding crisis represents both an ecological and human rights issue (Sweet et al. 2021; Camp et al. 2024 - Chapter 5b,2), disproportionately impacting vulnerable populations, including lower socio-economic communities, poor coastal States, States with weak governance and high corruption, and small island nations or large ocean States.

The occurrence of the fourth global mass coral bleaching event in 2024/2025, affected ~~ing~~ over 77% of the world's reefs and ~~,~~ marks another stark milestone in reef decline (Reimer et al. 2024). Further, the increasing frequency and severity of such stress events are compromising coral resilience by reducing recovery windows between disturbances (Emslie et al. 2024). **Immediate climate action must include emission reductions and integration with economic policy.**

Local management requires addressing immediate threats through policy, while ensuring effective fisheries management, marine conservation, building local support with stakeholders, and fostering marine spatial planning.

Marine protected areas cover 8% of our oceans, however approximately one-quarter of the largest MPAs have been reported to lack effective implementation, and one-third have policies apparently incompatible with conservation goals (Pike et al. 2024). Two factors have been accredited to these findings, in that many reported MPAs lack regulations or management, and

some MPAs allow high-impact activities. Despite these challenges, when properly designed and managed, protected areas are well documented to support upwards of 10% higher fish biomass, improved ecosystem resilience, and enhanced recovery potential (Benedetti-Cecchi et al. 2024; Caldwell et al. 2024).

It should also be recognized that there are some examples of effective enhancement of reef ecosystem-based adaptation (Bindoff et al. 2019). Indeed, some have even shown measurable effects on reducing climate risks (*medium confidence*; Bindoff et al., 2019). That said, current restoration practices have been criticized as costly endeavors and fundamentally remain a local intervention at best. Some have gone so far to state that coral reefs need "evidence-based management not heroic interference" (Streit et al. 2024). Indeed, restorative practices will certainly not solve the global degradation of coral reefs due to anthropogenic climate change, and few would challenge that statement. However, the cost of inaction, the cost of further degradation, and the ultimate resulting loss of ecosystem services must also be weighed (Peixoto et al. 2022, 2024; Suggett et al. 2024).

The increasing acknowledgement of the ecosystem services offered by coral reefs (Reguero et al. 2021), along with the increased desire for using nature-based solutions to address the issues faced by humanity (Storalazzi et al. 2025), has resulted in the creation of large pre-disaster hazard mitigation funding pathways ($10s-1000s of millions) and/or post-disaster recovery funds - many of which are being directed at reef restoration and preservation (Stovall et al. 2022).

This is entirely justified as the anticipated continued decline of reefs threatens not only marine biodiversity but also the one billion people who depend on them.

The response to this crisis will determine not only the future of coral reefs, but also the well-being of human communities who depend on them for food, nutritional security and livelihoods (FAO, Du~~c~~ke University and World~~F~~fish 2023). Protecting, managing, conserving, and restoring reefs should not be viewed as an altruistic quest; ~~instead~~instead, it should be seen for what it is, **a pragmatic goal to sustain human civilization and all life on Earth**.

6 References

Adam, A.A., Garcia, R.A., Galaiduk, R., Tomlinson, S., Radford, B., Thomas, L. and Richards, Z.T., 2021. Diminishing potential for tropical reefs to function as coral diversity strongholds under climate change conditions. Diversity and Distributions, 27(11), pp.2245-2261.

AIMS. (2024). AIMS LTMP Report GBR coral status 2023-2024 final. Australian Institute of Marine Science.

Alvarez-Filip, L., González-Barrios, F. J., Pérez-Cervantes, E., Molina-Hernández, A., & Estrada-Saldívar, N. (2022). Stony coral tissue loss disease decimated Caribbean coral populations and reshaped reef functionality. Communications Biology, 5(1), 440. https://doi.org/10.1038/s42003-022-03398-6

Anton, A., Randle, J. L., Garcia, F. C., Rossbach, S., Ellis, J. I., Weinzierl, M., ... & Duarte, C. M. (2020). Differential thermal tolerance between algae and corals may trigger the proliferation of algae in coral reefs. Global Change Biology, 26(8), 4316-4327. https://doi.org/10.1111/gcb.15141

Aronson, R. B., Macintyre, I. G., Precht, W. F., Murdoch, T. J., & Wapnick, C. M. (2002). The expanding scale of species turnover events on coral reefs in Belize. Ecological Monographs, 72(2), 233-249.

Basurto, X., Gutierrez, N.L., Franz, N. *et al.* Illuminating the multidimensional contributions of small-scale fisheries. *Nature* **637**, 875–884 (2025). https://doi.org/10.1038/s41586-024-08448-z

Beger, M., Sommer, B., Harrison, P. L., Smith, S. D. A., & Pandolfi, J. M. (2014). Conserving potential coral reef refugia at high latitudes. Diversity and Distributions, 20(2), 245-257.

Benedetti-Cecchi, L., Bates, A. E., Strona, G., Bulleri, F., Horta e Costa, B., Edgar, G. J., ... & Kushner, D. J. (2024). Marine protected areas promote stability of reef fish communities under climate warming. Nature Communications, 15(1), 1822.

Benkwitt, C. E., D'Angelo, C., Dunn, R. E., Gunn, R. L., Healing, S., Mardones, M. L., ... & Graham, N. A. (2023). Seabirds boost coral reef resilience. Science Advances, 9(49), eadj0390.

Bindoff, N. L., Cheung, W. W., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., ... & O'Dongue, S. (2019). Changing ocean, marine ecosystems, and dependent communities. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Blockley, A.; Elliott, D.R.; Roberts, A.P.; Sweet, M. Symbiotic Microbes from Marine Invertebrates: Driving a New Era of Natural Product Drug Discovery. *Diversity* **2017**, *9*, 49. https://doi.org/10.3390/d9040049

Booth, D. J. (2020). Opposing climate-change impacts on poleward-shifting coral-reef fishes. Coral Reefs, 39(3), 577-581. https://doi.org/10.1007/s00338-020-01919-5

Brodnicke, O. B., M. R. Jensen, P. F. Thomsen, T. Brorly, B. L. Andersen, S. W. Knudsen, K. Præbel et al. (2024). Field collections and environmental DNA surveys reveal topographic complexity of coral reefs as a predictor of cryptobenthic biodiversity across small spatial scales. Environmental DNA 6, no. 3: e545.

Brown, K. T., Lenz, E. A., Glass, B. H., Kruse, E., McClintock, R., Drury, C., ... & Barott, K. L. (2023). Divergent bleaching and recovery trajectories in reef-building corals following a decade of successive marine heatwaves. Proceedings of the National Academy of Sciences, 120(52), e2312104120. https://doi.org/10.1073/pnas.2312104120

Byrne, M., Waller, A., Clements, M., Kelly, A.S., Kingsford, M.J., Liu, B., Reymond, C.E., Vila-Concejo, A., Webb, M., Whitton, K. and Foo, S.A. (2025), Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef. Limnol. Oceanogr. Lett. https://doi.org/10.1002/lol2.10456

Burt, J. (2024). From Phoenix to Sisyphus: Climate Change Impacts and Intervention Strategies for Arabian Gulf Coral Reefs. Journal of Coastal Research, 113, 839-845. https://doi.org/10.2112/JCR-SI113-165.1

Burke S, Pottier P, Lagisz M, Macartney EL, Ainsworth T, Drobniak SM, Nakagawa S. The impact of rising temperatures on the prevalence of coral diseases and its predictability: A global meta-analysis. Ecol Lett. 2023 Aug;26(8):1466-1481. doi: 10.1111/ele.14266. Epub 2023 Jun 6. PMID: 37278985.

Caldwell, I. R., McClanahan, T. R., Oddenyo, R. M., Graham, N. A., Beger, M., Vigliola, L., ... & Green, A. L. (2024). Protection efforts have resulted in ~10% of existing fish biomass on coral reefs. Proceedings of the National Academy of Sciences, 121(42), e2308605121.

Camp, E. F., Braverman, I., Wilkinson, G., & Voolstra, C. R. (2024). Coral reef protection is fundamental to human rights. Global Change Biology, 30(9), e17512.

Capdevila, P., Zentner, Y., Rovira, G. L., Garrabou, J., Medrano, A., & Linares, C. (2024). Mediterranean octocoral populations exposed to marine heatwaves are less resilient to disturbances. Journal of Animal Ecology.

Castellanos-Galindo, G. G., et al. (2020). A new wave of marine fish invasions through the Panama and Suez Canals. Nature Ecology & Evolution. https://doi.org/10.1038/s41559-020-01301-2

Ceccarelli, D.M., Logan, M., Evans, R.D., Jones, G.P., Puotinen, M., Petus, C., Russ, G.R., Sinclair-Taylor, T., Srinivasan, M. and Williamson, D.H., (2024). Regional-scale disturbances drive long-term decline of inshore coral reef fish assemblages in the Great Barrier Reef Marine Park. *Global Change Biology*, *30*(10), p.e17506.

Chan, Y. K. S., Affendi, Y. A., Ang, P. O., et al. (2023). Decadal stability in coral cover could mask hidden changes on reefs in the East Asian Seas. Communications Biology, 6(1), 1-11. https://doi.org/10.1038/s42003-023-05000-z

Chan, Y. K. S., Ng, C. S. L., Tun, K. P. P., Chou, L. M., & Huang, D. (2024). Decadal decline of functional diversity despite increasing taxonomic and phylogenetic diversity of coral reefs under chronic urbanisation stress. Ecological Indicators, 164, 112143. https://doi.org/10.1016/j.ecolind.2024.112143

Charlton KE, Russell J, Gorman E, Hanich Q, Delisle A, Campbell B, Bell J. Fish, food security and health in Pacific Island countries and territories: a systematic literature review. BMC Public Health. 2016 Mar 24;16:285. doi: 10.1186/s12889-016-2953-9. PMID: 27009072; PMCID: PMC4806432.

Cinner, J., Huchery, C., MacNeil, M. *et al.* Bright spots among the world's coral reefs. *Nature* **535**, 416–419 (2016). https://doi.org/10.1038/nature18607

Cinner, J., *et al.* Meeting fisheries, ecosystem function, and biodiversity goals in a human-dominated world.*Science***368**,307-311(2020).DOI:10.1126/science.aax9412

Copernicus 2024 Copernicus: 2024 is the first year to exceed 1.5°C above pre-industrial level | Copernicus

Cornwall, C. E., Comeau, S., Donner, S. D., Perry, C., Dunne, J., van Hooidonk, R., ... & Logan, C. A. (2023). Coral adaptive capacity insufficient to halt global transition of coral reefs into net erosion under climate change. Global Change Biology, 29(11), 3010-3018.

Davies, T.W., Levy, O., Tidau, S. *et al.* (2023). Global disruption of coral broadcast spawning associated with artificial light at night. Nature Communications 14, 2511. https://doi.org/10.1038/s41467-023-38070-y

Dayan, H., McAdam, R., Juza, M., Masina, S., & Speich, S. (2023). Marine heat waves in the Mediterranean Sea: An assessment from the surface to the subsurface to meet national needs. Frontiers in Marine Science, 10, 1045138.

De, K., Nanajkar, M., Mote, S., et al. (2023). Reef on the edge: resilience failure of marginal patch coral reefs in Eastern Arabian Sea under recurrent coral bleaching, coral diseases, and local stressors. Environmental Science and Pollution Research, 30, 7288-7302. https://doi.org/10.1007/s11356-022-22651-3

Deloitte. (2024). Need a reason to save the Great Barrier Reef? Deloitte Access Economics report. Deloitte Australia.

Dixon, A. M., Puotinen, M., Ramsay, H. A., & Beger, M. (2022). Coral reef exposure to damaging tropical cyclone waves in a warming climate. Earth's Future, 10, e2021EF002600. https://doi.org/10.1029/2021EF002600

Dobson, K. L., Jury, C. P., Toonen, R. J., et al. (2024). Ocean acidification does not prolong recovery of coral holobionts from natural thermal stress in two consecutive years. Communications Earth & Environment, 5, 515. https://doi.org/10.1038/s43247-024-01672-5

Doherty ML, Johnson JV, Goodbody-Gringley G (2025) Widespread coral bleaching and mass mortality during the 2023–2024 marine heatwave in Little Cayman. PLoS One 20(5): e0322636. https://doi.org/10.1371/journal.pone.0322636

Donovan, M. K., Adam, T. C., Shantz, A. A., Speare, K. E., Munsterman, K. S., Rice, M. M., ... & Burkepile, D. E. (2020). Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape. Proceedings of the National Academy of Sciences, 117(10), 5351-5357. https://doi.org/10.1073/pnas.1915395117

Donovan, M. K., Burkepile, D. E., Kratochwill, C., Shlesinger, T., Sully, S., Oliver, T. A., ... & van Woesik, R. (2021). Local conditions magnify coral loss after marine heatwaves. Science, 372(6545), 977-980. https://doi.org/10.1126/science.abd9464

Duarte, G. A., Villela, H. D., Deocleciano, M., Silva, D., Barno, A., Cardoso, P. M., ... & Santoro, E. P. (2020). Heat waves are a major threat to turbid coral reefs in Brazil. Frontiers in Marine Science, 7, 179.

Dube, K. (2024). A comprehensive review of climatic threats and adaptation of marine biodiversity. Journal of Marine Science and Engineering, 12(2), 344.

Eakin, C. M., Sweatman, H. P. A. & Brainard, R. E. The 2014–2017 global-scale coral bleaching event: insights and impacts. *Coral Reefs* https://doi.org/10.1007/s00338-019-01844-2 (2019).

Edgar, G. J., Stuart-Smith, R. D., Heather, F. J., Barrett, N. S., Turak, E., Sweatman, H., ... & Baker, S. C. (2023). Continent-wide declines in shallow reef life over a decade of ocean warming. Nature, 615(7954), 858-865.

Edmunds, P.J., Adjeroud, M., Baskett, M.L., Baums, I.B., Budd, A.F., Carpenter, R.C., Fabina, N.S., Fan, T.Y., Franklin, E.C., Gross, K. and Han, X., 2014. Persistence and change in community composition of reef corals through present, past, and future climates. *PLoS One*, *9*(10), p.e107525.

Eisenhauer, N., Bonn, A., & Guerra, C. A. (2019). Recognizing the quiet extinction of invertebrates. Nature Communications, 10, 50. https://doi.org/10.1038/s41467-018-07916-1

Emslie, M. J., et al. (2024). Increasing disturbance frequency undermines coral reef recovery. Ecological Monographs, 94(3), 31619. https://doi.org/10.1002/ecm.1619

FAO, Duke University & WorldFish. 2023. Illuminating Hidden Harvests – The contributions of small-scale fisheries to sustainable development. Rome. https://doi.org/10.4060/cc4576en

Fox, M. D., Cohen, A. L., Rotjan, R. D., et al. (2021). Increasing coral reef resilience through successive marine heatwaves. Geophysical Research Letters, 48(17), e2021GL094128. https://doi.org/10.1029/2021GL094128

Galil, B. S. (2023). A Sea, a Canal, a Disaster: The Suez Canal and the Transformation of the Mediterranean Biota. In C. Lutmar & Z. Rubinovitz (Eds.), The Suez Canal: Past Lessons and Future Challenges (pp. 1-20). Palgrave Studies in Maritime Politics and Security. https://doi.org/10.1007/978-3-031-15670-0_10

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2005). Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. Ecology, 86(1), 174-184.

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2003). Long-term region-wide declines in Caribbean corals. Science, 301(5635), 958-960.

Gonzalez, K., Daraghmeh, N., Lozano-Cortés, D. *et al.* Differential spatio-temporal responses of Red Sea coral reef benthic communities to a mass bleaching event. *Sci Rep* **14**, 24229 (2024). https://doi.org/10.1038/s41598-024-74956-7

Green, D. H., Edmunds, P. J., & Carpenter, R. C. (2008). Increasing relative abundance of Porites astreoides on Caribbean reefs mediated by an overall decline in coral cover. Marine Ecology Progress Series, 359, 1-10.

Henley, B. J., McGregor, H. V., King, A. D., Hoegh-Guldberg, O., Arzey, A. K., Karoly, D. J., ... & Linsley, B. K. (2024). Highest ocean heat in four centuries places Great Barrier Reef in danger. Nature, 632(8024), 320-326.

Hoegh-Guldberg, O., et al. (2023). Coral reefs in peril in a record-breaking year. Science, 382, 1238-1240. https://doi.org/10.1126/science.adk4532

Humanes, A., Lachs, L., Beauchamp, E., Bukurou, L., Buzzoni, D., Bythell, J., ... & Guest, J. R. (2024). Selective breeding enhances coral heat tolerance to marine heatwaves. Nature Communications, 15(1), 8703.

Jury, C. P., & Toonen, R. J. (2024). Widespread scope for coral adaptation under combined ocean warming and acidification. Proceedings of the Royal Society B: Biological Sciences, 291(2031). https://doi.org/10.1098/rspb.2024.1161

Kopp, R.E., Gilmore, E.A., Shwom, R.L. *et al.* 'Tipping points' confuse and can distract from urgent climate action. *Nat. Clim. Chang.* **15**, 29–36 (2025). https://doi.org/10.1038/s41558-024-02196-8

Kozachuk, A. (2024). Frequent Disease Intervention on the Largest Corals Prolongs Colony Life During Coral Disease Outbreaks [Unpublished manuscript].

Lachs, L., Sommer, B., Cant, J., Hodge, J. M., Malcolm, H. A., Pandolfi, J. M., & Beger, M. (2021). Linking population size structure, heat stress and bleaching responses in a subtropical endemic coral. Coral Reefs, 40, 777-790.

Lapointe, B. E., Brewton, R. A., Herren, L. W., Porter, J. W., & Hu, C. (2019). Nitrogen enrichment, altered stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade study. Marine Biology, 166(8), 108.

Logan, C.A., Dunne, J.P., Ryan, J.S. *et al.* Quantifying global potential for coral evolutionary response to climate change. *Nat. Clim. Chang.* **11**, 537–542 (2021). https://doi.org/10.1038/s41558-021-01037-2

Liew, Y. J., Howells, E. J., Wang, X., Michell, C. T., Burt, J. A., Idaghdour, Y., & Aranda, M. (2020). Intergenerational epigenetic inheritance in reef-building corals. Nature Climate Change, 10(3), 254-259.

McManus LC, Forrest DL, Tekwa EW, Schindler DE, Colton MA, Webster MM, Essington TE, Palumbi SR, Mumby PJ, Pinsky ML. Evolution and connectivity influence the persistence and

recovery of coral reefs under climate change in the Caribbean, Southwest Pacific, and Coral Triangle. Global change biology. 2021 Sep;27(18):4307-21.

Madin, E. M., Darling, E. S., & Hardt, M. J. (2019). Emerging technologies and coral reef conservation: Opportunities, challenges, and moving forward. Frontiers in Marine Science, 6, 727.

Magel, J. M. T., Burns, J. H. R., Gates, R. D., et al. (2019). Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. Scientific Reports, 9, 2512. https://doi.org/10.1038/s41598-018-37713-1

Mcleod, E., Anthony, K. R. N., Mumby, P. J., et al. (2019). The future of resilience-based management in coral reef ecosystems. Journal of Environmental Management, 233, 291-301.

Miller, M. W., Quiroz, S. M., Lachs, L., Banaszak, A. T., Chamberland, V. F., Guest, J. R., ... & Villalpando, M. F. (2024). Assisted sexual coral recruits show high thermal tolerance to the 2023 Caribbean mass bleaching event. PLoS One, 19(9), e0309719.

Mizerek, T. L., Madin, J. S., Benzoni, F., et al. (2021). No evidence for tropicalization of coral assemblages in a subtropical climate change hot spot. Coral Reefs, 40, 1451-1461.

Moriarty, T., Leggat, W., Heron, S. F., Steinberg, R. & Ainsworth, T. D. Bleaching, mortality and lengthy recovery on the coral reefs of Lord Howe Island. The 2019 marine heatwave suggests an uncertain future for high-latitude ecosystems. *PLOS Clim.* **2**, e0000080 (2023).

Nalley, E. M., Tuttle, L. J., Conklin, E. E., Barkman, A. L., Wulstein, D. M., Schmidbauer, M. C., & Donahue, M. J. (2023). A systematic review and meta-analysis of the direct effects of nutrients on corals. Science of The Total Environment, 856, 159093.

Neely, K. L., Lewis, C. L., Lunz, K. S., & Kabay, L. (2021). Rapid population decline of the pillar coral Dendrogyra cylindrus along the Florida Reef Tract. Frontiers in Marine Science, 8, 656515.

Neely, K. L., Macaulay, K. A., Hower, E. K., & Dobler, M. A. (2020). Effectiveness of topical antibiotics in treating corals affected by Stony Coral Tissue Loss Disease. PeerJ, 8, e9289.

Obura, D., Gudka, M., Samoilys, M., et al. (2022). Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. Nature Sustainability, 5, 104-113. https://doi.org/10.1038/s41893-021-00817-0

Obura, D. O., Aeby, G., Amornthammarong, N., Appeltans, W., Bax, N., Bishop, J., ... & Gramer, L. (2019). Coral reef monitoring, reef assessment technologies, and ecosystem-based management. Frontiers in Marine Science, 6, 580. https://doi.org/10.3389/fmars.2019.00580

Osman, E. O., Smith, D. J., Ziegler, M., Kürten, B., Conrad, C., El-Haddad, K. M., ... & Suggett, D. J. (2018). Thermal refugia against coral bleaching throughout the northern Red Sea. Global Change Biology, 24(2), e474-e484.

Ozer, T., Gertman, I., Gildor, H., & Herut, B. (2022). Thermohaline Temporal Variability of the SE Mediterranean Coastal Waters (Israel) – Long-Term Trends, Seasonality, and Connectivity. Frontiers in Marine Science, 8, 799457. https://doi.org/10.3389/fmars.2021.799457

Peixoto, R. S., Voolstra, C. R., Sweet, M., et al. (2022). Harnessing the microbiome to prevent global biodiversity loss. Nature Microbiology, 7, 1726-1735. https://doi.org/10.1038/s41564-022-01173-1

Peixoto RS, Voolstra CR, Baums IB, Camp EF, Guest J, Harrison PL, et al. The critical role of coral reef restoration in a changing world. Nat Clim Chang. 2024; 1–4. doi:10.1038/s41558-024-02202-z

Pezner, A. K., Courtney, T. A., Barkley, H. C., Chou, W. C., Chu, H. C., Clements, S. M., ... & Liang, Y. B. (2023). Increasing hypoxia on global coral reefs under ocean warming. Nature Climate Change, 13(4), 403-409.

Pike, E., Maccarthy, J., Hameed, S., Narayan, S., Grorud-Colvert, K., Sullivan-Stack, J., ... & Morgan, L. (2024). Ocean protection quality is lagging behind quantity: Applying a scientific framework to assess real marine protected area. Conservation Letters.

Pinheiro, H. T., MacDonald, C., Santos, R. G., Ali, R., Bobat, A., Cresswell, B. J., ... & Rocha, L. A. (2023). Plastic pollution on the world's coral reefs. Nature, 619(7969), 311-316. https://doi.org/10.1038/s41586-023-06113-5

Pitts, K.A., Scheuermann, M., Lefcheck, J.S., Ushijima, B., Danek, N., McDonald, E.M., Milanese, A.R., Schul, M.D., Meyer, J.L., Toth, K.A. and Ferris, Z., (2025). Evaluating the effectiveness of field-based probiotic treatments for stony coral tissue loss disease in southeast Florida, USA. *Frontiers in Marine Science*, *12*, p.1480966.

Precht, W. F., Aronson, R. B., Gardner, T. A., Gill, J. A., Hawkins, J. P., Hernández-Delgado, E. A., ... & Nugues, M. M. (2020). The timing and causality of ecological shifts on Caribbean reefs. In Advances in Marine Biology (Vol. 87, No. 1, pp. 331-360). Academic Press.

Precht, W. F., Gintert, B. E., Robbart, M. L., Fura, R., & Van Woesik, R. (2016). Unprecedented disease-related coral mortality in Southeastern Florida. Scientific Reports, 6(1), 31374.

Queensland Government, State of the Environment Report (2020). Land-based run-off pressure on the Great Barrier Reef | State of the Environment Report 2020 (des.qld.gov.au)

Reimer, J. D., Peixoto, R. S., Davies, S. W., et al. (2024). The Fourth Global Coral Bleaching Event: Where do we go from here? Coral Reefs, 43, 1121-1125. https://doi.org/10.1007/s00338-024-02504-w

~~Richards, Z.T., Juszkiewicz, D.J. & Hoggett, A. Spatio-temporal persistence of scleractinian coral species at Lizard Island, Great Barrier Reef. *Coral Reefs* **40**, 1369–1378 (2021). https://doi.org/10.1007/s00338-021-02144-4Richardson, L. E., Graham, N. A., Pratchett, M. S., Eurich, J. G., & Hoey, A. S. (2018). Mass coral bleaching causes biotic homogenization of reef fish assemblages. Global Change Biology, 24(7), 3117-3129.~~

Richards, Z. T., Juszkiewicz, D. J. and Hoggett, A. (2021). Spatio-temporal persistence of scleractinian coral species at Lizard Island, Great Barrier Reef. *Coral Reefs*, *40*, pp.1369-1378.

Röthig, T., Trevathan-Tackett, S. M., Voolstra, C. R., Ross, C., Chaffron, S., Durack, P. J., ... & Sweet, M. (2023). Human-induced salinity changes impact marine organisms and ecosystems. Global Change Biology, 29(17), 4731-4749.

Ruiz-Allais, J. P., Benayahu, Y., & Lasso-Alcalá, O. M. (2021). The invasive octocoral Unomia stolonifera (Alcyonacea, Xeniidae) is dominating the benthos in the Southeastern Caribbean Sea. Memoria de la Fundación La Salle de Ciencias Naturales, 79(187).

Salami, A. A., & Babatunde, O. R. (2024). Environmental challenges, the impacts of climate change in North Africa region: A review. Natural Resources Deterioration in MENA Region: Land Degradation, Soil Erosion, and Desertification, 281-294.

Salimi, P. A., Creed, J. C., Esch, M. M., Fenner, D., Jaafar, Z., Levesque, J. C., Montgomery, A. D., Salimi, M. A., Edward, J. P., Raj, K. D., & Sweet, M. (2021). A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. Marine Biodiversity Records, 14(1), 1.

Santoro, E. P., Borges, R. M., Espinoza, J. L., Freire, M., Messias, C. S., Villela, H. D., Pereira, L. M., Vilela, C. L., Rosado, J. G., Cardoso, P. M., & Rosado, P. M. (2021). Coral microbiome manipulation elicits metabolic and genetic restructuring to mitigate heat stress and evade mortality. Science Advances, 7(33), eabg3088.

Schill, S. R., Asner, G. P., McNulty, V. P., Pollock, F. J., Croquer, A., Vaughn, N. R., Escovar-Fadul, X., Raber, G., & Shaver, E. (2021). Site selection for coral reef restoration using airborne imaging spectroscopy. Frontiers in Marine Science, 8, 698004.

Schleussner, C. F., Ganti, G., Lejeune, Q., et al. (2024). Overconfidence in climate overshoot. Nature, 634, 366-373.

Schutte, V. G., Selig, E. R., & Bruno, J. F. (2010). Regional spatio-temporal trends in Caribbean coral reef benthic communities. Marine Ecology Progress Series, 402, 115-122.

Shaver, E. C., McLeod, E., Hein, M. Y., Palumbi, S. R., Quigley, K., Vardi, T., Mumby, P. J., Smith, D., Montoya-Maya, P., Muller, E. M., & Banaszak, A. T. (2022). A roadmap to integrating resilience into the practice of coral reef restoration. Global Change Biology, 28(16), 4751-4764.

Sing Wong, A., Vrontos, S., & Taylor, M. L. (2022). An assessment of people living by coral reefs over space and time. Global Change Biology, 28(23), 7139-7153.

Sommer, B., Hodge, J. M., Lachs, L., Cant, J., Pandolfi, J. M., & Beger, M. (2024). Decadal demographic shifts and size-dependent disturbance responses of corals in a subtropical warming hotspot. Scientific Reports, 14(1), 6327.

Souter, D., Planes, S., Wicquart, J., Logan, M., Obura, D., & Staub, F. (2021). Status of coral reefs of the world: 2020: Executive summary. Global Coral Reef Monitoring Network.

Storlazzi, C.D., Reguero, B.G., Alkins, K.C., Shope, J.B., Cole, A.D., Gaido-Lasserre, C., Viehman, T.S., and Beck, M.W., 2025. “Hybrid coral reef restoration can be a cost-effective solution to provide protection to vulnerable coastal populations” *Science Advances*, 11, eadn4004, doi: 10.1126/sciadv.adn4004

Stovall, A. E., Beck, M. W., Storlazzi, C., Hayes, J., Reilly, J., Koss, J., & Bausch, D. (2022). Coral reef restoration for risk reduction (CR4): A guide to project design and proposal development. University of California Santa Cruz. https://doi.org/10.5281/zenodo.7268962

Suggett, D. J., Edwards, M., Cotton, D., Hein, M., & Camp, E. F. (2023). An integrative framework for sustainable coral reef restoration. One Earth, 6(6), 666-681.

Suggett, D. J., Guest, J., Camp, E. F., Edwards, A., Goergen, L., Hein, M., Humanes, A., Levy, J. S., Montoya-Maya, P. H., Smith, D. J., & Vardi, T. (2024). Restoration as a meaningful aid to ecological recovery of coral reefs. npj Ocean Sustainability, 3(1), 20.

Sweet, M., Burian, A., & Bulling, M. (2021). Corals as canaries in the coalmine: Towards the incorporation of marine ecosystems into the 'One Health' concept. Journal of Invertebrate Pathology, 186, 107538.

Szereday, S., Chen, S. Y., Chew, K. L., Lee, L. K., Yusop, P. A. M., Fatta, A., Legada, C. J., Yaman, M. S., Zainudin, N. B. F., & Chelliah, A. (2025). The 4th global coral bleaching event in Malaysia: insights, outcomes, and paths forward. Coralku Publications

Toth, L. T., Stathakopoulos, A., Kuffner, I. B., Ruzicka, R. R., Colella, M. A., & Shinn, E. A. (2019). The unprecedented loss of Florida's reef-building corals and the emergence of a novel coral-reef assemblage. Ecology, 100(9), e02781.

Toth, L.T., Storlazzi, C.D., Kuffner, I.B. *et al.* The potential for coral reef restoration to mitigate coastal flooding as sea levels rise. *Nat Commun* **14**, 2313 (2023). https://doi.org/10.1038/s41467-023-37858-2

Van Der Mheen, M., & Pattiaratchi, C. (2024). Plastic debris beaching on two remote Indian Ocean islands originates from a handful of Indonesian rivers. Environmental Research Letters.

Voolstra, C. R., Peixoto, R. S., & Ferrier-Pagès, C. (2023). Mitigating the ecological collapse of coral reef ecosystems: Effective strategies to preserve coral reef ecosystems. EMBO Reports, 24(4), e56826.

Voolstra, C. R., Suggett, D. J., Peixoto, R. S., et al. (2021). Extending the natural adaptive capacity of coral holobionts. Nature Reviews Earth & Environment, 2, 747-762.

Walker, A. S., Kratochwill, C. A., & van Woesik, R. (2024). Past disturbances and local conditions influence the recovery rates of coral reefs. Global Change Biology, 30(1), e17112.

Zamborain-Mason, J., Cinner, J.E., MacNeil, M.A. *et al.* Sustainable reference points for multispecies coral reef fisheries. *Nat Commun* **14**, 5368 (2023). https://doi.org/10.1038/s41467-023-41040-z

Zinke, J, Gilmour, JP, Fisher, R et al. (2018) Gradients of disturbance and environmental conditions shape coral community structure for south-eastern Indian Ocean reefs. Diversity and Distributions, 24 (5). pp. 605-620. ISSN 1366-9516

Zummo, A. (2024). One-Time Broadscale SCTLD Intervention Effectiveness on Montastraea cavernosa in an Endemic Zone [Master's thesis, Nova Southeastern University]. NSUWorks. https://nsuworks.nova.edu/hcas_etd_all/178

Section 4

Sub-chapter 5e: Cold water corals and sponges

1. Keynote Points

- Exploration of our oceans has revealed the nearly ubiquitous presence of cold-water coral gardens, reefs, and sponge grounds on hard substrata throughout the world.
- Increasing evidence of profound changes in the physical and chemical environment of the deep ocean threatens cold-water coral and sponge (CWCS) habitats
- Offshore industrial development continues to pose threats to CWCS habitats globally, with emerging threats from deep-sea mining and marine carbon dioxide removal
- Additional CWCS are being discovered, protected, and are future targets for protections and the development of restoration strategies.
- Ecosystem-services based management is a new philosophy emerging from work in these areas, particularly to manage the ability of CWCS habitats to sequester carbon on large scales

2. Introduction

This Subchapter will focus on the cold-water corals and sponges (CWCS),the habitats they form, and services they provide in the deep sea (below 200 m depth). This includes many of the habitat forming corals that create Vulnerable Marine Ecosystems (VMEs) including scleractinian stony corals, antipatharian black corals, octocorals and stylasterid lace corals, and habitat forming sponges. The baseline state of CWCS has declined since the previous assessment. Fishing in deep waters continues around the world, and oil and gas development is entering new areas and moving deeper in the ocean. Deep-sea mining and marine Carbon Dioxide Removal (mCDR) have both begun trials and ~~are likely~~ have the potential to be near future stressors (Levin and others 2023). In addition, climate change is a pervasive threat, and the deep ocean absorbs a great amount of heat and carbon dioxide.

Among the most significant recent academic advances is the publication of an edited volume in the Springer Coral Reefs of the World series titled “Cold-Water Coral Reefs of the World” (Cordes & Mienis 2024). This includes descriptive summaries of CWCS ecosystems in

various regions of the world along with a summary chapter at the start with a new global model of scleractinian coral habitat suitability including the suitability of habitats for coral reef formation (Figure 1). This revealed that CWC reefs form in areas with especially high current speeds and dissolved oxygen availability, as compared to areas where corals are present but do not form large reef structures. Similar approaches have also been used to explore the future suitable areas for habitat forming sponges, highlighting how depth, temperature and dissolved oxygen are key drivers (Gregório and others 2024).

Over the last few years, the Blake Plateau along the Atlantic margin of the United States was completely mapped by multibeam sonar, which revealed over 30,000 km^2 of CWCS mounds, including a continuous area covering 26,000 km^2 (Sowers and others 2024). This revealed new areas of CWC reefs beneath the Gulf Stream that appeared to have some of the most variable oceanographic conditions observed, including temperature swings from 4ºC to over 10ºC in 24 hours, and among the highest nitrate concentrations recorded in the western Atlantic (Cordes and others 2023). Studies have also highlighted how CWCS mounds grow into the prevalent directions of the current (Corbera and others 2022), altering hydrodynamics to facilitate mound growth and sedimentation (van der Kaaden and others 2020). Paleoecological studies of CWC mounds have also revealed some of the key drivers of their persistence through time, emphasizing the importance of food supply and dissolved oxygen concentration (Raddatz and others 2020a, Portilho-Ramos and others 2022), which are also impacted by large and small scale hydrodynamics.

On a finer scale in the present day, the biomass distribution on CWCS reefs demonstrated meter-scale fauna clustering on reef structure (de Clippele and others 2021a). Sponges within CWCS reefs can act by recycling dissolved organic matter (DOM) into particulate detritus, which can then be ingested by other CWCS fauna (Bart and others 2021). This ‘sponge loop’ contributes to the overall food availability of CWCS habitats, and should be considered in future projections. The corals forming CWCS are well adapted to highly variable food delivery (Carrick and others 2024) and the communities they support have evolved to optimize carbon and energy transfer through the food web (Maier and others 2021, 2023). *Lophelia pertusa*, synonymised as *Desmophyllum pertusum* was found to be well adapted to fluctuations in food supply through high capture capacities, resource flexibility, investment in tissue reserves and synchronizing activity to seasonal fluctuations in food ability (Gómes and others 2022, Maier and others 2023). Recently developed methods determine that the carbon turnover of CWC reefs may be ~3 times higher than soft-sediment areas at similar depths (de Clippele and others 2021b). Biogeochemical metabolic flux models of how deep-sea sponges and their microbial communities transform different types of carbon and nitrogen support our understanding of how dissolved organic matter (DOM) acts as a primary energy source for sponges (de Kluijver and others 2021).

The threat of climate change to CWCS will be varied by region and depth, and will include changes in temperature, deoxygenation, ocean acidification, and reduced food supply. Corals or sponges with narrower environmental ranges will be more at risk (Dijkstra and others 2021), and the slow growth rate of these deep sea organisms, coupled with limited dispersal capabilities in some cases places them at particular risk (Cordes & Mienis 2024, Gregório and others 2024). The onset of ocean acidification is of particular concern to dead exposed coral skeleton, leading to dissolution of the aragonitic skeleton and 'coralporosis' (Hennige and others 2020). This can lead to a loss of structural integrity (Wolfram and others 2022) and collapse of coral framework (Figure 2). Loss of dead framework will act directly on the types of biodiversity within CWCS ecosystems as reef sessile suspension feeders cannot attach to strongly degraded reef framework and coral rubble (Maier and others 2021; 2023). This will in turn impact upon nutrient recycling within the habitat, and also change local hydrodynamics, which may impact upon food capture and growth of remaining live coral (Corbera and others 2022).

Restoration activities, and the understanding of the techniques and challenges for both framework and non-framework forming coral species are increasing. This includes guides on techniques (Boch and others 2020), reviews on the challenges to overcome with recommendations for future work (Liu and others 2024, Montseny and others 2021a, Bravo and others 2023), and how local communities and stakeholders can be integrated in restoration efforts (Montseny and others 2021b). At the current time there is no overarching, global scheme for the conservation and/or restoration of CWCS ecosystems, although they are generally considered vulnerable marine ecosystems (VMEs) in the European parlance, and managed as essential fish habitat (EFH) in the United States.

3. The environmental change since WOAII

While advances have been made in our understanding of environmental changes since WOAI, the lack of long term baseline data at CWCS sites still limits the understanding of long term change. It is clear that the deep sea is warming (**well established**), but it is difficult to say how quickly (**inconclusive**). There is evidence of more frequent "marine heat waves" (**well established**) but less information on how deep they penetrate and how frequently they reach the deep seafloor (**unresolved)**. The risks and potential impacts of typical offshore industrial activities (Cordes and others 2016) as well as catastrophic incidents like the Deepwater Horizon are **Well Established** (Schwing and others 2020). However, this has not curtailed offshore drilling. Similarly, for fisheries, the impacts of bottom trawling on benthic communities are understood (well established), especially CWCS (DuPreez and others 2020, Williams and others 2020).

To understand the threat of climate change to CWCS ecosystems, there is a need to combine both experimental and *in situ* studies and observations. Environmental niche modeling has used this combination to predict changes in habitat suitability for key CWC species, with declines predicted from 28-100% by the end of the century with high emission scenarios (**established but incomplete**). The largest reductions were for the framework forming *Desmophylum pertusum* and the octocoral *Paragorgia arborea* (Morato and others 2020). Predicted distribution models for sponges have highlighted a similar trend to CWC, where habitats may shift (and expand, in some cases, with the area suitable for the glass sponge *Vazella pourtalesii* on the Scotian Shelf increasing by 4), but overall with a trend of reduced suitability in areas where these habitats are currently found(Beazley and others 2021). An added complication is that the impacts of climate change will happen in conjunction with established (fishing) and emerging human stressors (e.g. mining, mCDR). For example, bottom trawling deeper than 800 m in Europe was banned in 2016, but these activities continue in many other areas of the world.

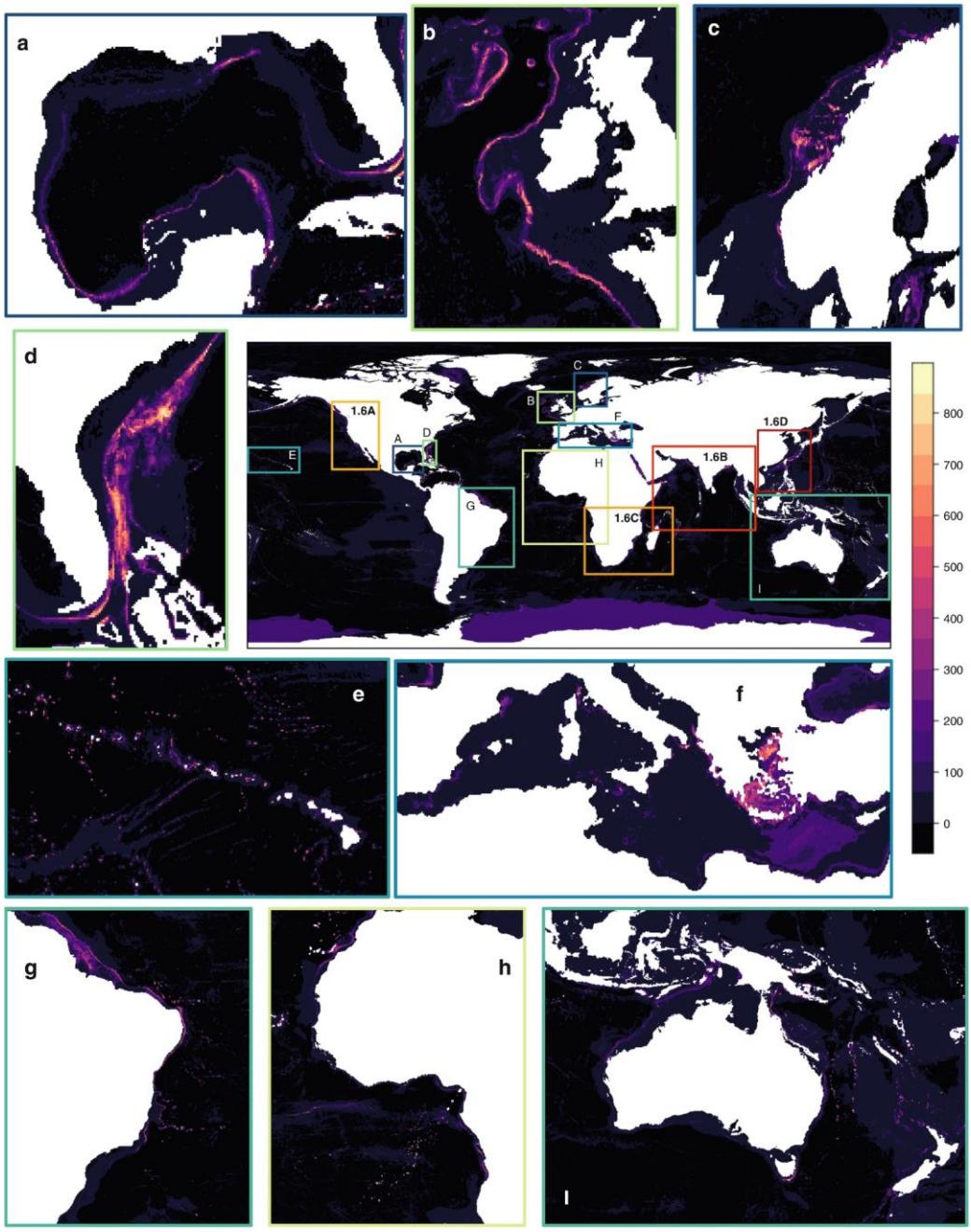


Figure 1: Map of ensemble weighted mean habitat suitability index (HSI) scores for CWCS reefs and reef-forming taxa known to occur within the regions of the world (Cordes and others 2023) (a) Southeastern US, (b) UK & Ireland, (c) Norway, (d) Southeast USA, (e) Hawaii, (f) Mediterranean Sea, (g) East Brazil, (h) West Africa, and (i) Southwest Pacific CWCS reef regions. HSI scores shown on color ramp, from highly unsuitable (0, black) to highly suitable (1000, yellow) for reef development. Major land masses are shown in white.

There is a lack of data on the timescales of how long it may take for CWC reefs to be impacted by climate change. Paleo-records of key framework forming species are of great benefit in this regard (Potilho-Ramos 2022), as observation of impacts in situ is limited by regional capacity for monitoring and repeated observation over potentially decadal timescales. Paleo-records can also

be used to identify key drivers of past impacts (e.g. food supply through local hydrodynamics) and provide insights into how present day reefs can survive in sub-optimal conditions (such as low oxygen) , such as CWCS off the Mauritanian Margin (Potilho-Ramos 2022). There have been very few studies of the effects of climate change on coral gardens (consisting of octocoral sea fans, antipatharian black corals, stylasterid hydrocorals, and others) and sponge beds (unresolved).

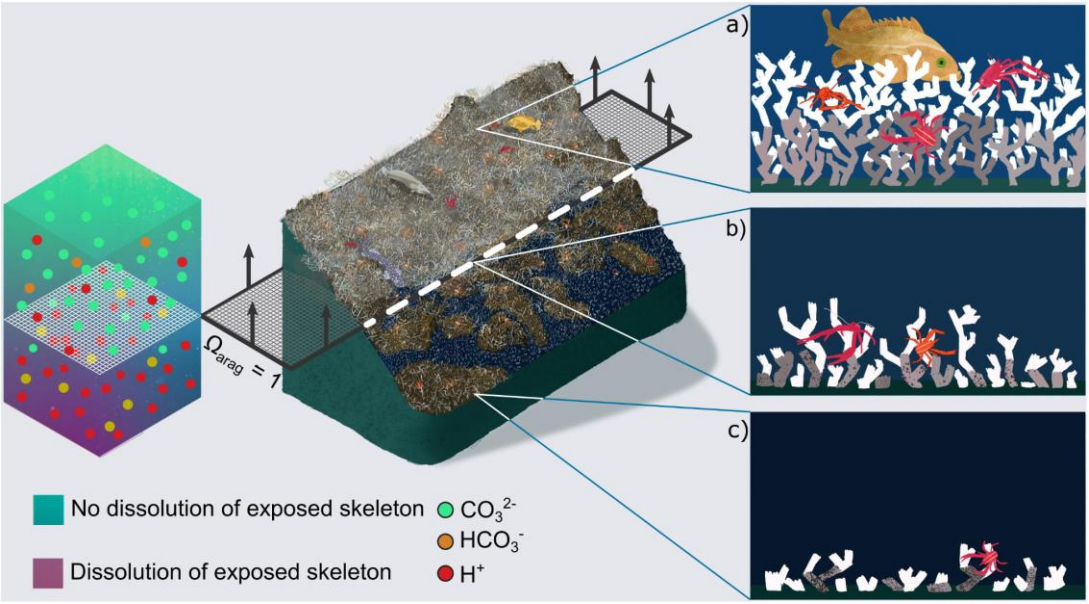


Figure 2: Concept of cold-water coral habitat loss in a future ocean. Central image shows Desmophyllum pertusum reefs under present day conditions (top), and their projected habitat loss in a future ocean, once the aragonite saturation horizon (ASH, dashed layer at ΩArag = 1) rises above them. A qualitative chemistry scale bar indicates dissolution of exposed aragonite beneath the horizon driven by increased [H^+] and decreased [CO_3^{2-}] ions. Arrows on the dashed layer indicate projected direction of ASH movement driven by ocean acidification. Panels on the right zoom into areas of present day and future reefs related to the position of the ASH. (a) Shows a healthy reef with substantial live (white) and dead (grey) coral framework. In (b) porosity has started to appear in the dead, exposed skeletal framework leading to crumbling. In (c) exposed skeletal framework exhibits large porosity and is unable to support complex 3D habitat, although high abundances of live coral can still exist. Hennige and others (2020).

4. Region-Specific Changes

4.1 Arctic Ocean

CWCS are pan-Arctic ecosystems, and studies have increased since 2018 to identify key biodiversity hot spots of CWCS across several areas, including the continental shelves of Greenland and Norway, as well as in fjords around Svalbard (Puerta and others 2020). The Davis Strait hosts important sponge grounds and soft coral fields (Maier and others 2024), but due to the inaccessibility of some areas (e.g, due to sea ice) these studies are often based on singular or episodic observations. The Karasik seamount expedition revealed that some deep-sea

sponges, such as *Geodia parva* and *Stelletta rhaphidiophora* can move across the seafloor (Morganti and others 2021).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

The understanding of how overturning circulations provide surface food supply to reefs around the North and Eastern Atlantic has improved (Juva and others 2020, de Froe and others 2022), including historically in the Baltic Sea (Raddatz and others 2020a), highlighting that current CWCS reefs may be at risk due to water column stratification associated with climate change. Quantification of water mass dynamics also supports better understanding of larval flow between CWCS areas (Schulz and others 2020) and in identifying unique sponge fauna in the Mediterranean (Santin and others 2021). Since 2019, there has been some progress in the protection of CWC habitat, e.g. Eastern Canyons Marine Refuge in Canada, the West of Scotland MPA, and Tristan da Cunha MPA in the Southern Atlantic).

4.3 The South Atlantic Ocean and the Wider Caribbean

Despite the dire need to curb our fossil fuel use, offshore drilling continues to expand around the world, moving into frontier areas of the deep ocean in the southern Caribbean, West Africa, ~~Brazil, Argentina, and Falkland Islands/Malvinas~~and South America. Detailed mapping of the mounds off Brazil (Raddatz and others 2020b) and Mauritania have revealed the wider distribution and abundance of CWCS. The systems off West Africa seem to be surviving and in some cases thriving in waters with extremely low oxygen, in contrast to findings elsewhere (Hebbeln and others 2019). New taxonomic and coral distribution work in South Africa (Filader and others 2021, 2024) is strengthening the knowledge base with the discovery of many coral gardens, and new offshore MPAs have improved CWCS habitat protection with fisheries eco-certification initiatives supporting further improvements in the management of CWCS and VMEs (Sink and others 2023).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Taxonomic knowledge of CWCs and sponges is advancing in Africa (Filander and others 2021, 2024, Hanafi-Portier and others 2024, Samaai and others 2020) and museum records are being used to examine diversity patterns in the Indian and Atlantic ocean (Filander and others 2024). There has been little progress in mapping CWC habitats along the African continental margin but new expeditions in the Red Sea have increased CWC species and reef discovery and baseline data in that region (Qurban and others 2020, Chimienti and others 2022, Maggioni and others

2022). CWC protection is lacking along most of the African margin for both the Indian and Atlantic Ocean and there is no/limited progress in protecting CWC habitats in the high seas of this region. Offshore drilling continues to expand in the Bay of Bengal, Indonesia, and elsewhere and continues to threaten CWCS ecosystems before they are even discovered.

4.5 The North Pacific Ocean

In the Northwest Hawaiian Islands, gradients in fishery pressure were related to the size and density of corals on seamounts (Baco and others 2023). In seamounts where fishing had historically occurred but had been stopped since the 1970s, there was some recovery of corals on seamounts that were inside of marine protected areas. The CWCS ecosystems of the Eastern Tropical Pacific (ETP) have been investigated primarily in Costa Rica and Ecuador (Cortés 2019). Near the Galápagos Islands, large deep-sea coral reefs (400-600 m) were discovered recently. All studies have been single observations which makes evaluations of change almost impossible. Additionally CWCS have recently been surveyed in t, the South China Sea thereby filling a data gap that previously existed in this region (Ta and others, 2024).

4.6 The South Pacific Ocean

In addition to long-standing industrial activity, the commercial exploitation of deep-sea mineral resources is an additional threat to CWCS habitats, and coral gardens in particular. This is of particular concern in the Central Pacific where most interest has been focused. The potential impacts of mining involve physical destruction of the seabed and damage to the habitat and fauna by the mining equipment, and changes in seafloor topography and geochemical characteristics in the direct vicinity of the mining site (Carreiro-Silva and others 2022). The generated sediment plumes can affect the entire water column, disperse for hundred kilometers, and last several years (Muñoz-Royo and others 2021, Morato and others 2022). The extent and nature of ecosystem impacts resulting from these plumes is detrimental, with mortality and tissue loss observed in the octocoral *Dentomuricea aff. meteor* (Carreiro-Silva and others, 2022), but to date, combined effects with environmental change is poorly understood (Van Dover and others, 2017; Van Dover and others, 2020).

4.7 The Southern Ocean

There has been little exploration of CWCS systems in the Southern Ocean in recent years. However, the presence of the Schmidt Ocean Institute RV Falkor (too) will be adding significant amounts of data from Antarctica, the South Sandwich Islands, and other parts of the area of application of the Convention on the Conservation of Antarctic Marine Living resources (CCAMLR) ~~Southern Ocean~~ in 2024 and 2025. ~~Southern Ocean p~~Proposals for additional MPAs in

East Antarctica, the Weddell Sea, and the Antarctic Peninsula have been under negotiation within ~~the Commission for the Conservation of Antarctic Marine Living Resources (~~CCAMLR~~)~~ but have not yet reached consensus for implementation (CCAMLR, 2024). CCAMLR developed binding measures for the identification, designation, monitoring, and management of fragile benthic ecosystems including CWCS from in 2007. These ecosystems have been included in the subsequent design of marine protected areas throughout the Convention Area. In addition, prohibition of high seas bottom trawling and targeting toothfish shallower than 550 m beginning in 2009 closed much of the Continental shelf to impacts from bottom contact from fisheries in an effort to avoid significant adverse impacts on CWCS.

5. Remaining key knowledge, capacity changes, and new gaps

Global awareness of the importance of CWCs continues to grow with discoveries of new ecosystems, the services and biodiversity they support, and the threats they are under. Research on ecosystem services, climate risks and foundational biodiversity science are being increasingly used in communication efforts. Programs such as The Deep Ocean Stewardship Initiative (DOSI), Rev Ocean, OceanX, Ocean Census, the Ocean Exploration Trust with their vessel EV *Nautilus*, and the Schmidt Ocean Institute with their vessel RV *Falkor (too)*, have led to increased international expeditions and philanthropic investment, offshore live streaming and increased focus, training and multiple-media efforts (art, animation, documentaries, podcasts, etc.) on science communication are helping to increase access and global awareness.

While the awareness of CWCS grows, we are also entering a time where the deep sea is being looked at as a resource for mCDR. A number of marine carbon dioxide removal (mCDR) projects suggest storing carbon in the deep sea ~~(Levin and others 2023)~~, but ~~often~~ there is a danger in overlooking the ecological complexity of the deep sea, or failing to account for the habitats and ecosystem processes that may be impacted, including CWCS (Levin and others 2023). For example, alkalinity enhancement, direct CO2 injection, or organic carbon deposition could directly or indirectly alter local pH, O2 levels, and sedimentation dynamics and CWCS, including their larval stages, are potentially sensitive to smothering from an excess of organic matter or mineral deposition (see Levin and others 2023 for a review of these issues).

Looking forward, the conservation and sustainable management of CWCS aligns with the UN Sustainable Development Goals (SDGs), particularly SDG 14: Life Below Water “conserve and sustainably use the oceans, seas and marine resources for sustainable development.” Ecosystem services from CWCS habitats are at risk including climate regulation, food production, and provision of livelihoods (Morato and others 2020, Cordes and others 2023). CWCS also play an indirect and important role in intermediate-term (100s - 1000s of years) carbon sequestration

by provisioning their complex skeletons and building the habitats that support a diverse range of marine life, which all contribute to the deep-sea carbon cycle (Bax and others 2021).

Integrating CWCS into climate adaptation and mitigation policies—such as through Nationally Determined Contributions (NDCs)—would aid their role in supporting biodiversity, maintaining ecosystem services, and contributing to global decarbonization goals. For example, aligning the Antarctic Treaty System with the Paris Agreement could facilitate the inclusion of Antarctic CWCS conservation targets in NDCs. (Bax and others 2021). Morato and others (2020) emphasize the need to better include climate refugia in spatial management efforts. There have also been improvements in accounting for ecosystem services of CWC habitat (Cordes and others 2023) and new work to support consideration of these services into climate-smart marine spatial planning (Bravo and others 2023, La Bianca and others 2023). This supports ecosystem service based management.

There is also increasing recognition of the importance of Indigenous Peoples' knowledge and appreciation for cultural values in understanding and managing deep-sea ecosystems (Escobar and others 2021). Cultural connections to the deep sea include spiritual connections, and coastal Iindigenous Peoples ~~coastal communities~~ are expressing increased concern for deep-sea habitats including CWCs. Policy briefs and arts-based approaches have offered new avenues for understanding, documenting and sharing traditional and Iindigenous Peoples' knowledge (Escobar and others 2021).

The capacity for monitoring and research is overwhelmingly in the global north. Most countries lack deep water monitoring, and in many instances, lack research vessels so they depend on outside technologies and data sharing. While FAIR data principles (Findable, Accessible, Interoperable, and Reusable) are essential for promoting open and equitable data sharing, they are complemented by a framework of CARE, ensuring that data collection and sharing are conducted ethically, inclusively, and with respect for the rights and knowledge of local communities. The Nagoya Protocol on Access to Genetic Resources provides an important framework on how benefits arising from samples and data are fair and equitable with regard to local communities.

To support growing observation efforts, technologies that enhance monitoring and protection for management increasingly include autonomous systems (Zelada-Leon and others 2020). These advances support the development of indicators for assessing key deep-sea habitats in national waters and areas beyond national jurisdiction, and effectively reduce habitat disturbance by improving marine spatial planning (Kazanidis and others 2020, Orejas and others 2020). eDNA technologies are rapidly advancing and could enable low-cost, non-invasive, efficient monitoring of biodiversity and ecosystem health (McCartin and others 2022), especially when combined with curated sequence libraries and taxonomic reference collections. In addition to eDNA, recent advancements in technology, including manned submersibles and artificial intelligence (AI), have also significantly enhanced understanding of CWCS. While these tools still face certain limitations, these technologies enable deeper and more detailed exploration, allowing for in situ observations of growth, behavior, and species interactions (Mogstad and others, 2023, Prado and others, 2023; Aguzzi and others, 2024; Gallego and others, 2024; Wang and others, 2024). These advances in technology and data acquisition in combination with early detection of stressors (such as pollution, temperature changes, or invasive species) enables faster management responses, reducing damage to CWCS and potentially preventing habitat degradation.

References

Aguzzi, J., Thomsen, L., Flögel, S., Robinson, N. J., Picardi, G., Chatzievangelou, D., and others (2024). New technologies for monitoring and upscaling marine ecosystem restoration in deep-sea environments. Engineering 34, 195-211

Baco AR, Morgan NB, Roark EB, Biede V. (2023). Bottom-contact fisheries disturbance and signs of recovery of precious corals in the Northwestern Hawaiian Islands and Emperor Seamount Chain. Ecological Indicators. 148:110010.

Barnhill, K.A., Roberts, J.M., Myers-Smith, I. and others (2023). Incorporating dead material in ecosystem assessments and projections. Nat. Clim. Chang. 13, 113–115. https://doi.org/10.1038/s41558-022-01565-5Bart MC, Hudspith M, Rapp HT, Verdonschot PFM and de Goeij JM (2021) A Deep-Sea Sponge Loop? Sponges Transfer Dissolved and Particulate Organic Carbon and Nitrogen to Associated Fauna. Front. Mar. Sci. 8:604879. doi: 10.3389/fmars.2021.604879

Bax, N., Sands, C.J., Gogarty, B., Downey, R.V., Moreau, C.V., Moreno, B., Held, C., Paulsen, M.L., McGee, J., Haward, M. and Barnes, D.K., (2021). Perspective: increasing blue carbon around Antarctica is an ecosystem service of considerable societal and economic value worth protecting. Global Change Biology, 27(1), pp.5-12.

Beazley L, Kenchington E, Murillo FJ, Brickman D, Wang Z, Davies AJ, Roberts EM, Rapp HT. (2021). Climate change winner in the deep sea? Predicting the impacts of climate change on the distribution of the glass sponge *Vazella pourtalesii*. Marine Ecology Progress Series, 657:1-23. https://doi.org/10.3354/meps13566

Boch, C.A., A. DeVogelaere, E.J. Burton, C. King, C. Lovera, K. Buck, J. Lord, L. Kuhnz, M. Kaiser, C. ReidRose, and J. P. Barry. Guide to translocating coral fragments for deep-sea restoration. National Marine Sanctuaries Conservation Series ONMS-20-10. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 25 pp.

Bravo ME, Brandt MI, Van Der Grient JMA, Dahlgren TG, Garrote PE, Gollner S, Jones DOB, Levin LA, McClain CR, Narayanaswamy BE, Sutton TT, Vicorero L, Cordes EE. (2023) Insights from the management of offshore energy resources: Towards an ecosystem-services based management approach for deep-ocean industries. Front Mar Sci. 9: 994632. doi: 10.3389/ fmars.2022.994632

Büscher JV, Juva K, Flögel S, Wisshak M, Rüggeberg A, Riebesell U, Form AU (2024) Water mass characteristics and hydrodynamics at an inshore versus an offshore mid-Norwegian cold-water coral reef habitat. Front. Mar. Sci. 11:1363542. https://doi.org/10.3389/fmars.2024.1363542

Carreiro-Silva M., Martins I., Riou V., Raimundo J., Caetano M., Bettencourt R., and others (2022) Mechanical and toxicological effects of deep-sea mining sediment plumes on a habitat-forming cold-water octocoral. *Frontiers in Marine Science*, 9:915650. https://doi.org/10.3389/fmars.2022.915650

Chimienti, G., Terraneo, T. I., Vicario, S., Marchese, F., Purkis, S. J., Eweida, A.A., Rodrigue, M., & Benzoni, F. (2022). A new species of *Bathypathes* (Cnidaria, Anthozoa, Antipatharia, Schizopathidae) from the Red Sea and its phylogenetic position. *ZooKeys*, 1116, 1–22. https://doi.org/10.3897/zookeys.1116.79846.

Corbera, G., Lo Iacono, C., Simarro, G. *and others* (2022). Local-scale feedbacks influencing cold-water coral growth and subsequent reef formation. *Sci Rep* 12, 20389. https://doi.org/10.1038/s41598-022-24711-7

Cordes EE, Jones DOB, Schlacher TA, Amon DJ, Bernardino AF, Brooke S, Carney R, DeLeo DM, Dunlop KM, Escobar E, Gates AR, Génio L, Gobin J, Henry L-A, Herrera S, Hoyt S, Joye S, Kark S, Mestre NC, Metaxas A, Pfeifer S, Sink K, Sweetman AK, Witte U. (2016) Environmental impacts of the deep-water oil and gas industry: a review to guide management strategies. Front Environ Sci 4: 58. doi: 10.3389/fenvs.2016.00058

Cordes, E.E., Demopoulos, A.W.J., Davies, A.J. *and others* (2023). Expanding our view of the cold-water coral niche and accounting of the ecosystem services of the reef habitat. *Sci Rep* 13, 19482. https://doi.org/10.1038/s41598-023-45559-5

Cordes E.E, Mienis (2024). *The Cold-Water Coral Reefs of the World*. Volume 19: Coral Reefs of the World series. Springer International Publishing. doi: 10.1007/978-3-031-40897-7

Cortés, J. (2019). Chapter 26: Isla del Coco, Costa Rica, Eastern Tropical Pacific, pp. 465-474. *In*: Y. Loya, K.A. Puglise, T.C.L. Bridge (Eds.), Mesophotic Coral Ecosystems. Coral Reefs of the World 12. Springer Nature, Switzerland. https://doi.org/10.1007/978-3-319-92735-0_26

de Clippele, L. H., Rovelli, L., Ramiro-Sánchez, B., Kazanidis, G., Vad, J., Turner, S., Glud, R. N. & Roberts, J. M. (2021a). Mapping cold-water coral biomass: an approach to derive ecosystem functions. Coral Reefs 40, 215–231.

de Clippele, L. H., van der Kaaden, A.-S., Maier, S. R., de Froe, E. & Roberts, J. M. (2021b). Biomass mapping for an improved understanding of the contribution of cold-water coral carbonate mounds to C and N cycling. Frontiers in Marine Science 8, 1608.

de Kluijver A, Bart MC, van Oevelen D, de Goeij JM, Leys SP, Maier SR, Maldonado M, Soetaert K, Verbiest S and Middelburg JJ (2021) An integrative model of carbon and nitrogen metabolism in a common deep-sea sponge (*Geodia barretti*). Front. Mar. Sci. 7, 596251. https://doi.org/10.3389/fmars.2020.596251

de Froe, E., Maier, S. R., Horn, H. G., Wolff, G. A., Blackbird, S., Mohn, C., Schultz, M., van der Kaaden, A.-S., Cheng, C. H., Wubben, E., van Haastregt, B., Moller, E. F., Lavaleye, M., Soetaert, K., Reichart, G.-J., and others (2022). Hydrography and food distribution during a tidal cycle above a cold-water coral mound. Deep–Sea Research I 189, 103854. https://doi.org/10.1016/j.dsr.2022.103854 Dijkstra, J. A., Mello, K., Sowers, D., Malik, M., Watling, L., & Mayer, L. A. (2021). Fine-scale mapping of deep-sea habitat-forming species densities reveals taxonomic specific environmental drivers. Global Ecology and Biogeography, 30(6), 1286-1298.

Du Preez C, Swan KD, Curtis JM. Cold-water corals and other vulnerable biological structures on a North Pacific seamount after half a century of fishing. (2020). Frontiers in Marine Science. 7:17.

Escobar, E., B. Guilloux, K. Howell, D. Jones, C. Koyavakauta, L. Levin, C.Y. Mulalap, P. Singh, K. Sink, V. Tilot, P. Turner, A. Vencatesan, K. Willaert. (2021). The necessity of traditional knowledge for management of deep-seabed mining." Deep-Ocean Stewardship Initiative.

Filander, Z.N., Kitahara, M.V., Cairns, S.D., Sink, K.J. and Lombard, A.T. (2021). Azooxanthellate Scleractinia (Cnidaria, Anthozoa) from South Africa. ZooKeys, 1066, 1-198. https://doi.org/10.3897/zookeys.1066.69697

Filander ZN, Sink KJ, Kitahara MV, Cairns SD, Lombard AT (2024) Diversity patterns of the South African azooxanthellate scleractinians (Cnidaria: Anthozoa), with considerations of

environmental correlates. PLoS ONE 19(8): e0296188. https://doi.org/10.1371/journal.pone.0296188

Gallego, R., Arias, M. B., Corral-Lou, A., Díez-Vives, C., Neave, E. F., Wang, C., ... & Riesgo, A. (2024). North Atlantic deep-sea benthic biodiversity unveiled through sponge natural sampler DNA. Communications Biology, 7(1), 1015.

Gregório, I., Xavier, J. R., & Davies, A. J. (2024). Present and future distribution of the deep-sea habitat-forming sponge-Pheronema carpenteri () in a changing ocean. Deep Sea Research Part I: Oceanographic Research Papers, 213, 104390.

Hanafi-Portier, M., Samadi, S., Corbari, L., Boulard, M., Miramontes, E., Penven, P., Leroy, B., Napoléon, T., Jorry, S.J. and Olu, K. (2024). Multiscale spatial patterns and environmental drivers of seamount and island slope megafaunal assemblages along the Mozambique channel. Deep Sea Research Part I: Oceanographic Research Papers, 203, 104198. https://doi.org/10.1016/j.dsr.2023.104198

Hebbeln D, Portilho-Ramos RD, Wienberg C, Titschack J. (2019). The fate of cold-water corals in a changing world: a geological perspective. Frontiers in Marine Science. 6:119.

Hennige SJ, Wolfram U, Wickes L, Murray F, Roberts JM, Kamenos NA, Schofield S, Groetsch A, Spiesz EM, Aubin-Tam ME, Etnoyer PJ. (2020). Crumbling reefs and cold-water coral habitat loss in a future ocean: evidence of “Coralporosis” as an indicator of habitat integrity. Frontiers in Marine Science 7, 668. https://doi.org/10.3389/fmars.2020.00668

Juva K, Flögel S, Karstensen J, Linke P and Dullo W-C (2020) Tidal dynamics control on cold-water coral growth: A high-resolution multivariable study on Eastern Atlantic cold-water coral sites. Front. Mar. Sci. 7:132. https://doi.org/10.3389/fmars.2020.00132

Kazanidis G, Orejas C., Borja A, Kenchington E, Henry L-A, Callery O, Carreiro-Silva M, Egilsdottir H, Giacomello E, Grehan A, Menot L, Morato T, Ragnarsson SA, Rueda JL, Stirling D, Stratmann T, van Oevelen D, Palialexis A, Johnson D, Roberts JM. (2020). Assessing the environmental status of selected North Atlantic deep-sea ecosystems. Ecological Indicators 119: 106624.

La Bianca G, Rees S, Attrill MJ, Lombard AT, McQuaid KA, Niner HJ, van Rein H, Sink KJ, Howell KL. (2023). A standardised ecosystem services framework for the deep sea. Frontiers in Marine Science. 10: 1176230.

Levin L, Alfaro-Lucas J, Colaço A, Cordes EE, Craik N, Danovaro R, Hoving H-J, Ingels J, Mestre N, Seabrook S, Thurber A, Vivian C, Yasuhara M. (2023) Deep-sea impacts of climate interventions. Science. 379: 978-981. doi: 10.1126/science.ade7521

Liu and others (2024) CORDAP RandD roadmap for conservation and restoration of cold-water corals. CORDAP. www.cordap.org

Maier SR, Arboe NH, Christiansen H, Krawczyk DW, Meire L, Mortensen J, Planken K, Schulz K, van der Kaaden AS, Vonnahme TR, Zwerschke N. (2024). Arctic benthos in the

Anthropocene: Distribution and drivers of epifauna in West Greenland. Science of the Total Environment. 951:175001.

Maier, F.M., E. de Froe, K. Soetaert, M. Lavaleye, G. Duineveld, O. Beauchard, A.-S. van der Kaaden, B.P. Koch, D. van Oevelen. (2021). Reef communities associated with 'dead' cold-water coral framework drive resource retention and recycling in the deep sea. Deep Sea Research Part I: Oceanographic Research Papers, 75, 103574. https://doi.org/10.1016/j.dsr.2021.103574.

Maier, S.R., Brooke, S., De Clippele, L.H., de Froe, E., van der Kaaden, A.-S., Kutti, T., Mienis, F., van Oevelen, D. (2023), On the paradox of thriving cold-water coral reefs in the food-limited deep sea. Biol Rev, 98: 1768-1795. https://doi.org/10.1111/brv.12976

Maggioni, D., Terraneo, T. I., Chimienti, G., Marchese, F., Pica, D., Cairns, S. D., Eweida, A. A., Rodrigue, M., Purkis, S. J., & Benzoni, F. (2022). The first deep-sea stylasterid (Hydrozoa, Stylasteridae) of the Red Sea. *Diversity, 14* (4), 241. https://doi.org/10.3390/d14040241.

McCartin LJ, Voshen SA, Ambrose SW, Layden M, McFadden CS, Cordes EE, McDermott JM, Herrera S (2022) Temperature controls eDNA persistence across physiochemical conditions in seawater. ES&T. 56: 8629-8639. doi: 10.1021/acs.est.2c01672

Mogstad, A. A., Løvås, H. S., Sture, Ø., Johnsen, G., & Ludvigsen, M. (2022). Remote sensing of the Tautra Ridge: an overview of the World's shallowest cold-water Coral Reefs. Frontiers in Marine Science, 9, 848888.

Montseny, M., Linares, C., Carreiro-Silva, M., Henry, L.-A., Billett, D., Cordes, E. E., Smith, C. J., Papadopoulou, N., Bilan, M., Girard, F., Burdett, H. L., Larsson, A., Strömberg, S., Viladrich, N., Barry, J. P., Baena, P., Godinho, A., Grinyó, J., Santín, A., ... Gori, A. (2021a). Active Ecological Restoration of Cold-Water Corals: Techniques, Challenges, Costs and Future Directions. Frontiers in Marine Science, 8, Article 621151. https://doi.org/10.3389/fmars.2021.621151

Montseny, M., Linares, C., Viladrich, N., Biel, M., Gracias, N., Baena, P., Quintanilla, E., Ambroso, S., Grinyó, J., Santín, A. and Salazar, J., 2021b. Involving fishers in scaling up the restoration of cold-water coral gardens on the Mediterranean continental shelf. Biological conservation, 262, p.109301

Morato T, J.M. González-Irusta, C. Dominguez-Carrió, C.L. Wei, A. Davies, A.K. Sweetman, and others (2020). Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. Glob Chang Biol. 26(4), 2181-2202. https://doi.org/10.1111/gcb.14996

Morato, T., Juliano, M., Pham, C.K., Carreiro-Silva, M., Martins, I. & Colaço A. (2022) Modelling the dispersion of Seafloor Massive Sulphide mining plumes in the Mid Atlantic Ridge around the Azores. *Frontiers in Marine Science*, 9. https://doi.org/10.3389/fmars.2022.910940

Morganti TM, Slaby BM, de Kluijver A, Busch K, Hentschel U, Middelburg JJ, Grotheer H, Mollenhauer G, Dannheim J, Rapp HT, Purser A. (2022). Giant sponge grounds of Central Arctic seamounts are associated with extinct seep life. Nature communications. 13:638.

Muñoz-Royo, C., Peacock, T., Alford, M. H., Smith, J. A., Le Boyer, A., Kulkarni, C. S., and others (2021) Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. *Communications Earth & Environment,* 2, 148.

+Orejas C, Kenchington E, Rice J, Kazanidis G, Palialexis A, Johnson D, Gianni M, Danovaro R, Roberts JM. (2020). Towards a common approach to the assessment of the environmental status of deep-sea ecosystems in areas beyond national jurisdiction. Marine Policy 121, 104182. https://doi.org/10.1016/j.marpol.2020.104182

Portilho-Ramos, R. D., Titschack, J., Wienberg, C., Siccha Rojas, M. G., Yokoyama, Y., & Hebbeln, D. (2022). Major environmental drivers determining life and death of cold-water corals through time. PLoS BIOLOGY, 20(5), e3001628. https://doi.org/10.1371/journal.pbio.3001628

Prado, E., Abad-Uribarren, A., Ramo, R., Sierra, S., González-Pola, C., Cristobo, J., ... & Sánchez, F. (2023). Describing polyps behavior of a deep-sea gorgonian, Placogorgia sp., using a deep-learning approach. Remote Sensing, 15(11), 2777.

Puerta P, Johnson C, Carreiro-Silva M, Henry LA, Kenchington E, Morato T, Kazanidis G, Rueda JL, Urra J, Ross S, Wei CL. (2020). Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. Frontiers in Marine Science. 7:239.

Qurban, M.A., Krishnakumar, P.K., Joydas, T.V. *and others* (2020). Discovery of deep-water coral frameworks in the northern Red Sea waters of Saudi Arabia. *Sci Rep* 10, 15356. https://doi.org/10.1038/s41598-020-72344-5

Raddatz, J., Liebetrau, V., Rüggeberg, A. and others (2020a). Living on the edge: Environmental variability of a shallow late Holocene cold-water coral mound. Coral Reefs 41, 1255–1271. https://doi.org/10.1007/s00338-022-02249-4

Raddatz J, Titschack J, Frank N, Freiwald A, Conforti A, Osborne A, Skornitzke S, Stiller W, Rüggeberg A, Voigt S, Albuquerque AL. (2020b). *Solenosmilia variabilis*-bearing cold-water coral mounds off Brazil. Coral Reefs 39, 69-83.

Santín A, Grinyó J, Uriz MJ, Lo Iacono C, Gili JM and Puig P (2021) Mediterranean Coral Provinces as a Sponge Diversity Reservoir: Is There a Mediterranean Cold-Water Coral Sponge Fauna? Front. Mar. Sci. 8, 662899. https://doi.org/10.3389/fmars.2021.662899

Samaai T, Kelly M, Ngwakum B, Payne R, Teske PR Janson L , Kerwath S , Parker D, Gibbons MJ (2020). New Latrunculiidae (Demospongiae, Poecilosclerida) from the Agulhas ecoregion of temperate southern Africa. Zootaxa, 4896(3). https://doi.org/10.11646/zootaxa.4896.3.4

Schulz K, Soetaert K, Mohn C, Korte L, Mienis F, Duineveld G, van Oevelen D. (2020). Linking large-scale circulation patterns to the distribution of cold water corals along the eastern Rockall Bank (northeast Atlantic). Journal of Marine Systems 212, 103456.

Schwing P, Montagna PA, Joye SB, Paris CB, Cordes EE, McClain CR, Kilborn JP, Murawski SA. (2020) Deep benthic ecosystem impacts of the *Deepwater Horizon* oil spill: Assembling the record of species and community change. Front Mar Sci. 7:560012. doi: 10.3389/fmars.2020.560012

Sink KJ, Lombard AT, Attwood CG, Livingstone TC, Grantham H, Holness SD. (2023). Integrated systematic planning and adaptive stakeholder process support a 10-fold increase in South Africa's Marine Protected Area estate. Conservation Letters. 16:e12954.

Ta, K., Song, X., Wei, Z., Du, M., Xu, H., Chen, S., ... & Peng, X. (2024). Oasis of the deep: Cold-water corals of the South China Sea. Marine Environmental Research, 195, 106354.

Van der Kaaden, A.S., Van Oevelen, D., Rietkerk, M., Soetaert, K., Van de Koppel, J. (2020). Spatial self-organization as a new perspective on cold-water coral mound development. Frontiers in Marine Science, 7, 631.

Van Dover, C. L., Ardron, J. A., Escobar, E., Gianni, M., Gjerde, K. M., Jaeckel, A., and others (2017). Biodiversity loss from deep-sea mining. *Nature Geoscience*, *10*(7), 464-465.

Van Dover, C. L., Colaço, A., Collins, P. C., Croot, P., Metaxas, A., Murton, B. J., and others (2020). Research is needed to inform environmental management of hydrothermally inactive and extinct polymetallic sulfide (PMS) deposits. *Marine Policy*, *121*, 104183.

Wang, W., Sun, Y. F., Gao, W., Xu, W., Zhang, Y., & Huang, D. (2024). Quantitative detection algorithm for deep-sea megabenthic organisms based on improved YOLOv5. Frontiers in Marine Science, 11, 1301024.

Williams A, Althaus F, Maguire K, Green M, Untiedt C, Alderslade P, Clark MR, Bax N, Schlacher TA. The fate of deep-sea coral reefs on seamounts in a fishery-seascape: what are the impacts, what remains, and what is protected?. Frontiers in Marine Science. 2020 Sep 25;7:567002.

Wolfram U, Peña Fernández M, McPhee S, Smith E, Beck RJ, Shephard JD, Ozel A, Erskine CS, Büscher J, Titschack J, Roberts JM. (2022). Multiscale mechanical consequences of ocean acidification for cold-water corals. Scientific Reports. 12: 8052.

Zelada Leon A, Huvenne VA, Benoist NM, Ferguson M, Bett BJ, Wynn RB. (2020). Assessing the repeatability of automated seafloor classification algorithms, with application in marine protected area monitoring. Remote Sensing. 12:1572.

Chapter 5F: Estuaries and deltas

1 Keynotes

Intensified human activities, combined with stronger winds and increasingly frequent extreme events associated with climate warming, have caused complex changes in estuaries and deltas (Venturini et al., 2024).

Coastal sediment suspension and river plumes increasingly reflect global trends, nevertheless, these changes are highly region diverse (Laignel et al., 2023).

Changing estuarine and deltaic environments have significantly altered sediment dynamics (Sengupta et al., 2023), water quality and ecosystem structures (De Souza et al., 2024), exacerbating ecological risks like hypoxia and acidification as well as socio-economic loss (Zhou et al., 2017; Meng et al., 2022; Ma et al., 2024).

Governance efforts in estuaries and deltas have made some progress. Local improvements such as reduced hypoxia in the Black Sea and Long Island Sound, and less eutrophication in the Yangtze River estuary. However, ecosystem responses remain slow comparing with management intensity, reflecting the complexity of multifactorial risks and delays in restoration (Uber et al., 2022; Pein et al., 2023).

Sustained efforts are essential for the sustainability of estuarine and deltaic ecosystems. Such efforts should emphasize monitoring, risk forecasting and integrated socio-economic assessments.

2 Introduction

Estuaries and deltas are highly complex ecosystems with diverse hydrodynamic and biogeomorphological settings facing considerable ecological and socioeconomic challenges (Laignel et al., 2023). These provide numerous significant ecological functions and are particularly biologically productive ecosystems. These ecosystems, such as coastal wetlands, offer vital ecosystem services such as safeguarding coastal populations and infrastructure from erosion, flooding, and storms; they filter pollutants and toxins from coastal waters, and support fisheries by serving as significant spawning grounds. These systems are among the most affected by human impacts, such as land reclamation (Sengupta et al., 2023), eutrophication, invasive species (De Souza et al., 2024), and climate change, including sea level rise, storm surges, delta subsidence, waves, and river flooding (Xuan et al., 2021; Ma et al., 2022).

In addition, a combination of several processes can lead to significant disasters as these processes can occur simultaneously: storm surge, waves, high tide, coastal river inundation, groundwater inundation, and sea level rise. Many of the world's coastlines are eroding and therefore retreating. The marine ecosystem in estuaries and deltas is also largely affected by compound weather and climate extremes, which can lead to severe ecological disaster such as enhanced summertime hypoxia due to heavy precipitation in the Changjiang watershed (Meng et al., 2022; Ma et al., 2024; Zhang et al., 2025).

This chapter provides an update to the second assessment, emphasizing the significant challenges faced by estuaries and deltas due to both human activities and weather and climate extremes. Such ecosystems are affected by multi-scale oceanic and atmospheric processes in addition to human disturbance which make their governance more challenging than before.

3 The environmental change since WOAII

Since the previous assessment, estuaries and deltas worldwide have undergone significant shifts in both physical and ecological states. Anthropogenic impacts on river runoff and suspended sediment flux exhibit strong spatial heterogeneity. In the Northern Hemisphere, extensive dam construction has reduced riverine sediment loads to about 49% of pre-dam levels, whereas in the Southern Hemisphere, intensified land-use changes have boosted suspended sediment concentrations by 41 ± 7% compared to the 1980s average (Dethier et al., 2022). As a result, the global riverine sediment supply to the ocean is being rapidly restructured, with the primary source shifting from Asia to South America.

Declining sediment supply poses a serious challenge to many deltas that rely on continuous accretion to offset relative sea-level rise and subsidence (Figure 1). Widespread groundwater abstraction, urban development and natural compaction are exacerbating these pressures, accelerating subsidence in large river deltas (Harris et al., 2020; Karlsrud et al., 2020). Where geologic instability intersects with ongoing sea-level rise, the net effect often leads to heightened flood risk and coastal retreat (Zhu et al., 2019). In parallel, anthropogenic changes to river discharge—both reductions and occasionally increases—can alter estuarine and deltaic circulation patterns, modifying nutrient delivery and affecting biological productivity in nearshore waters.

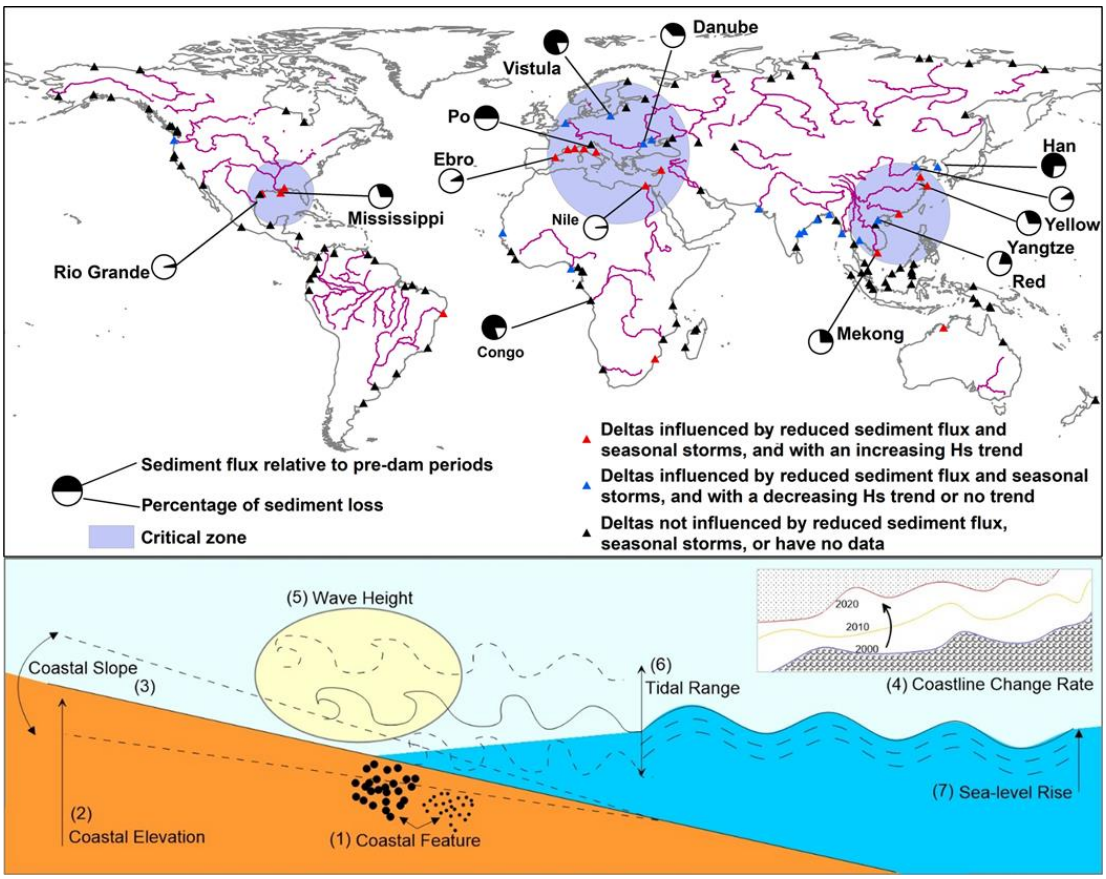


Fig.1 Global distribution of deltas influenced by both reduced sediment flux and seasonal storms and seven factors affecting coastal vulnerability (Zhu et al., 2024, Pang et al., 2023)

Climate change adds further stress by intensifying extreme weather and climate events such as heavy precipitation, droughts, marine heatwaves, and tropical cyclones (Iles et al., 2024; Studholme et al., 2022; Li et al., 2024; Zhao et al., 2024). These events disrupt salinity regimes, shift sediment transport pathways, and exacerbate erosion, undermining the stability of deltaic shorelines. There is growing evidence linking climate change to an upsurge in infectious diseases (Tsui et al., 2024) and to shifts in marine species distribution (Duffy et al., 2022; Hutchins & Capone, 2022). Ocean warming, marine heatwaves, eutrophication, acidification, and low-oxygen extremes continue to pose significant threats to estuarine and deltaic ecosystems (Guo et al., 2022; Johnson & Lyman, 2020; Li et al., 2024; Sampaio et al., 2021). In some estuarian areas, severe hypoxia episodes have led to ecological disasters that affect fisheries, benthic habitats and broader food webs (Ma et al., 2024). To mitigate these impacts, local stakeholders put efforts in demonstrating commitments to alleviating ecological stresses through engineering interventions and management measures (Meng et al., 2024).

Estuaries across the globe have experienced nutrient loading from urban, agricultural, and aquaculture sources, prompting eutrophication, harmful algal blooms (Brown et al., 2020), and bottom-water hypoxia (Chen et al., 2020; He et al., 2022; Ke et al., 2022; Zamora et al., 2023; Sudradjat et al., 2024; Zhou et al., 2020). While improved wastewater treatment has mitigated problems in some developed regions (Lenstra et al., 2020), many populous coastal zones continue to deteriorate. Coordinated nutrient management and integrated coastal planning remain key to long-term eutrophication control.

Invasive species pose another serious concern for estuarine and deltaic environments (Hensel, 2021; Ren et al., 2021). Maritime traffic and trade facilitate introductions, while warming waters expand the suitable habitat range for non-native organisms (Norton, 2020). Effective control hinges on targeted removal strategies and understanding complex ecological interactions (Creed et al., 2021; Liu et al., 2023).

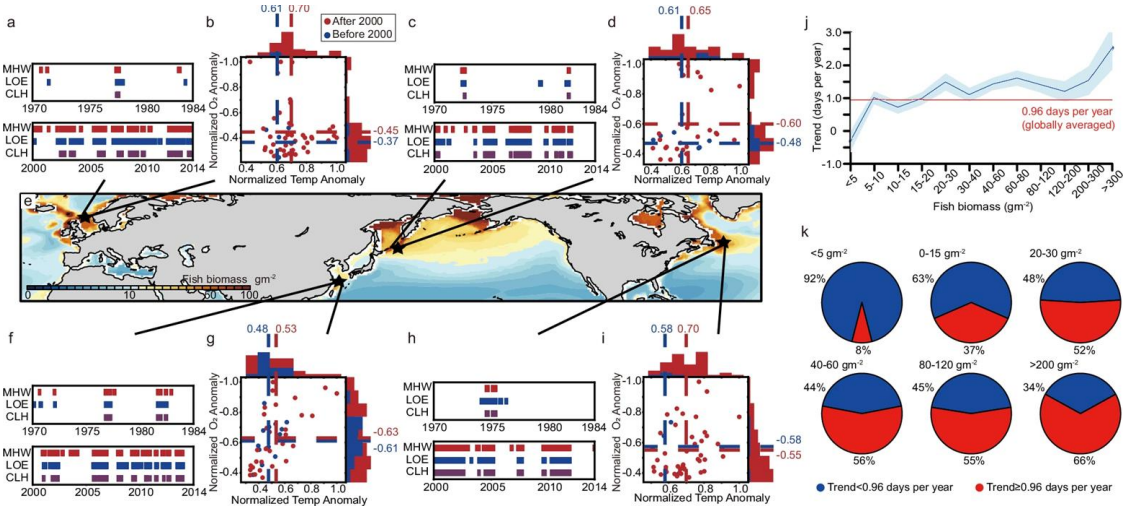


Fig.2 Compound low-oxygen extreme and heatwave events in relationship with marine fish biomass (Li et al., 2024)

Beyond ecological shifts, geomorphological and hydrological changes still demand high-resolution monitoring. Accurate bathymetric and shoreline data are vital for understanding erosion, deposition, and coastal flooding patterns. Yet an estimated 70–80% of the global coastal zone lacks reliable bathymetric coverage (McCarthy et al., 2022). This gap impedes the ability to develop marine planning strategies, to forecast coastal hazards, manage navigation channels, and design adaptive measures for aquaculture or infrastructure protection (Han & Zhou, 2025). In locations with pronounced sediment deficits, even small errors in bathymetric data can lead to underestimating erosion rates and thus exacerbate vulnerabilities to storm surges or sea-level rise.

Overall, the global picture since WOA II reveals mounting pressures on estuaries and deltas from multiple sources. Anthropogenic activities—especially dam construction, intensive groundwater pumping, sediment extraction and land-use changes—have reshaped sediment fluxes and accelerated subsidence in many heavily populated deltas. Pollution problems are prevalent in those systems with high population density. Inadequate investment in pollution control exacerbates these issues, particularly in underdeveloped areas. These problems often co-exist, exhibiting the interconnectedness between hydrogeomorphic processes, ecological processes, and economic development. Concurrently, a warming climate has amplified extreme events, contributing to erosion, salinity regime alterations and more frequent low-oxygen conditions and marine heatwaves. Meanwhile, emerging challenges such as invasive species underscore the delicate balance of these interconnected ecosystems. As these trends intensify, the combination of physical alterations, biogeochemical perturbations and shifting species distributions continue to transform estuarine and deltaic environments worldwide.

4 Region-specific changes

4.1 The Arctic Ocean

Including the Lena Delta in Russia and Mackenzie Delta in Canada, over 387 deltas filter sediment and carbon fluxes from the Arctic landscape to the ocean (Mann et al., 2022). Compared with lower-latitude deltas, Arctic deltas have subdued morphodynamics due to ice-cover. However, the warming climate has led to an expansion of the open-water season in Arctic deltas, which has caused increased wave influence and unknown changes in sediment transport and carbon cycling (Overeem et al., 2022). Nevertheless, Greenlandic deltas experience weak wave impacts because of the enclosed topography of their locations. The elongated open-water season potentially induces increased sediment loading (Bendixen et al., 2019), leading to a mean progradation rate of 0.011 km^2/yr of the 75 Greenlandic deltas (Overeem et al., 2022).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Several deltas are experiencing significant changes due to subsidence, erosion, and human interventions. Subsidence rates reach 16 mm/yr in the Mississippi Delta (Harris et al., 2020) and 12-20 mm/yr in the Nile Delta (Rateb & Abotalib, 2020). Erosion is worsened by extreme weather, especially in the Mississippi and Elbe deltas (Zhu et al., 2024; Uber et al., 2022). Dam construction and river modifications have reduced sediment delivery, slowing delta growth in the Rhône and Danube deltas (Mikhailova & Isupova, 2006; Constantinescu et al., 2023). Saltwater intrusion affects the Rhône and

Nile deltas, while ecological degradation is evident in the Dnieper Delta (Minaieva et al., 2024). Effective management is critical for restoration (Uber et al., 2022; Pein et al., 2023).

4.3 The South Atlantic Ocean and the Wider Caribbean

The Amazon Delta's ecosystem is largely intact, supporting diverse species and transporting 2,300–3,100 million tons of sediment annually, aiding coastline growth without significant subsidence. However, population growth and sea-level rise will require improved management (Anthony et al., 2021).

The Río de la Plata estuary, the second most important in South America, is experiencing a continuous but moderate sea level rise and suffered an extraordinary increase in the flow of the main tributaries from the early 70s. The frequency of extreme events, mainly wind-induced storm surges, has risen over the last three decades. At present, anthropogenic eutrophication (causing by nutrient inputs linked to human activities) is one of the most important environmental impacts on the ecosystem`s health and services. Massive cyanobacteria blooms promoted by nutrient enrichment associated with hydrological, oceanographic and meteorological factors have been reported more frequently in the last years, generating a loss of water quality, cultural ecosystem services and tourism revenues (Venturini et al., 2024).

The Niger Delta has seen significant coastline retreat, particularly from 1950-1987 and 2007-2012, linked to runoff changes and human activities (Dada et al., 2018). The Congo River Basin faces future drought and food scarcity risks, necessitating adaptive measures (Karam et al., 2023).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

The Ganges–Brahmaputra–Meghna (GBM) Delta faces risks from climate change, extreme hazards, and human activities, including a subsidence rate of 5.6 mm/yr. Riverbank erosion displaces 300,000 people annually, damaging land and infrastructure (Paszkowski et al., 2021). While sediment supply generally offsets sea-level rise, dams and water diversions threaten this balance, making upstream sediment management crucial (Raff et al., 2023). The Indus Delta has seen a decline in organic carbon fluxes due to damming and reduced river discharge, worsened by coastal erosion and changing monsoons (Ahmed et al., 2021). Human activities, like sediment mining, have caused erosion in the west and accretion in the east (Chen et al., 2020). Bangladesh's delta also

faces severe subsidence (20 ± 10 mm/yr), increasing sea-level rise risks (Steckler et al., 2024).

4.5 The North Pacific Ocean

Dams and sediment mining have reduced suspended sediment in Asian estuaries, worsening coastal ecosystem degradation (Yunus et al., 2022). The Mekong Delta faces subsidence (17-44 mm/yr) due to over 130 dams and groundwater extraction (Hecht et al., 2019). The Yangtze Delta's expanding coastline shows declining sediment concentrations and worsening hypoxia (Ma et al., 2024). The Pearl River Estuary suffers severe subsidence (~87.3 mm/yr, Liu et al., 2023), while the Yellow River Delta faces erosion from reduced sediment supply (Zhu et al., 2024). In Osaka Bay, warming has caused the shift in fish distributions. Overall, human impacts like dams, sediment extraction, and land reclamation are key drivers of these environmental changes.

4.6 The South Pacific Ocean

Sediment transport from the deltas to the ocean has generally increased in the South Pacific Ocean, especially in Australia (Hou et al., 2024). For example, despite dam-building upstream of the Burdekin River, located in the dry tropics of northeast Australia, coarse sediments downstream of the dam have nevertheless reached the river delta. The riverbed of Burdekin River Delta measurably rose in the past few decades, which has caused an increase of flood levels by approximately 1 m (Wolanski & Hopper, 2022). The trapping of sediment in the delta induced erosion of the offshore Cape Bowling Green Peninsula, which has essential ecological impacts on the coastal ecosystem.

4.7 The Southern Ocean

The surface of ice shelves in Antarctica melt during the austral summer, for instance, the meltwater volume reached as high as 0.83×10^9 m^3 in the summer of 2016-2017 on Amery Ice Shelf (Spergel et al., 2021). The meltwater forms surface lakes on the sea ice, which play essential roles on the surface energy balance of sea ice (Dell et al., 2024). Increased surface meltwater on ice shelves associated with climate warming may trigger the development of estuaries in Antarctica, which could lead to accelerated ice loss and sea level rise (Boghosian et al., 2021).

5 Remaining key knowledge and capacity changes and any new gaps

Intensified human activities, coupled with climate change, have exposed estuaries and deltas to severe hydrological and ecological threats. Human-induced (such as dam-building, groundwater

extraction) and natural subsidence of deltas and climate-associated sea level rise gradually squeeze the inland space of coastal zones. Inland flooding compounded by astronomical high tide may cause substantial losses to coastal zones and surrounding megacities. Besides inland flooding, extreme estuarine upstream drought compounding with astronomical high tide causes serious salt-water intrusion threatening drinking water safety by affecting drinking water reservoirs of coastal zone megacities. Global warming has caused extreme atmospheric and oceanic events to occur with higher frequency. Populations have increasingly concentrated in coastal areas, which may put stressed ecosystems and local environments at higher risk, entailing greater complexity and uncertainty.

Socioeconomic structures directly influence human activities, which have significant impacts on the sustainability and resilience of estuarine and deltaic systems. In return, estuarine and deltaic environments influence coastal zone societies and economies in multiple and complex ways, which potentially could require their restructuring. It is difficult to project the future changing directions of the societies and economies in coastal zones. It would be even more difficult to project the effects of feedback from local marine ecosystems, and estuarine and deltaic environments, to coastal societies and economies. Integrated monitoring systems and scientific investigations can effectively advance human abilities in comprehensively understanding inland-estuary/delta as a continuum. Science-based cooperation, planning, and strategy are required to build sustainable and resilient estuarine and deltaic systems.

Both short-term and long-term strategies are urgently needed for sustainable development and use of inland as well as coastal zones. Existing modeling lacks the ability to perform timely early warnings of extreme events and accurate long-term prediction of their occurrence in coastal zones. Currently, although theories regarding two-way feedbacks between upstream activities and estuarine/deltaic environments are improving, integrated monitoring systems and engineered protections can also be beneficial, especially during short-term emergency response and treatment. Integrated planning is required for coastal megacity emergency treatments of extreme events to effectively reduce losses. Public science education can help people sustainably utilize resources and respond effectively to extreme events, such as storm surge, and flooding. Long-term integrated investigations are crucial for sustaining estuarine and deltaic environments and the ecosystem services they provide for human well-being. A well-documented database and improved modeling, offering reliable tools for short-term predictions and long-term projections, are essential for the sustainability and resilience of estuarine and deltaic services.

6 References

Anthony, E. J., Brondizio, E. S., dos Santos, V. F., Gardel, A., & Besset, M. (2021). Sustainable management, conservation, and restoration of the Amazon River Delta and Amazon-influenced Guianas coast: a review. Water, 13(10), 1371. doi: 10.3390/w13101371.

Ahmed W., Wu Y., Kidwai S., Li X., Mahmood T., Zhang J. (2021). Do Indus Delta mangroves and Indus River contribute to organic carbon in deltaic creeks and coastal waters (Northwest Indian Ocean, Pakistan)? Continental Shelf Research, 231, 104601, doi:10.1016/j.csr.2021.104601.

Bendixen M., Overeem I., Rosing M.T., Bjørk A.A., Kjær K.H., Kroon A., Zeitz G., Iversen L.L. (2019). Promises and perils of sand exploitation in Greenland. Nature Sustainability, 2 (2), 98−104, doi:10.1038/s41893-018-0218-6.

Boghosian A.L., Pitcher L.H., Smith L.C., Kosh E., Alexander P.M., Tedesco M., Bell R.E. (2021). Development of ice-shelf estuaries promotes fractures and calving. Nature Geoscience, 14 (12), 899−905, doi:10.1038/s41561-021-00837-7.

Brown, Andrew Ross, Martin Lilley, Jamie Shutler, Chris Lowe, Yuri Artioli, Ricardo Torres, Elisa Berdalet, and Charles R. Tyler. (2020). Assessing Risks and Mitigating Impacts of Harmful Algal Blooms on Mariculture and Marine Fisheries. Reviews in Aquaculture, 12 (3), 1663−1688, doi:10.1111/raq.12403.

Bussi, G., Darby, S. E., Whitehead, P. G., Jin, L., Dadson, S. J., Voepel, H. E., et al. (2021). Impact of dams and climate change on suspended sediment flux to the Mekong delta. Science of The Total Environment, 755, 142468. doi: 10.1016/j.scitotenv.2020.142468.

Chen J, Li D, Jin H, Jiang Z, Wang B, Wu B, Hao Q and Sun X, 2020. Changing nutrients, oxygen and phytoplankton in the East China Sea. In: Chen C A, Guo X (Eds.), Changing Asia-Pacific Marginal Seas. Springer Singapore, Singapore, 155-178.

Chen, Z., Yu, L., & Hu, J. (2024). Disentangling the contributions of anthropogenic nutrient input and physical forcing to long-term deoxygenation off the Pearl River Estuary, China. Water Research, 265, 122258. doi: 10.1016/j.watres.2024.122258.

Constantinescu, A. M., Tyler, A. N., Stanica, A., Spyrakos, E., Hunter, P. D., Catianis, I., & Panin, N. (2023). A century of human interventions on sediment flux variations in the Danube-Black Sea transition zone. Frontiers in Marine Science, 10, 1068065. doi: 10.3389/fmars.2023.1068065.

Creed J.C., Casares F.A., Oigman-Pszczol S.S., Masi B.P. (2021). Multi-site experiments demonstrate that control of invasive corals (Tubastraea spp.) by manual removal is effective. Ocean & Coastal Management, 207, 105616, doi:10.1016/j.ocecoaman.2021.105616.

Dada, O. A., Li, G., Qiao, L., Asiwaju-Bello, Y. A., & Anifowose, A. Y. B. (2018). Recent Niger Delta shoreline response to Niger River hydrology: Conflict between forces of Nature and Humans. Journal of African Earth Sciences, 139, 222-231. doi:10.1016/j.jafrearsci.2017.12.023.

Dell R.L., Willis I.C., Arnold N.S., Banwell A.F., de Roda Husman S. (2024). Substantial contribution of slush to meltwater area across Antarctic ice shelves. Nature Geoscience, 17 (7), 624-630, doi:10.1038/s41561-024-01466-6.

Dethier, E. N., Renshaw, C. E., & Magilligan, F. J. (2022). Rapid changes to global river suspended sediment flux by humans. Science, 376(6600), 1447 – 1452. doi: 10.1126/science.abn7980.

Duffy, K., Gouhier, T. C., & Ganguly, A. R. (2022). Climate-mediated shifts in temperature fluctuations promote extinction risk. Nature Climate Change, 12(11), 1037-1044. doi: 10.1038/s41558-022-01490-7.

Guo, X., Gao, Y., Zhang, S., Wu, L., Chang, P., Cai, W., Zscheischler, J., Leung, L. R., Small, J., Danabasoglu, G., Thompson, L., & Gao, H. (2022). Threat by marine heatwaves to adaptive large marine ecosystems in an eddy-resolving model. Nat Clim Chang, 12(2), 179-186. doi: 10.1038/s41558-021-01266-5.

Han H., Zhou F. (2025). Fusion method for water depth data from multiple sources based on image recognition. Journal of Oceanology and Limnology, doi:10.1007/s00343-024-4009-9.

Harris, J. B., Joyner, T. A., Rohli, R. V., Friedland, C. J., & Tollefson, W. C. (2020). It's all Downhill from Here: A forecast of subsidence rates in the lower Mississippi River industrial corridor. Applied Geography, 114, 102123. doi: 10.1016/j.apgeog.2019.102123.

He, D., et al. (2022). Eutrophication and watershed characteristics shape changes in dissolved organic matter chemistry along two river-estuarine transects. Water Research, 214, 118196. doi:10.1016/j.watres.2022.118196.

Hecht, J. S., Lacombe, G., Arias, M. E., Dang, T. D., & Piman, T. (2019). Hydropower dams of the Mekong River basin: A review of their hydrological impacts. Journal of Hydrology,568,285-300.doi:10.1016/j.jhydrol.2018.10.045.

Hensel MJS, Silliman BR, Van De Koppel J, Hensel E, Sharp SJ, Crotty SM, Byrnes JEK (2021). A large invasive consumer reduces coastal ecosystem resilience by disabling positive species interactions. Nature Communications, 12, 6290. doi:10.1038/s41467-021-26504-4.

Hou, X., Xie, D., Feng, L., Shen, F., & Nienhuis, J. H. (2024). Sustained increase in suspended sediments near global river deltas over the past two decades. Nature Communications, 15(1), 3319. doi: 10.1038/s41467-024-47598-6.

Hutchins, D. A., & Capone, D. G. (2022). The marine nitrogen cycle: new developments and global change. Nature Reviews Microbiology, 20(7), 401-414. doi: 10.1038/s41579-022-00687-z.

Iles CE, Samset BH, Sandstad M, Schuhen N, Wilcox LJ, Lund MT, 2024. Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways. Nature Geoscience, 17, 845–850. doi:10.1038/s41561-024-01511-4.

Itsukushima, R. (2023). Effects of climate change-induced water temperature changes on the distribution of tidal river fish fauna in the Japanese archipelago. Regional Environmental Change, 23(3), 100. doi:10.1007/s10113-023-02098-z.

Joice Silva de Souza, Ana Clara Sampaio Franco, Marcela Rosa Tavares, Taís de Fátima Ramos Guimarães, Luciano Neves dos Santos, (2024). Shipping traffic, salinity and temperature shape non-native fish richness in estuaries worldwide, Science of The Total Environment, 908, 168218. doi:10.1016/j.scitotenv.2023.168218.

Johnson, G. C., & Lyman, J. M. (2020). Warming trends increasingly dominate global ocean. Nature Climate Change, 10(8), 757-761. doi: 10.1038/s41558-020-0822-0

Karam, S., Zango, B.-S., Seidou, O., Perera, D., Nagabhatla, N., & Tshimanga, R. M. (2023). Impacts of Climate Change on Hydrological Regimes in the Congo River Basin. Sustainability, 15(7), 6066; doi:10.3390/su15076066.

Karlsrud, K., Tunbridge, L., Quoc Khanh, N., & Quoc Dinh, N. (2020). Preliminary results of land subsidence monitoring in the Ca Mau Province. Proceedings of the International Association of Hydrological Sciences, 382, 111–115. doi: 10.5194/piahs-382-111-2020

Ke S., Zhang P., Ou S., Zhang J., Chen J., Zhang J. (2022). Spatiotemporal nutrient patterns, composition, and implications for eutrophication mitigation in the Pearl River Estuary, China. Estuarine, Coastal and Shelf Science, 266, 107749. doi:10.1016/j.ecss.2022.107749.

Laignel B, Vignudelli S, Almar R, Becker M, Bentamy A, Benveniste J, Birol F, Frappart F, Idier D, Salameh E, Passaro M, Menende M, Simard M, Turki E I and Verpoorter C (2023). Observation of the Coastal Areas, Estuaries and Deltas from Space. Surveys in Geophysics. 44 (5), 1309-1356, doi:10.1007/s10712-022-09757-6

Lei S., Bu D., Guo X., Xu Y., Yang Y., An S., Li Y., Pang J., Zhou K. (2024). Mitigation of hypoxia and ocean acidification on the inner East China Sea shelf impacted by the 2023 summer drought. Marine Pollution Bulletin, 207, 116830, doi:10.1016/j.marpolbul.2024.116830.

Lenstra W.K., Hermans M., Séguret M.J.M., Witbaard R., Severmann S., Behrends T., Slomp C.P. (2020). Coastal hypoxia and eutrophication as key controls on benthic release and water column dynamics of iron and manganese. Limnology and Oceanography, 9999, 1-20. doi:10.1002/lno.11644.

Li, C., Huang, J., Liu, X., Ding, L., He, Y., & Xie, Y. (2024). The ocean losing its breath under the heatwaves. Nature Communications, 15(1), 6840. doi: 10.1038/s41467-024-51323-8

Li D., Chen J., Wang B., Jin H., Shou L., Lin H., Miao Y., Sun Q., Jiang Z., Meng Q., Zeng J., Zhou F., Cai W.J. (2024). Hypoxia Triggered by Expanding River Plume on the East China Sea Inner Shelf During Flood Years. Journal of Geophysical Research: Oceans, 129 (8), doi:10.1029/2024JC021299.

Liu, Z., Ng, A.H.-M., Wang, H., Chen, J., Du, Z., Ge, L.(2023). Land subsidence modeling and assessment in the West Pearl River Delta from combined InSAR time series, land use and geological data. International Journal of Applied Earth Observation and Geoinformation, 118, 103228. doi: 10.1016/j.jag.2023.103228

Luo, W., Shen, F., He, Q., Cao, F., Zhao, H., & Li, M. (2022). Changes in suspended sediments in the Yangtze River Estuary from 1984 to 2020: Responses to basin and estuarine engineering constructions. Science of The Total Environment, 805, 150381. doi: 10.1016/j.scitotenv.2021.150381

Ma H., Nittrouer J.A., Fu X., Parker G., Zhang Y., Wang Y., Wang Y., Lamb M.P., Cisneros J., Best J., Parsons D.R., Wu B. (2022). Amplification of downstream flood stage due to damming of fine-grained rivers. Nature Communications, 13 (1), 3054, doi:10.1038/s41467-022-30730-9.

Ma X, Meng Q, Li D, Zhu Y, Ni X, Zeng D, Di T, Huang T, Jiang Z, Jin H and Zhou F (2024). Coastal hypoxia response to the coupling of catastrophic flood, extreme marine heatwave and typhoon: a case study off the Changjiang Estuary in summer 2020. Acta Oceanologica Sinica. 43 (6), 1-12, doi:10.1007/s13131-024-2311-1

Mann P.J., Strauss J., Palmtag J., Dowdy K., Ogneva O., Fuchs M., Bedington M., Torres R., Polimene L., Overduin P., Mollenhauer G., Grosse G., Rachold V., Sobczak W.V., Spencer R.G.M., Juhls B. (2022). Degrading permafrost river catchments and their impact on Arctic Ocean nearshore processes. Ambio, 51 (2), 439—455, doi:10.1007/s13280-021-01666-z.

McCarthy M J, Otis D B, Hughes D and Muller-Karger F E (2022). Automated high-resolution satellite-derived coastal bathymetry mapping. International Journal of Applied Earth Observation and Geoinformation, 107, 102693. doi:10.1016/j.jag.2022.102693

Meng Q, Pan Y, Xuan J, Zhou F, Fan W, Di Y, Jiang Z-P, Xiao C, Zhang W, Daewel U, Chen J, Huang D and Chen Y, 2024. Leveraging Artificial Oxygenation Efficacy for Coastal Hypoxia by Taking Advantage of Local Hydrodynamics. Environmental Science & Technology, 58(49), 21629-21640, doi: 10.1021/acs.est.4c07386

Meng Q, Zhou F, Ma X, Xuan J, Zhang H, Wang S, Ni X, Zhang W, Wang B, Li D, Tian D, Li J, Zeng J, Chen J and Huang D, 2022. Response process of coastal hypoxia to a passing typhoon in the East China Sea. Frontiers in Marine Science. 9, 892797, doi:10.3389/fmars.2022.892797

Michael S. Steckler, Bar Oryan, Carol A. Wilson, Cé
line Grall, Scott L. Nooner, Dhiman R. Mondal, S. Humayun Akhter, Scott DeWolf, Steve L. Goodb
red (2022). Synthesis of the distribution of subsidence of the lower Ganges-
Brahmaputra Delta, Bangladesh, Earth-
Science Reviews, 224, 103887, doi:10.1016/j.earscirev.2021.103887

Minaieva H., Korzhov Y. (2024). Chapter 16: Forecast of changes in algocenoses richness of the dnieper floodplain after the Kakhovka Heps Dam destruction in the context of food security in southern Ukraine. 03 the European Union and Ukraine relevant regulatory, economictechnological and sociohumanitarian aspects of interaction on the way to Ukraine's membership, Izdevniecība “Baltija Publishing”, Valdeķu iela 62 – 156, Rīga, LV-1058, pp. 389—408.

Overeem I., Nienhuis J.H., Piliouras A. (2022). Ice-dominated Arctic deltas. Nature Reviews Earth & Environment, 3 (4), 225-240, doi:10.1038/s43017-022-00268-x.

Pang, T., Wang, X., Nawaz, R. A., Keefe, G., & Adekanmbi, T. (2023). Coastal erosion and climate change: A review on coastal-change process and modeling. Ambio, 52(12), 2034-2052. doi: 10.1007/s13280-023-01901-9.

Paszkowski, A., Goodbred, S., Borgomeo, E., Khan, M. S. A., & Hall, J. W. (2021). Geomorphic change in the Ganges–Brahmaputra–Meghna delta. Nature Reviews Earth & Environment, 2(11), 763-780. doi:10.1038/s43017-021-00213-4.

Pein, J., Staneva, J., Mayer, B., Palmer, M. D., & Schrum, C. (2023). A framework for estuarine future sea-level scenarios: Response of the industrialised Elbe estuary to projected mean sea

level rise and internal variability. Frontiers in Marine Science, 10, 1102485. doi: 10.3389/fmars.2023.1102485.

Raff J.L., Goodbred S.L., Pickering J.L., Sincavage R.S., Ayers J.C., Hossain M.S., Wilson C.A., Paola C., Steckler M.S., Mondal D.R., Grimaud J., Grall C.J., Rogers K.G., Ahmed K.M., Akhter S.H., Carlson B.N., Chamberlain E.L., Dejter M., Gilligan J.M., Hale R.P., Khan M.R., Muktadir M.G., Rahman M.M., Williams L.A. (2023). Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts. Nature Communications, 14 (1), 2429, doi:10.1038/s41467-023-38057-9.

Rateb, A., & Abotalib, A.Z. (2020). Inferencing the land subsidence in the Nile Delta using Sentinel-1 satellites and GPS between 2015 and 2019. Science of the Total Environment, 729, 138868. doi: 10.1016/j.scitotenv.2020.138868.

Ren J, Chen J, Xu Changlin, Van De Koppel J, Thomsen MS, Qiu S, Cheng F, Song W, Liu Q-X, Xu Chi, Bai J, Zhang Y, Cui B, Bertness MD, Silliman BR, Li B, He Q (2021). An invasive species erodes the performance of coastal wetland protected areas. Science Advances, 7, eabi8943. doi:10.1126/sciadv.abi8943.

Sampaio E, Santos C, Rosa I C, Ferreira, V, Pörtner H-O, Duarte C M, Levin L A and Rosa R (2021). Impacts of hypoxic events surpass those of future ocean warming and acidification. Nature Ecology & Evolution, 5(3), 311-321. doi:10.1038/s41559-020-01370-3.

Sengupta, D., Choi, Y. R., Tian, B., Brown, S., Meadows, M., Hackney, C. R., et al. (2023). Mapping 21st century global coastal land reclamation. Earth's Future, 11, e2022EF002927. doi:10.1029/2022EF002927.

Spergel JJ, Kingslake J, Creyts T, van Wessem M, Fricker HA (2021). Surface meltwater drainage and ponding on Amery Ice Shelf, East Antarctica, 1973–2019. Journal of Glaciology, 67(266), 985–998. doi:10.1017/jog.2021.46.

Steckler, M.S., Jaman, M.H., Grall, C.J., Goodbred, S.L., Wilson, C.A., & Oryan, B. (2024). Contribu tion of campaign GNSS toward parsing subsidence rates by time and depth in coastal Banglades h. Frontiers in Earth Science, 12, 1–15. doi: 10.3389/feart.2024.1354686

Studholme J, Fedorov AV, Gulev SK, Emanuel K, Hodges K (2022). Poleward expansion of tropical cyclone latitudes in warming climates. Nature Geoscience, 15, 14–28. doi:10.1038/s41561-021-00859-1

Sudradjat A., Muntalif B.S., Marasabessy N., Mulyadi F., Firdaus M.I. (2024). Relationship between chlorophyll-a, rainfall, and climate phenomena in tropical archipelagic estuarine waters. Heliyon, 10 (4), e25812, doi:10.1016/j.heliyon.2024.e25812.

Tsui, J. L. H., Pena, R. E., Moir, M., Inward, R. P. D., Wilkinson, E., San, J. E., Poongavanan, J., Bajaj, S., Gutierrez, B., Dasgupta, A., de Oliveira, T., Kraemer, M. U. G., Tegally, H., & Sambaturu, P. (2024). Impacts of climate change-related human migration on infectious diseases. Nature Climate Change, 14(8), 793-802. doi: 10.1038/s41558-024-02078-z.

Uber, M., Rössler, O., Astor, B., Hoffmann, T., Van Oost, K., & Hillebrand, G. (2022). Climate change impacts on soil erosion and sediment delivery to German federal waterways: A case study of the Elbe Basin. Atmosphere, 13(11), 1752. doi:10.3390/atmos13111752.

Wang, J., Tong, Y., Feng, L., Zhao, D., Zheng, C., & Tang, J. (2021). Satellite-Observed Decreases in Water Turbidity in the Pearl River Estuary: Potential Linkage With Sea-Level Rise. Journal of Geophysical Research: Oceans, 126(4), e2020JC016842. doi: 10.1029/2020JC016842

Wolanski E, Hopper C (2022). Dams and climate change accelerate channel avulsion and coastal erosion and threaten Ramsar-listed wetlands in the largest Great Barrier Reef watershed. Ecohydrology & Hydrobiology 22(2), 197-212, doi:10.1016/j.ecohyd.2022.01.001.

Xuan J., Ding R., Zhou F. (2021). Storm surge risk under various strengths and translation speeds of landfalling tropical cyclones. Environmental Research Letters, 16, 124055, doi:10.1088/1748-9326/ac3b78.

Yunus, A. P., Masago, Y., Boulange, J., & Hijioka, Y. (2022). Natural and anthropogenic forces on suspended sediment dynamics in Asian estuaries. Science of The Total Environment, 836, 155569. doi: 10.1016/j.scitotenv.2022.155569

Zamora-López A., Guerrero-Gómez A., Torralva M., Zamora-Marín J.M., Guillén-Beltrán A., Oliva-Paterna F.J. (2023). Shallow waters as critical habitats for fish assemblages under eutrophication-mediated events in a coastal lagoon. Estuarine, Coastal and Shelf Science, 291, 108447, doi:10.1016/j.ecss.2023.108447.

Zhang W., Pan S., Yu L., Zhang H., Chen F., Song G., Hu J., Wei Q., Zhao H., Chen J., Zhou F. (2025). Dissolved oxygen depletion in Chinese coastal waters. Water Research, 272, 123004, doi:10.1016/j.watres.2024.123004.

Zhao H, Zhao K, Klotzbach PJ, Chand SS, Camargo SJ, Cao J, Wu L (2024). Decreasing global tropical cyclone frequency in CMIP6 historical simulations. Science Advances, 10, eadl2142. doi:10.1126/sciadv.adl2142

Zhao, G., Jiang, W., Wang, T., Chen, S., & Bian, C. (2022). Decadal Variation and Regulation Mechanisms of the Suspended Sediment Concentration in the Bohai Sea, China. Journal of Geophysical Research: Oceans, 127(3), e2021JC017699. doi: 10.1029/2021JC017699

Zhou F, Chai F, Huang D, Wells M, Ma X, Meng Q, Xue H, Xuan J, Wang P, Ni X, Zhao Q, Liu C, Su J and Li H (2020). Coupling and decoupling of high biomass phytoplankton production and hypoxia in a highly dynamic coastal system: The Changjiang (Yangtze River) estuary. Frontiers in Marine Science. 7 (259), doi:10.3389/fmars.2020.00259

Zhou F., Chai F., Huang D., Xue H., Chen J., Xiu P., Xuan J., Li J., Zeng D., Ni X., Wang K. (2017). Investigation of hypoxia off the Changjiang Estuary using a coupled model of ROMS-CoSiNE. Progress in Oceanography, 159, 237?254, doi:10.1016/j.pocean.2017.10.008.

Zhu Q, Xing F, Wang YP, Syvitski J, Overeem I, Guo J, Li Y, Tang J, Yu Q, Gao J, Gao S, 2024. Hidden delta degradation due to fluvial sediment decline and intensified marine storms. Science Advances, 10, eadk1698. doi:10.1126/sciadv.adk1698

Zhu, B., Chu, Z., Shen, F., Tang, W., Wang, B., Wang, X.,(2019). Land subsidence (2004–2013) in Changzhou in Central Yangtze River delta revealed by MT-InSAR. Natural Hazards, 97,(1), 379-394. doi: 10.1007/s11069-019-03650-z

Section 4

Sub-chapter 5g: Seagrass meadows

1 Keynotes

Seagrass Meadows are experiencing accelerated degradation due to urbanization, pollution, and climate change, leading to a decline in extent, biodiversity and ecological function.

Seagrass Meadows play a crucial role in carbon storage, habitat provision, and water quality improvement, yet their functions are not widely recognized or fully utilized.

There is insufficient systematic monitoring, protection and restoration technologies for seagrass meadow degradation, with insufficient scientific knowledge and policy support, highlighting the need for enhanced international collaboration and capacity building.

2 Introduction

Seagrass meadows are found across all climatic zones except Antarctica(https://data.unep-wcmc.org/datasets/7)(Fig S4.5g-1), providing essential services such as carbon sequestration, climate regulation, nutrient cycling, and habitat for various marine species. Despite their importance, these ecosystems are facing alarming rates of decline, with an estimated 29% of their global extent lost since records began in 1879 (Waycott et al., 2009). The primary causes of this decline include poor water quality, physical disturbances, coastal development, and overfishing. These pressures have placed seagrass meadows among the most threatened ecosystems globally, comparable to mangroves, coral reefs, and tropical rainforests. Urgent and effective management strategies are needed to reverse this loss and preserve the critical role of seagrasses in maintaining coastal biodiversity and resilience. The sub-chapter emphasizes ecosystem-level changes in seagrass meadows from 2018-2023, covering environmental change, contributing factors, socio-economic impacts, and the knowledge gaps in addressing these changes. It focuses on condition, trends, and responses, rather than taxonomy or species diversity.

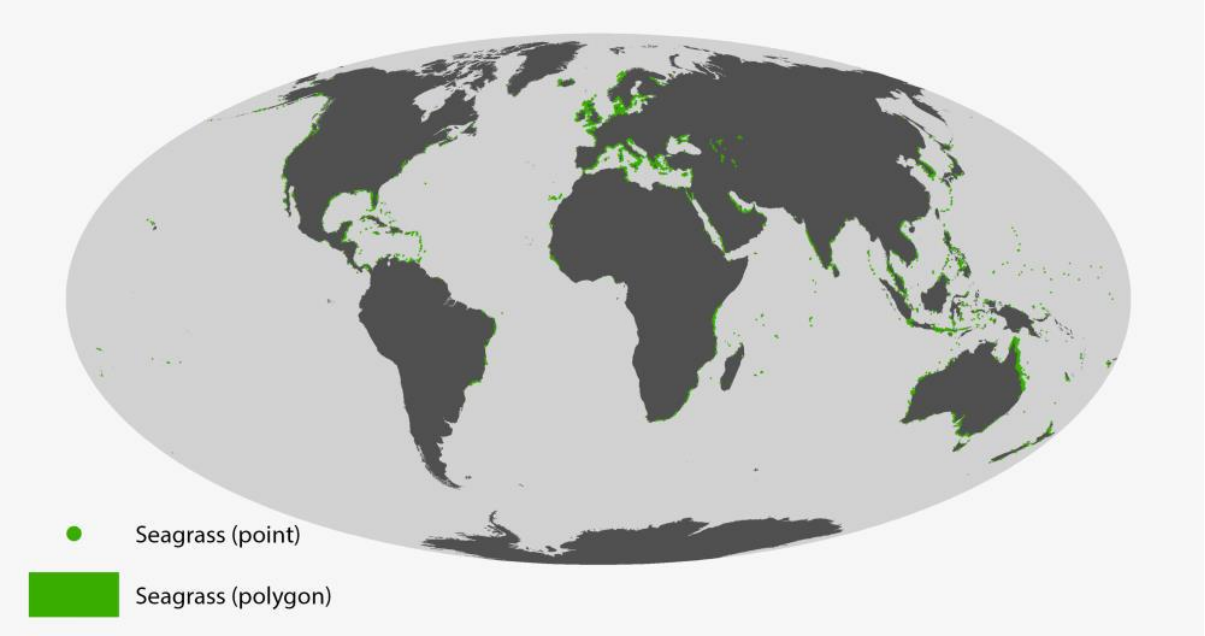


Fig S4.5g-1 Global distribution of seagrass (UNEP-WCMC & Short, 2021)

3 The environmental change since WOAII

3.1 Changes in the overall status

Estimates of the global seagrass area range between 160,387 and 266,562 km² (McKenzie et al., 2020), though measuring losses remains challenging. Dunic et al. (2021) found individual meadows lose 1-2% annually, with larger meadows (>1,000 ha) declining more slowly. Europe, North America, Japan, China and Southeast Asia face the greatest risks. Between 2000 and 2020, 60% of seagrass meadows in Southeast Asia (68 sites across nine regions) declined by 10.9% annually, while 20% increased by 8.1% annually (Sudo et al., 2021).

3.2 Factors contributing to the change observed

Seagrass decline is predominantly driven by poor water quality and coastal development (Dunic et al., 2021). Coastal development leads to both direct impacts, such as habitat loss due to port construction, and indirect impacts, like reduced light availability from sediment plumes caused by dredging activities. Light deprivation caused by nutrient-induced algal growth and sedimentation, compromises photosynthesis. Destructive fishing practices, including unsustainable bottom trawling in vulnerable habitat can also cause loss, with heavy gear damaging seagrass habitat~~Destructive fishing practices, including unsustainable trawling also cause loss, with heavy gear damaging seagrass habitat~~s. Other methods like seining and gleaning also contribute to losses in some areas (Mwikamba et al., 2024). Climate change is an increasing threat, with rising temperatures and intensified storms (Wernberg et al., 2024) leading to significant seagrass loss. Marine heatwaves and storms have already caused extensive damage (Correia & Smee, 2022;

Strydom et al., 2020). Additionally, climate change may alter the distribution of herbivores and pathogens, further impacting seagrass health (Wernberg et al., 2024). Overgrazing by herbivores, such as sea urchins and sea turtles, has led to seagrass decline in multiple regions of the Atlantic, Indian, and Pacific Oceans. Mitigating these pressures and restoring seagrass meadows is now a pressing conservation challenge. Restoration efforts, combined with addressing root causes of decline, have demonstrated potential for substantial seagrass recovery in several regions (Fernandes et al., 2022; Orth et al., 2020).

3.3 Impacts of the change on and interactions with other components of the marine system

Seagrass ecosystems are shaped by interconnected factors such as herbivory, climate change, habitat connectivity, and interspecies interactions. Rising sea temperatures and ocean acidification due to climate change affect species distribution and seagrass productivity (James et al., 2023; Becca Carretoro et al., 2022). Herbivory by sea turtles and fish plays a critical role in regulating seagrass dynamics, with shifts in herbivory patterns observed in the Mediterranean (Santana-Garcon et al., 2023). Habitat connectivity supports organism movement and genetic exchange, strengthening ecosystem resilience (De Fouw, 2018). Additionally, seagrass meadows play a crucial role in sediment storage and carbon export, which can extend hundreds of kilometers (Donatelli, 2018; Huxham et al., 2018), highlighting their importance for coastal sustainability and ecosystem health.

3.4 The social, economic and cultural aspects associated with any change

Seagrasses socially support livelihoods, especially in small-scale fisheries, ensuring food security for millions. (Unsworth et al., 2018). Economically, seagrasses protect coastlines, enhance fisheries productivity, sequester carbon, and stabilize sediment. Culturally, they are integral to Iindigenous Peoples and local traditions, shaping fishing practices, rituals, and community identities (Nordlund et al., 2016). The degradation of seagrass ecosystems disrupts biodiversity and socio-economic benefits, with reduced fisheries productivity threatening economic stability and eroding cultural ties, undermining community resilience.

Although public awareness of seagrass importance has increased (Cullen-Unsworth & Unsworth, 2018), full recognition of their value among all stakeholders remains incomplete (UNEP, 2020). However, seagrass restoration efforts are becoming more common, often involving local communities. This increased focus on seagrass has also led to their more frequent inclusion in management plans (Nordlund et al., 2018). Effective management requires a deeper understanding of seagrass dynamics and reliable baselines. Implementing policies that balance ecological, economic, and cultural needs is essential to ensuring the long-term

resilience of both ecosystems and the communities that depend on them (Unsworth et al., 2019).

In addition, programmes like the GEF-funded Dugong and Seagrass Conservation Project (https://www.dugongconservation.org/), the Convention on Migratory Species (CMS) Memorandum of Understanding (MOU) on the Conservation and Management of Dugongs and their Habitats (https://www.cms.int/dugong/en/page/mou-text-0) and the International Climate Initiative (IKI)-funded Seagrass Ecosystem Services Project (https://www.seagrasswatch.org/iki-seagrass-ecosystem/) support conservation projects in countries by promoting coordinated, international action to ensure the long-term survival of dugongs and the associated seagrass habitats they depend on.

3.5 Implications for achieving the targets of SDGs

Seagrasses contribute to several Sustainable Development Goals (SDGs), including carbon sequestration and disaster resilience (SDG 13), protection of coastal communities (SDG 11), and food and economic security (SDG 10), while promoting sustainable use (SDG 12), marine conservation (SDG 14), and partnerships (SDG 17) (United Nations, 2015). Their value was highlighted in UNEP's 2020 report *Out of the Blue: The Value of Seagrasses to the Environment and People* (UNEP, 2020). Seagrass conservation efforts, including the 2030 Seagrass Breakthrough, align with global climate commitments (UNFCCC COP28, 2023) and all ten targets listed within SDG 14. ~~However, unintended consequences of development initiatives remain a concern~~

4 Region-specific changes

4.1 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

In the Northwestern Atlantic, *Zostera marina* dominates in the north, while *Syringodium filiforme* is prevalent in the south, leading to research and restoration efforts shifting along a latitudinal gradient. While *S. filiforme* populations remain stable, *Z. marina* has experienced declines due to eutrophication, sedimentation and climate warming. In the Northeastern Atlantic, including the Baltic, Black, Mediterranean, and North Seas, research has focused on dominant species like *Z. marina* and *Posidonia oceanica*, particularly in Western Europe and the Mediterranean. Between 1869 and 2016, Europe's seagrass area saw a net loss of 35,000 hectares, though recent trends show slower losses and some gains (de los Santos et al., 2019), such as *Z. marina* recolonizing Portugal's Mira Channel (Guerrero-Meseguer et al., 2021). Restoration efforts, like the recovery of 40,000 hectares of seagrass in Chesapeake Bay, USA,

offer hope. However, in Europe, outdated or incomplete spatial data—mainly covering the Natura 2000 network—hinder accurate tracking of seagrass changes, making it difficult to assess both losses and gains comprehensively (Huber et al., 2022; Poursanidis et al., 2023).

4.3 The South Atlantic Ocean and the Wider Caribbean

Understanding of seagrass meadows in the South Atlantic Ocean and the Wider Caribbean remains limited. Although the region has historically experienced significant seagrass losses, recent trends indicate a balance, with losses matching gains. *Thalassia testudinum* forms extensive, dense, and stable beds, but when disturbed, it is replaced by faster-growing species like *S. filiforme* and *Halodule wrightii*, all classified as least concern. In 2022, a vast seagrass ecosystem, covering between 66,000 and 92,000 km², was discovered on the Bahamas Banks （Gallagher et al., 2022). Of the 18 seagrass species in the region, *Halodule bermudensis* and *Halodule ciliata* are critically endangered, with several others near threatened or vulnerable. Seagrass abundance has drastically declined across the Bermuda Platform due to overgrazing by sea turtles (Fourqurean et al., 2019). Additionally, *Halophila ovalis* and *Halophila stipulacea* are invasive species expanding in the Caribbean (Winters et al., 2020). Global climate change is also causing shifts in the distribution of some species, such as *H, wrightii* and *Halophila decipiens*, as tropicalization alters habitat conditions.

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

East Africa, with 14 recorded seagrass species, faces seagrass decline primarily due to ~~poor management of~~ destructive fishing techniques in sensitive areas, like seine net fishing~~East Africa, with 14 recorded seagrass species, faces seagrass decline primarily due to fishing intensity and destructive techniques like seine net fishing~~. The collection of gastropods and crustaceans further disturbs seagrass meadows (Chitará-Nhandimo et al., 2022; Amone-Mabuto et al., 2023; Mwikamba et al., 2024). In Maputo Bay, Mozambique, seagrass cover decreased by 33.4% between 1991 and 2023 due to anthropogenic disturbances (Amone-Mabuto et al., 2024). In Kenya, *Thalassodendron ciliatum* has experienced significant decline due to the proliferation of the sea urchin (Uku et al., 2021). In southern Mozambique, *Thalassodendron leptocaule* is considered near-threatened, while *Zostera capensis* in South African estuaries is endangered (Duarte et al., 2012; Adams & van der Colff, 2018). In the Persian Gulf and Red Sea, research gaps hinder comprehensive understanding of seagrass ecosystems, though recent studies have recorded *Halophila decipiens* in Iraqi waters for the first time, expanding known biodiversity (Ibrahim, 2024). Invasion of *Halophila stipulacea* from the Red Sea to the Mediterranean highlights ecological shifts (Nguyen et al., 2018), while unique evolutionary processes in Halophila ovalis populations in the Red Sea underscore the region's distinct

biodiversity. Additionally, the discovery of *Halophila beccarii* in Bangladesh's Bay of Bengal emphasizes the importance of continued marine assessments (Haque et al., 2024).

4.5 The North Pacific Ocean

In the Northeastern Pacific, *Z. marina* is the dominant seagrass species, ranging from the Arctic to Mexico, where it coexists with *Ruppia maritima* and the invasive *Zostera japonica*. A recent genetic split of *Zostera pacifica* from *Z. marina* leaves the population status of this species uncertain. Localized seagrass declines in this region are attributed to coastal development and eutrophication. Similarly, since 2000, ~~seagrass beds~~ seagrass beds across Southeast Asia and East Asia have experienced significant losses~~across Southeast Asia, southern mainland China, Taiwan, and the Ryukyu Islands of Japan have experienced significant losses~~, with over 60% declining at an annual rate of 10.9%, largely due to human activities and natural factors (Sudo et al., 2021). The widespread degradation of Southeast Asian seagrass ecosystems is further exacerbated by significant knowledge gaps in subtidal seagrass meadows, which limit effective conservation strategies and a persistent disconnect between scientific research, policy, and management implementation (Fortes, 2018).

4.6 The South Pacific Ocean

Seagrass meadows are found in 17 of the 22 Pacific Island Countries and Territories with the highest species richness in Papua New Guinea, which hosts 13 species. However, seagrasses remain understudied compared to coral reefs and mangroves. Recent studies from 2018-2023 highlight increasing threats to these ecosystems, particularly from coastal development, pollution, and climate change. For instance, seagrass cover in parts of Fiji and Solomon Islands has declined due to land-based pollution and destructive fishing practices. There are also emerging threats from habitat loss, with projections suggesting a 5-20% loss in seagrass habitat by 2035 (Waycott et al., 2011). Over 5% of seagrass extent has been lost in Australia since the 1930s, with substantial losses of temperate Posidonia species (Statton et al. 2018). *Posidonia australis* in parts of New South Wales is now listed as a threatened ecological community under Australian legislation. Tropical and subtropical seagrass meadows have also been lost, with substantial losses following extreme storm events with very heavy rain, causing runoff and high turbidity. Multiple restoration efforts are now underway around Australia, with success of efforts steadily improving (Sinclair et al 2021).

5 Remaining key knowledge and capacity changes and any new gaps

5.1 Key changes in knowledge, understanding gaps

A key knowledge gap recognized by seagrass scientists and managers today is how to raise societal awareness about the global significance of seagrasses, which remain relatively unknown (Unsworth et al., 2019). This is a top challenge, as increasing awareness can lead to broader support for seagrass conservation, citizen science, informed decision-making on marine biodiversity, improved funding for research and management, and ultimately a healthier planet (UNEP, 2020). Engaging the public through education and collaboration with communication experts is crucial for achieving this. While advances have been made in seagrass mapping and monitoring, particularly with remote sensing technology (Traganos et al., 2020), significant gaps remain in understanding the distribution of seagrass in the tropical Atlantic, Pacific, Indian, and Southern Oceans, particularly in deep or turbid waters. The knowledge of seagrass ecosystem services has improved in some regions, but remains incomplete in many others (Creed et al., 2023). Additionally, economic assessments are limited, often undervaluing seagrass systems. Better models linking ecological and economic factors are needed for a more integrated approach. Identifying local drivers and stressors continues to challenge targeted management efforts, and how seagrasses will adapt to climate change, particularly under the combined pressures of human activities and environmental shifts, is still poorly understood.

5.2 Key changes in capacity gaps

In addition to knowledge gaps, significant capacity gaps exist in the management of seagrass ecosystems, particularly in habitat mapping, centralized data repositories, restoration, and management frameworks.

a. Habitat Mapping and Monitoring: Accurate and updated information on seagrass distribution is essential for effective conservation. The current global seagrass map is outdated, and reports of habitat loss (Dunic et al., 2021; Sudo et al., 2021; Adi et al., 2024) highlight the need for improvement. New tools, such as drones, artificial intelligence, and cloud-based platforms, are enhancing seagrass mapping capacity, especially at regional and local scales (Malerba et al., 2023).

b. Centralized Data Repositories: As seagrass research expands, the volume of data grows significantly (Strydom et al., 2023). However, cross-platform incompatibility continues to hinder efficient data exchange. Establishing a centralized repository with a standardized framework would streamline integration and improve access to seagrass data across various platforms.

c. Restoration: Seagrass restoration is a key nature-based solution for climate change mitigation, but projects often fail due to challenges in site selection, seed germination, and maintenance (Unsworth et al., 2023). Scaling up restoration efforts requires practical, simple methods and better understanding of diverse components interaction in seagrasses to improve success rates (Orth & Heck Jr., 2023).

d. Management Framework: Effective management of seagrass ecosystems requires strong legal, policy, and planning frameworks. These vary widely across countries, from well-developed systems, like in Canada (Murphy et al., 2021), to ineffective or nonexistent policies, as seen in India and Belize (Acharyya et al., 2023; Grimm et al., 2021). Robust frameworks are necessary to allocate resources for seagrass conservation, including funding, personnel, and law enforcement.

5.3 Remaining Gaps

While significant progress has been made in understanding seagrass biology and ecology (Orth & Heck Jr., 2023), several knowledge gaps remain. Key areas include developing cost-effective technologies for habitat mapping and monitoring with improved spatio-temporal accuracy, as well as innovations in seagrass restoration techniques, from site selection to habitat maintenance. The impacts of climate change on seagrasses, particularly in temperate and tropical regions, are still not fully understood. and the role of seagrasses in carbon sequestration and emissions. Furthermore, there is a lack of coordination and transparency in global seagrass observations, which limits the collective understanding of seagrass ecosystems and the drivers of change. Making seagrass data more accessible, standardized, and easily shareable across platforms would greatly enhance efforts to better understand and conserve seagrass habitats worldwide.

6 References

Acharyya, T., Raulo, S., Singh, S., Sudatta, B. P., Srichandan, S., Baliarsingh, S. K., Samal, R. N., & Sahoo, C. K. (2023). Status and Conservation Challenges of the Second-Largest Seagrass Bed in India: Chilika Lagoon. Environmental Science and Pollution Research, 30(45), 100265–100281.

Adi, N., Marpaung, K., Haris, & Nur, R. (2024). Remote Sensing Applications in Seagrass Mapping in Southeast Asia. Environmental Monitoring, 102, 34-47.

Adi, W., Hartoko, A., Purnomo, P. W., Supratman, O., Pringgenies, D., & Hernawan, U. E. (2024). Ecological Condition of Seagrass Meadows around Sea-Based Tin Mining Activities in the Waters of Bangka Belitung Islands, Indonesia. Marine Pollution Bulletin, 209, 117151.

Al-Mansoori, N., & Das, H. S. (2024). Seagrasses of the United Arab Emirates. In J. A. Burt (Ed.), A Natural History of the Emirates (pp. 267-285). Springer Nature Switzerland.

Amone-Mabuto, M., Bandeira, S., Hollander, J., Hume, D., Campira, J., & Adams, J. B. (2024). Monitoring Seagrass Meadows in Maputo Bay Using Integrated Remote Sensing Techniques and Machine Learning. Regional Studies in Marine Science, 79.

Amone-Mabuto, M., Mubai, M., Bandeira, S., Shalli, M., Adams, J. B., Lugendo, B., & Hollander, J. (2023). Coastal Communities' Perception on the Role of Seagrass Ecosystems for Coastal Protection and Implications for Management. Ocean and Coastal Management, 244, 106811.

Bai, J., Li, Y., Chen, S., Du, J., & Wang, D. (2023). Long-time Monitoring of Seagrass Beds on the East Coast of Hainan Island Based on Remote Sensing Images. Ecological Indicators, 157.

Beca-Carretero, P., Azcárate-García, T., Teichberg, M., Patra, P., Feroze, F., González, M. J., & Winters, G. (2022). Predicted Warming Intensifies the Negative Effects of Nutrient Increase on Tropical Seagrass: A Physiological and Fatty Acid Approach. Ecological Indicators, 142.

Chitará-Nhandimo, S., Chissico, A., Mubai, M., Cabral, A., Guissamulo, A., & Bandeira, S. (2022). Seagrass Invertebrate Fisheries, Their Value Chains and the Role of LMMAs in Sustainability of the Coastal Communities—Case of Southern Mozambique. Diversity, 14(2), 170.

Correia, K. M., & Smee, D. L. (2022). A Meta-analysis of Tropical Cyclone Effects on Seagrass Meadows. Wetlands, 42(8).

Creed, J. C., Aranda, L. S., de Sousa, J. G., Brito do Bem, B. C., Dutra, B. S., de Sousa, V. E., Lanari, M., Magalhães, K. M., Magris, R. A., & Vivanco-Bercovich, M. (2023). A Synthesis of Provision and Impact in Seagrass Ecosystem Services in the Brazilian Southwest Atlantic. Sustainability, 15.

Cullen-Unsworth, L. C., & Unsworth, R. (2018). A call for seagrass protection. Science, 361(6401), 446-448.

de Fouw, J., van Der Heide, T., van Belzen, J., Govers, L. L., Sidi Cheikh, M. A., Olff, H., van De Koppel, J., & van Gils, J. A. (2018). A Facultative Mutualistic Feedback Enhances the Stability of Tropical Intertidal Seagrass Beds. Scientific Reports, 8(1).

de los Santos, C. B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C. M., Van Katwijk, M. M., … & Santos, R. (2019). Recent trend reversal for declining European seagrass meadows. Nature communications, 10(1), 3356.

Dong, J.-Y., Guo, M., Wang, X., Yang, X., Zhang, Y.-H., & Zhang, P.-D. (2023). Dramatic Loss of Seagrass Zostera Marina L. Suitable Habitat Under Projected Climate Change in Coastal Areas of the Bohai Sea and Shandong Peninsula, China. Journal of Experimental Marine Biology and Ecology, 565.

Duarte, M. C., Bandeira, S., & Romeiras, M. M. (2012). Systematics and Ecology of a New Species of Seagrass (Thalassodendron, Cymodoceaceae) from Southeast African Coasts. Novon: A Journal for Botanical Nomenclature, 22(1), 16–24.

Du, J., Chen, B., Nagelkerken, I., Chen, S., & Hu, W. (2023). Protect Seagrass Meadows in China's Waters. Science, 379, 447.

Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., & Côté, I. M. (2021). Long-term Declines and Recovery of Meadow Area across the World's Seagrass Bioregions. Global Change Biology, 27(17), 4096–4109. https://doi.org/10.1111/gcb.15684

Fernandes, M. B., Hennessy, A., Law, W. B., Daly, R., Gaylard, S., Lewis, M., & Clarke, K. (2022). Landsat Historical Records Reveal Large-scale Dynamics and Enduring Recovery of Seagrasses in an Impacted Seascape. Science of The Total Environment, 813.

Fortes, M. D., Ooi, J. L. S., Tan, Y. M., Prathep, A., Bujang, J. S., & Yaakub, S. M. (2018). Seagrass in Southeast Asia: A review of status and knowledge gaps, and a road map for conservation. Botanica Marina, 61(3), 269-288.

Fourqurean, J. W., Manuel, S. A., Coates, K. A., Massey, S. C., & Kenworthy, W. J. (2019). Decadal monitoring in Bermuda shows a widespread loss of seagrasses attributable to overgrazing by the green sea turtle Chelonia mydas. Estuaries and Coasts, 42, 1524-1540.

Gallagher, A. J., Brownscombe, J. W., Alsudairy, N. A., … et al. (2022). Tiger sharks support the characterization of the world's largest seagrass ecosystem. Nature Communications, 13, Article 6328.

Grimm, K. E., Archibald, J. L., Bonilla-Anariba, S. E., Bood, N., & Canty, S. W. J. (2023). Framework for Fostering Just and Equitable Seagrass Policy, Management, and Social-Ecological Outcomes: Lessons Learned from Belizean Marine Resource Managers. Marine Policy, 152, 105606. https://doi.org/10.1016/j.marpol.2023.105606

Guerrero-Meseguer, L., Veiga, P., Sampaio, L., & Rubal, M. (2021). Resurgence of Zostera marina in the Ria de Aveiro lagoon, Portugal. Aquatic Botany, 169, 103338.

Haque, M. A., Ullah, M. R., Hasan, M. M., Bosu, A., Yasmin, F., Islam, M. A., & Mahmud, Y. (2024). First Report of Seagrass (Halophila beccarii) from the Mid-Southern Coast of Bangladesh, Bay of Bengal. Aquatic Botany, 190, 103727.

Huber, S., Nielsen, L. T., Auluck, M., Daniel, P., Malathounis, C., Radulescu, A. S., … & Hansen, L. B. (2024). Mapping and Monitoring of Blue Ecosystems at Scale with Copernicus Sentinel-2 Imagery-a Tropical System Application. In IGARSS 2024-2024 IEEE International Geoscience and Remote Sensing Symposium (pp. 1438-1442). IEEE.

Huxham, M., Whitlock, D., Githaiga, M., & Dencer-Brown, A. (2018). Carbon in the Coastal Seascape: How Interactions Between Mangrove Forests, Seagrass Meadows and Tidal Marshes Influence Carbon Storage. Current Forestry Reports, 4(2).

Ibrahim, F. H. (2021). Mapping the Distribution and Occurrence of Four Newly Recorded Species of Seagrasses in the North-West Persian Gulf. Mesopotamian Journal of Marine Sciences, 33(1).

James, R. K., Keyzer, L. M., Van De Velde, S. J., Herman, P. M. J., Van Katwijk, M. M., & Bouma, T. J. (2023). Climate Change Mitigation by Coral Reefs and Seagrass Beds at Risk: How Global Change Compromises Coastal Ecosystem Services. Science of The Total Environment, 857.

Malerba, M. E., Costa, M. D. P., Friess, D. A., Schuster, L., Young, M. A., Lagomasino, D., Serrano, O., et al. (2023). Remote Sensing for Cost-Effective Blue Carbon Accounting. Earth-Science Reviews, 238, 104337. https://doi.org/10.1016/j.earscirev.2023.104337

McKenzie, L. J., Nordlund, L. M., Jones, B. L., Cullen-Unsworth, L. C., Roelfsema, C., & Unsworth, R. K. (2020). The global distribution of seagrass meadows. Environmental Research Letters, 15(7), 074041.

Murphy, G. E., Dunic, J. C., Adamczyk, E. M., Bittick, S. J., Côté, I. M., Cristiani, J., … & Wong, M. C. (2021). From coast to coast to coast: ecology and management of seagrass ecosystems across Canada. Facets, 6(1), 139-179.

Mwikamba, E. M., Githaiga, M. N., Briers, R. A., & Huxham, M. (2024). A Review of Seagrass Cover, Status and Trends in Africa. Estuaries and Coasts, 47(4).

Nguyen, X.-V., Kletschkus, E., Rupp-Schröder, S. I., El Shaffai, A., & Papenbrock, J. (2018). rDNA Analysis of the Red Sea Seagrass, Halophila, Reveals Vicariant Evolutionary Diversification. Systematics and Biodiversity, 16(7).

Nordlund, L. M., Koch, E. W., Barbier, E. B., & Creed, J. C. (2016). Seagrass ecosystem services and their variability across genera and geographical regions. Plos one, 11(10), e0163091.

Orth, R. J., & Heck, K. L. (2023). The Dynamics of Seagrass Ecosystems: History, Past Accomplishments, and Future Prospects. Estuaries and Coasts, 46(7), 1653–1676.

Orth, R. J., Lefcheck, J. S., McGlathery, K. S., Aoki, L., Luckenbach, M. W., Moore, K. A., Oreska, M. P. J., Snyder, R., Wilcox, D. J., & Lusk, B. (2020). Restoration of Seagrass Habitat Leads to Rapid Recovery of Coastal Ecosystem Services. Science Advances, 6(41).

Poursanidis, D., Mylonakis, K., Christofilakos, S., & Barnias, A. (2023). Mind the gap in data poor Natura 2000 sites and how to tackle them using earth observation and scientific diving surveys. Marine Pollution Bulletin, 188, 114595.

Santana-Garcon, J., Bennett, S., Marbà, N., Vergés, A., Arthur, R., & Alcoverro, T. (2023). Tropicalization Shifts Herbivore Pressure from Seagrass to Rocky Reef Communities. Proceedings of the Royal Society B: Biological Sciences, 290.

Sinclair, E. A., Sherman, C. D. H., Statton, J., Copeland, C., Matthews, A., Waycott, M., van Dijk, K.-J., Vergés, A., Kajlich, L., McLeod, I., & Kendrick, G. A. (2021). Advances in approaches to seagrass restoration in Australia. Ecological Management and Restoration, 22, 10-21.

Statton, J., Dixon, K. W., Irving, A. D., Jackson, E. L., Kendrick, G. A., Orth, R. J., et al. (2018). Decline and restoration ecology of Australian Seagrasses. In A. W. D. Larkum, G. A. Kendrick, & P. J. Ralph (Eds.), Seagrasses of Australia: Structure, Ecology and Conservation (pp. 665–704). Springer International Publishing.

Strydom, S., Murray, K., Wilson, S., Huntley, B., Rule, M., Heithaus, M., Bessey, C., Kendrick, G. A., Burkholder, D., Fraser, M. W., & Zdunic, K. (2020). Too Hot to Handle: Unprecedented Seagrass Death Driven by Marine Heatwave in a World Heritage Area. Global Change Biology, 26(6).

Strydom, S., McCallum, R., Lafratta, A., Webster, C. L., O'Dea, C. M., Said, N. E., Dunham, N., et al. (2023). Global Dataset on Seagrass Meadow Structure, Biomass and Production. Earth System Science Data, 15(1), 511–519.

Sudo, K., Quiros, T. E. A. L., Prathep, A., Luong, C. V., Lin, H.-J., Bujang, J. S., Ooi, J. L. S., Fortes, M. D., Zakaria, M. H., Yaakub, S. M., Tan, Y. M., Huang, X., & Nakaoka, M. (2021). Distribution, Temporal Change, and Conservation Status of Tropical Seagrass Beds in Southeast Asia: 2000–2020. Frontiers in Marine Science, 8, 637722.

Traganos, D., Lee, C. B., Blume, A., Poursanidis, D., Čižmek, H., Deter, J., … & Reinartz, P. (2022). Spatially explicit seagrass extent mapping across the entire mediterranean. Frontiers in marine science, 9, 871799.

Turschwell, M. P., Connolly, R. M., Dunic, J. C., Sievers, M., Buelow, C. A., Pearson, R. M., Tulloch, V. J. D., Côté, I. M., Unsworth, R. K. F., Collier, C. J., & Brown, C. J. (2021). Anthropogenic Pressures and Life History Predict Trajectories of Seagrass Meadow Extent at a Global Scale. Proceedings of the National Academy of Sciences, 118(45), e2110802118.

Uku, J., Daudi, L., Muthama, C., Alati, V., Kimathi, A., & Ndirangu, S. (2021). Seagrass Restoration Trials in Tropical Seagrass Meadows of Kenya. Western Indian Ocean Journal of Marine Science, 22(1), 1–14.

UNEP-WCMC, & Short, F. T. (2021). Global distribution of seagrasses (version 7.1). Seventh update to the data layer used in Green and Short (2003). Cambridge (UK): UN Environment World Conservation Monitoring Centre.

Unsworth, R. K. F., Bertelli, C. M., Coals, L., Cullen-Unsworth, L. C., Den Haan, S., Jones, B. L. H., Rees, S. R., Thomsen, E., Wookey, A., & Walter, B. (2023). Bottlenecks to Seed-Based Seagrass Restoration Reveal Opportunities for Improvement. Global Ecology and Conservation, 48, e02736. https://doi.org/10.1016/j.gecco.2023.e02736

Unsworth, R. K. F., McKenzie, L. J., Collier, C. J., Cullen-Unsworth, L. C., Duarte, C. M., Eklöf, J. S., Jarvis, J. C., Jones, B. L., & Nordlund, L. M. (2019). Global Challenges for Seagrass Conservation. Ambio, 48.

Waycott, M., Duarte, C. M., Carruthers, T. J., Orth, R. J., Dennison, W. C., Olyarnik, S., … & Williams, S. L. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences, 106(30), 12377-12381.

Wernberg, T., Thomsen, M. S., Baum, J. K., Bishop, M. J., Bruno, J. F., Coleman, M. A., Filbee-Dexter, K., Gagnon, K., He, Q., Murdiyarso, D., Rogers, K., Silliman, B. R., Smale, D. A., Starko, S., & Vanderklift, M. A. (2024). Impacts of Climate Change on Marine Foundation Species. Annual Review of Marine Science, 16, 247-282.

Winters, G., Beer, S., Willette, D. A., Viana, I. G., Chiquillo, K. L., Beca-Carretero, P., … & Rilov, G. (2020). The tropical seagrass *Halophila stipulacea*: Reviewing what we know from its native and invasive habitats, alongside identifying knowledge gaps. Frontiers in Marine Science, 7, 300.

Section 4
Sub-chapter 5h: Mangroves

Punyasloke Bhadury, India (Coordinating Author)

Anwesha Ghosh, India

Krishna Ray, India

Alexander Muhammad Akbar Khan, Indonesia

Agnes Wangui Muthumbi, Kenya

Li Lee Chew, Malaysia

Nasrin Azizi, Iran

Rahil Nozarpour, Iran

Jose Ernesto Mancera Pineda, Colombia

Introduction and Context

Mangroves, found mostly across the globe, represent a unique ecotone that bridges land, freshwater, ocean and atmosphere (The First World Ocean Assessment 2016; United Nations 2017). Mangroves harbor rich biological diversity and support livelihood, protect from floods, among others, amounting to economic value of at least $65 billion annually (Hagger et al., 2022). This biotope is representative of rich cultural heritages of I~~i~~ndigenous Peoples, traidtional and local communities including conservation of inter-generational ~~ITLK~~knowledges, who live along the coastlines globally (Faridah-Hanum et al., 2018; Freiss et al., 2020; Longépée et al., 2021; Moore et al., 2022). Besides, mangroves protect other coastal biotopes as well as human settlements against waves, cyclones and flooding (Trégarot et al., 2021). Geographically, mangroves are spread across 128 countries with a total coverage of approximately 147,000 km^2 area (The State of the World's Mangroves 2024). Alarmingly, only 40% of the world's remaining mangrove forests are protected, despite being a part of coastal blue carbon ecosystems and sequestering 168 g C m^{-2} y^{-1} (State of the Ocean Report 2024). On a global scale, net mangrove loss has declined to 102.4 km^2 between 2010-2020 compared to previous decade (The Second World Ocean Assessment 2021; The State of the World's Mangroves 2024).

Biodiversity of global mangroves

Globally, there has been systematic efforts towards documentation of biodiversity in the mangroves with an emphasis on mangrove plants. The Chapter 6G from the Second World Ocean Assessment Report stated 65 "valid" or correct names of mangrove plant taxa spread across 14 families and inclusive of five hybrids (The Second World Ocean Assessment 2021). As of 2024, 82 mangrove plant taxa have been reported including hybrid (Duke, 2020; Duke et al., 2023; IUCN Mangrove Specialist Group; The State of the World's Mangroves 2024). Besides, mangrove plants are covered in ~~S~~sub-chapter 4h of the present assessment, with their occurrence ~~including in~~ in estuaries and deltas ~~as discussed~~futher detailed in ~~S~~sub-chapter 5f. ~~and also share attributes with seagrass meadows (Sub chapter 5g) and salt marshes (Sub chapter 5i).~~ Mangroves are key for other biodiversity attributes such as rich fisheries (Reis-Filho et al., 2019), as well as benthic invertebrates (Sub-chapter 4c in present assessment). As part of biodiversity pool, microbiome present across diverse microniches within mangroves including plant rhizosphere, are important players in maintaining overall health, yet less documented globally (Ghosh and Bhadury 2019; Allard et al., 2020). Mangroves drive carbon budget which has been discussed extensively in Sub-chapter (Sub chapter 5b.1).

Description of environmental changes since the second World Ocean Assessment

Since the last World Ocean Assessment 2021, mangrove cover globally has shown a general decline, albeit with some exceptions. The trends in changes of mangrove cover along with potential threats have been highlighted under respective oceanic regions (Figure 1) while clearly emphasizing documented changes in mangrove cover, drivers of such changes as well as for adjacent ecosystems from designated ocean systems for the period between 2018 and 2021. In the last decade, aquaculture contributed to 21% loss of mangrove which is approximately 10% lesser compared to previous decade (The State of the World's Mangroves 2024). Sea level rise is one of the prominent factors that could affect global mangroves and it has been projected that 25% mangrove will be submerged in next five decades (IUCN Red List of Ecosystems).

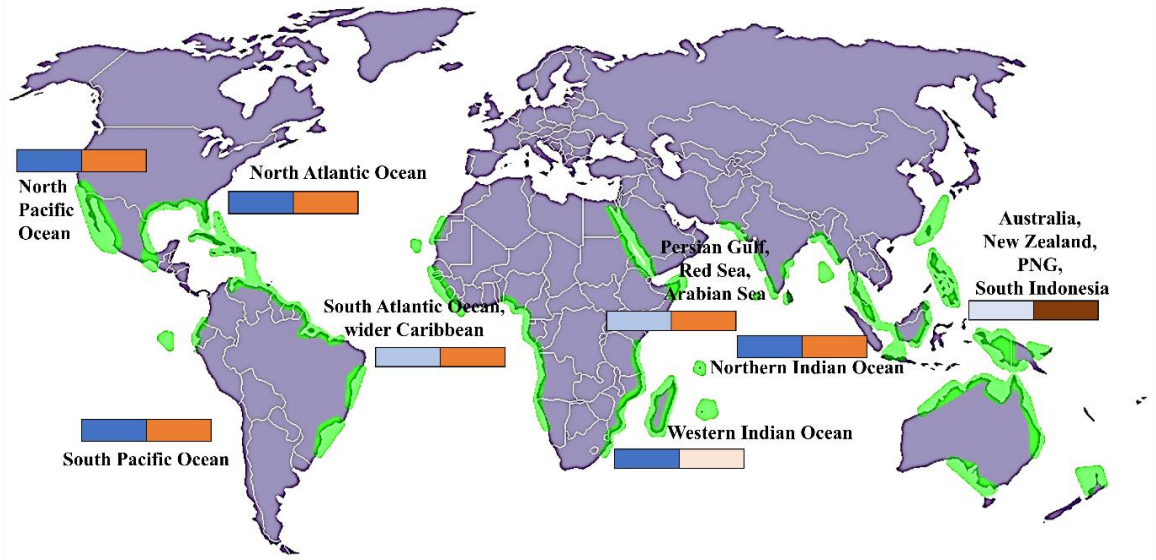


Figure 1: Causes of loss of mangrove cover across major oceanic realms; (a) light blue colour indicates anthropogenic causes not the main driver of mangrove covers (b) dark blue colour indicate effect of anthropogenic causes are pertinent; (c) orange colour indicate natural causes are the main driver of mangrove loss; (d) brown colour indicate natural causes are the sole drivers for mangrove loss.

Region specific changes reflecting the period 2018-2022

The North Atlantic Ocean (NIO)

Mangroves in the NIO region, encompassing the Caribbean, Gulf of Mexico, and parts of West Africa, have seen both positive and negative changes between 2018 and 2023. The mangroves of the northwest Atlantic Ocean have an area of approximately 17,408 km^2 (until 2020) covering 11.8% of the global mangrove. In Caribbean Sea and surrounding regions, mangrove cover has shrunk to 7000 sq. km^2 and may disappear within next few decades (Caribbean Biodiversity Fund). Until 2020, Cuba has reported an increase of 115,000 ~~hectares~~ha of mangroves (UN CEPAL 2021). The main factors that have contributed to observed changes are due to rapid coastal urbanization, pollution mainly from industrial discharge, agricultural runoff, and disposal of plastic waste. Climate change impacts such as rise in sea level and increase in frequency of storms have resulted

in erosion and submergence of mangrove habitats. Besides, changes in precipitation patterns have affected salinity and resulting stress for mangroves. Over the years conservation efforts including designation of protected areas and community-based initiatives have helped stabilise and improve mangrove area in Bahamas and Cuba. In Caribbean, mangroves are central to ecotourism, artisanal practitioners, and hold immense cultural significance, particularly for ~~I~~indigenous Peoples and Afro-descendant communities. It has been observed over the years that 4% of mangroves are showing signs of degradation and can increase to 12% in next 50 years (IUCN 2024). By 2060, 75.9% of the mangroves could get submerged ~~by 2060~~ (IUCN 2024).

The South Atlantic Ocean and the Wider Caribbean

The mangroves of the South Atlantic Ocean encompassing South America and the wider Caribbean represent around 26% global mangroves. There has been an average decline of 0.33% per year of the Caribbean mangrove area coverage of 6031.3 km^2 as per estimates of 2020 (Bunting et al. 2022). Satellite data spanning over three decades (until 2018) have shown that mangroves in Brazil are spread across 9000 km^2 (Diniz et al., 2019). The rise in sea level with a prediction of 0.4-0.6 cm, increase in salinity, change in sediment flow, geomorphic changes, along with 20-30% reduction in rainfall have resulted in loss of mangroves (Rull, 2022). Major human induced drivers are creation of shrimp farms and salt production resulting between 38-50% loss of mangroves (Diniz et al., 2019). Besides, other marine ecosystems in the region such as the Caribbean coral reefs are showing signs of bleaching due to increase in temperature as well as loss of mangroves which acted as a buffer. Overall, there has been changes due to landward migration of mangroves. The mangroves across this region have shown a net loss of 3.7% and projected to change to -6.7% for next 50 years. Approximately, 10.5% of mangrove cover would be submerged by 2060 (IUCN 2024).

~~**Mangroves of the North Atlantic Ocean**~~

~~Mangroves in the North Atlantic Oceanic region, encompassing the Caribbean, Gulf of Mexico, and parts of West Africa, have seen both positive and negative changes between 2018 and 2023. While some regions have implemented successful restoration and conservation programs, others have faced mangrove loss due to continuous anthropogenic and environmental pressures. The~~

main factors that have contributed to observed changes are from coastal development activities driven by rapid urbanization, pollution mainly from industrial discharge, agricultural runoff, and disposal of plastic waste impacting mangroves. In North Atlantic, climate change impacts such as rise in sea level and increase in frequency of storms have resulted in erosion and submergence of mangrove habitats. Besides, changes in precipitation patterns have affected salinity and resulting stress for mangroves. Over the years conservation efforts including designation of protected areas and community-based initiatives have helped stabilise and improve mangrove area coverage such as in Bahamas and Cuba. In Caribbean, mangroves are central to ecotourism, artisanal practitioners, and hold immense cultural significance, particularly for indigenous and Afro-descendant communities and loss of mangroves will result in overall loss of indigenous knowledge.

Mangroves of the South Atlantic Ocean and the wider Caribbean

The mangroves of the South Atlantic Ocean encompassing South America and the wider Caribbean represent around 26% of the total mangroves worldwide. The Caribbean mangrove extent has reduced due to natural and anthropogenic factors. There has been an average decline of 0.33% per year in the region with area coverage of 6031.3 km^2 as per estimates of 2020 (Bunting et al. 2022). Satellite data spanning over three decades (until 2018) have shown that mangroves in Brazil span across 9000 km^2 (Diniz et al 2019). The rise in sea level with a prediction of 0.4-0.6 cm, increase in salinity, change in sediment flow, geomorphic changes, along with 20-30% reduction in rainfall have resulted in loss of mangroves (Souza-Filho and Paradella 2003; Stennett-Brown et al. 2017; Taylor et al. 2018). The major human induced drivers are creation of shrimp farms and salt production resulting between 38-50% loss of mangroves (Diniz et al 2019). The overall change in mangrove cover will result in tree mortality and lowered capacity of forest regeneration owing to seed and propagule dispersion potential. Besides, other marine ecosystems in the region such as the Caribbean coral reefs are showing signs of bleaching due to increase in temperature as well as loss of mangroves which acted as a buffer. Overall, there has been changes due to landward migration of mangroves that could affect indigenous livelihood. In 2018, 13,000 traditional fishing families of Brazil were dependent on mangrove bioresources.

Indian Ocean (mangroves of the Western Indian Ocean)

The Western Indian Ocean (WIO) region has experienced significant changes in mangrove cover (2018-2023). By 2020, overall coverage mangrove forest was 745,518 ha from a total of 752,650 ha in 2018 (and 7,75,675 ha in 1996) showing a general loss of 7132 ha (0.95%) (Erftemeijer et al 2022). In Kenya and Madagascar, mangroves experienced a slight increase in coverage by 110 ha (0.2%) and 346 ha (0.12%) respectively. On the contrary, Mozambique and Tanzania experienced a loss of 6825 ha (2.2%) and 755 ha (0.68%) of mangrove cover respectively (Erftemeijer et al 2022). The increase in mangrove cover in Madagascar could be attributed to accretion and alluvial deposits as well from sustained conservation efforts (Bardou et al 2024). The loss of mangroves in Mozambique have been attributed due to cyclone impacts (Macamo et al 2016). In WIO, loss of mangrove forests is mainly due to over-exploitation including for timber and aquaculture (Nyangoko Baraka et al 2022). Pollution including from oil spills and untreated sewage are cumulatively affecting mangrove cover in WIO (Hamza et al 2022). Extreme weather events have resulted in smothering of roots and overall degradation of mangroves with die backs (Machava-António et al 2024; Ramarokoto et al 2024). The WIO mangroves are closely interlinked with seagrass meadows and coral reefs where mangroves tend to be more landward in location (Bosire et al 2012). Reduction in mangrove cover and loss of quality status could lead to loss of biodiversity (Mrabu Elisha et al 2024). Loss of mangroves in WIO had a negative impact on provision of fish and fisheries products, among others. These collectively pose challenges in achieving SDGs across WIO.

Indian Ocean (mangroves of Australia, New Zealand, Papua New Guinea and South Indonesia)

Between 2018 and 2023, mangroves of Australia have experienced both loss and recovery. The mangroves have recovered in the Great Barrier Reef due to sustained restoration. The loss of mangroves has been attributed to coastal developments. In New Zealand, mangrove cover has remained relatively stable with some areas experiencing slight expansion due to sedimentation. It has been observed that citizen awareness and adequate protection measures have helped mangrove health and coverage in New Zealand. The Papua New Guinea mangroves are facing threats from human induced drivers such as logging and mining. While there are significant losses in this country, however community led conservation have shown improvements locally

and regionally. In Indonesia which has the largest areas of mangroves, has faced severe deforestation pressures due to large scale coastal aquaculture activities in its South. Overall, mangroves of Indian countries are reeling from climate change impacts such as rise in sea level, increased sea surface temperature and increase in frequency of cyclones and hurricanes. In some areas, mangroves are expanding inland due to rising sea levels, while erosion is also continuous.

Indian Ocean (mangroves of Southeast Asia)

In Southeast Asia, Myanmar have experienced an overall increase in mangrove cover of 0.26% while the Ayeyarwady region has experienced loss of 0.95% (UN REDD- https://www.un-redd.org/). In Thailand, more than 50% of the mangrove forests which were lost until 1990s, have shown remarkable recovery through conservation with an increase in total coverage of 277,923 ha (Chaiklang et al 2024). Malaysia has lost approximately 3.3% of its mangroves from 650,000 ha in 1990s to 629,038 ha in 2017 (Omar et al 2020). Singapore, with a relatively small mangrove forest area, has remained well-managed. Based on available data until 2019, there has been a loss of 30% mangrove cover in Indonesia equivalent to the rate of 18,209 ha per year (Arifanti et al 2021). According to a separate estimate, more than 637,000 ha of mangroves have been lost in Indonesia (Nurbaya et al 2020). Deforestation pose a major threat to mangroves of Southeast Asia. Besides, conversion of mangroves for agriculture, aquaculture, among others, have also contributed towards overall (World Bank, 2019; De Albans et al. 2020). The visible impacts of climate change constitute risks to mangrove cover across the region (IPCC, 2019). Coastal fisheries and ecotourism, being the economic lifelines, are directly or indirectly dependent on the extent of mangrove forest coverage across this region (World Bank 2019). There has been regional effort towards restoration of mangroves such as the National Mangrove Rehabilitation Program of Indonesia with an aim to restore 600,000 ha of degraded mangroves by 2024 and contribute to SDG goals (Sasmito et al 2023).

Mangroves of the Indian Ocean (Bay of Bengal)

Mangroves of the Bay of Bengal is spread across east coast of India, along with Bangladesh and also parts of Myanmar (Ayeyarwady Delta and Gulf of Mottama). Over the last several years, 110 km^2 of the forest in Indian part of Sundarbans has been lost due to coastal erosion while 81 km^2 were gained based on ground level conservation such as plantation, ecological restoration

~~measures (Ray et al 2024) and regeneration (Samanta et al 2021). Pollution, in particular plastic and anthropogenic nitrogen pose risk to mangroves in this region (Kumar et al 2022; Ghosh et al 2022). Besides, conversion of mangroves for coastal aquaculture or for firewood poses challenges, in particular for Bangladesh and Myanmar. The effects of climate change such as increase in erosion, increase in land surface and sea surface temperatures, along with increase in frequency of cyclones pose challenges to this region. Cyclones such as '*Amphan*' of 2020 had an impact on 1200 km^2 area of mangroves in the Bay of Bengal (Bhargava and Friess 2022). Overall, Bay of Bengal mangroves show a net area loss of 3% (between 1996 and 2020) (Bunting et al 2022), although there is scarcity of data.~~

~~**Mangroves of the Persian Gulf, Red Sea and Arabian Sea**~~

~~Iran boasts about 240 km^2 of natural mangrove forest in Persian Gulf and Oman Sea, with 123 km^2 distributed across 30 habitats. Interestingly, mangroves of Iran have increased over the years contrary to global trends. Besides, mangrove forests in the Persian Gulf are key for carbon storage. The above-ground biomass in the Goater-Bahu habitat has an average density of 80 mg/ha, which equates to approximately 0.3 mg/ha. In general, mangroves across this region are protected and crucial for livelihoods of local communities. The effects of climate change are also evident with rise in sea level reported within the overall Persian Gulf region at a rate similar to the global average (IPCC 2021) that will affect mangrove forests. For achieving SDG targets, restoration and conservation efforts are underway including planting of 10,00,000 mangrove seedlings encompassing10,000 hectares of mangrove forest habitat in the Persian Gulf. The mangroves of Red have not diminished over the years based on satellite data (Blanco-Sacristán et al 2022). Besides, carbon sequestration values of mangroves in the Red Sea have been calculated as 1034.09 ± 180.53 Mg C yr^{-1}, and potential sequestration rate as 2424.49 ± 423.26 Mg C yr^{-1} (Blanco-Sacristán et al 2022). There are ambitious programs to plant 50 million mangroves in the Red Sea by 2030 (Redseaglobal: https://www.redseaglobal.com/).~~

The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and the Persian Gulf

Mangroves in the Indian Ocean realm have broad geographical coverage represented mostly by Western Indian Ocean (WIO) and the Northern Indian Ocean (NIO). By 2020, overall coverage mangrove forest was 745,518 ha from a total of 752,650 ha in 2018 (and 7,75,675 ha in 1996)

showing a general loss of 7132 ha (0.95%) (Erftemeijer et al., 2022). In Kenya and Madagascar, mangroves experienced a slight increase in coverage by 110 ha (0.2%) and 346 ha (0.12%) respectively. Mozambique and Tanzania experienced a loss of 6825 ha (2.2%) and 755 ha (0.68%) of mangrove cover respectively (Erftemeijer et al., 2022). The increase in mangrove cover in Madagascar is due to accretion, alluvial deposits and sustained conservation efforts (Bardou et al., 2024). Cyclones have led to the loss of mangroves in Mozambique (Macamo et al., 2016). In WIO, loss of mangrove forests is driven by timber and aquaculture activities (Nyangoko Baraka et al., 2022), along with pollution (Hamza et al., 2020). Extreme weather events have led to mangrove degradation with die backs (Ramarokoto et al., 2024). The WIO mangroves are closely interlinked with seagrass meadows and coral reefs where mangroves tend to be more landward in location (Nyangoko Baraka et al., 2022). Mangroves loss in WIO have affected fish and fisheries products, among others. The mangroves of the Red Sea and Gulf of Aden span across the Gulf of Aden, Northern and Central Red Sea, and Southern Red Sea have coverage of 189.2 km^2 and represent 0.1 % of the global mangroves. Interestingly, decrease in mangrove cover has been only around 4% over the last one decade. Moreover, 1.7% of the mangroves is undergoing degradation, with potential to increase to 5.2% within a 50-year period. Approximately 67.1% of the mangroves in this region may get submerged by 2060 (IUCN Red List Ecosystem). There have been continuous conservation efforts for mangroves of Red Sea and Gulf of Aden countries. An ambitious program to plant 50 million mangroves in the Red Sea by 2030 has been initiated (Redseaglobal: https://www.redseaglobal.com/). The carbon sequestration values of Red Sea mangroves have been calculated as 1034.09 ± 180.53 Mg C yr^{-1}, and potential sequestration rate as 2424.49 ± 423.26 Mg C yr^{-1} providing potential to tackle climate change (Blanco-Sacristán et al., 2022). Iran hosts approximately 240 km^2 of mangrove forests along the Persian Gulf and the Oman Sea, distributed across 30 distinct habitats. This reflects a gradual increase over past decades, supported by plantation and restoration efforts, as well as sediment accretion, a process increasingly influenced by climate change (Naderloo et al., 2023). Notably, over the past few decades, Iran has successfully planted around 30 km^2 of mangroves and is planning to plant an additional 10 km^2 in the coming years, with a focus on coastal restoration and climate resilience (Naderloo et al., 2023). In addition, the country has initiated the development of a National Action Plan involving a broad range of stakeholders aimed to support effective protection, scientifically informed restoration, and sustainable management of mangrove ecosystems. ~~The mangroves of Persian Gulf in Iran and~~

~~spanning up to Oman Sea with a total area of 363 km^2 are home to 30 habitats. Mangroves such as in Nayaband of Iran have expanded and found to be healthy based on satellite-based estimations (Etemadi et al., 2021). It has been reported that the surface water carbonate chemistry in mangroves of Iran may be influenced by petroleum related industrial developments which could accelerate coastal ocean acidification (Ghaemi et al., 2024).~~

The mangroves in the NIO are spread across South and Southeast Asia. The mangroves of Bay of Bengal (BoB) of NIO are represented by India, Bangladesh and Myanmar. Over the last several years, 110 km^2 of forest in Indian part of Sundarbans has been lost due to coastal erosion while 81 km^2 were gained due to plantation, ecological restoration (Ray et al., 2024) and regeneration (Samanta et al., 2021). Pollution including anthropogenic nitrogen and microplastics pose long-term risk to mangroves in this region (Ghosh et al., 2022; Kumar et al., 2022) Conversion of mangroves for coastal aquaculture or for firewood have increased over the years in Bangladesh and Myanmar. In recent years, sustainable mangrove fisheries (SMF), also known as integrated mangrove aquaculture (IMA), has been implemented in coastal aquaculture ponds which were historically part of Indian Sundarbans (Dubey 2023; The State of the World's Mangroves 2024) (Figure 2).

Figure 2: SMF/IMA pond adjacent to coastal Sundarbans, Bay of Bengal

The increase in erosion along with frequency of cyclones pose long-term challenges to this region. Cyclones such as '*Amphan*' of 2020 had an impact on 1200 km^2 area of mangroves in the BoB (Bhargava and Friess 2022). Overall, BoB mangroves show a net area loss of 3% (between 1996 and 2020) (Bunting et al., 2022), although there is scarcity of data across scales.

Myanmar have experienced an overall increase in mangrove cover of 0.26% with Ayeyarwady region experiencing a loss of 0.95% (UN REDD- https://www.un-redd.org/). In Thailand, more than 50% of mangrove forests which were lost until 1990s, have recovered based on conservation with an increase in total coverage of 277,923 ha (Chaiklang et al., 2024). Malaysia has lost approximately 3.3% of its mangroves from 650,000 ha in 1990s to 629,038 ha in 2017 (Omar et al., 2020). Singapore, with a small mangrove forest area, has remained well-managed. In NIO, aquaculture has solely accounted for 35% loss of mangroves (The State of the World's Mangroves 2024). Based on available data until 2019, approximately 30% of mangrove cover has been lost in Indonesia equivalent to 18,209 ha per year (Arifanti et al., 2021). Another estimate reported loss of 637,000 ha of mangroves in Indonesia (Nurbaya et al., 2020). Deforestation poses a major threat

to mangroves across the region. The conversion of mangroves for agriculture and aquaculture have led to decline (Ferreira et al., 2022). There has been regional effort towards restoration of mangroves such as the National Mangrove Rehabilitation Program of Indonesia aiming to restore 600,000 ha of degraded mangroves by 2024 (Sasmito et al., 2023).

Between 2018 and 2023, mangroves of Australia have experienced both loss due to coastal developments as well as recovery. In Great Barrier Reef, mangroves have recovered due to sustained restoration. In New Zealand, mangrove cover has remained relatively stable with some areas experiencing slight expansion due to sedimentation. It has been observed that citizen awareness and adequate protection measures have helped mangrove coverage in New Zealand. Contrary, in Papua New Guinea (PNG) mangroves are facing continuous threats from logging and mining while only a fraction has proper protection.

The North Pacific Ocean

In Mexico, 44,788 ~~hectares~~ha of mangrove have been lost over the last two decades (Global Mangrove Watch; Troche-Souza et al., 2023). The main drivers of such changes have been shrimp farming, urban developments, among others. In Costa Rica, significant amounts of mangroves that were lost are changing due to robust conservation practices including implementation of innovative payment for ecosystem service (PES) program (https://www.pewtrusts.org/).

The South Pacific Ocean

Although less well studied than the mangroves of North America, Southeast Asia and Australia, mangroves of the South Pacific Ocean cover large areas (approximately 11% of global mangrove cover) and probably represent a larger proportion of their coastlines. Over the last three decades, mangrove forest cover has changed in Colombia with gradual transformation of dense mangrove vegetation to other vegetation types impacting an area of 38,469 ± 2,829 ha (Murillo-Sandoval et al., 2022). Mangroves in Colombia have decreased by 48,000 ha spanning across three decades until 2020~~)~~ (Murillo-Sandoval et al., 2022). While in Ecuador, there was 4.56% loss of mangroves in previous decades, but around 2018, mangroves have recovered by 2.9% (Morocho et al., 2022). The major drivers are expanding shrimp farms, agriculture and construction activities. Fiji has lost

of 1,135 ha of mangroves over last several years (out of 65,243 ha) (Cameron et al., 2021). This is due to increasing intensity of tropical cyclones. Overall management of mangrove cover in South Pacific region has remained highly complex with lack of effective on-ground assessments (Gorman, 2018).

Remaining key knowledge and capacity change including gaps

Although earth observation technologies have had significant improvements but there is scarcity of information on loss or increase of mangrove cover (The State of the World's Mangroves 2024). New technologies such as environmental DNA (eDNA) and machine learning can fill up the gaps (Mandal et al., 2025). Regions such as BoB or South Pacific Ocean require further ground validations. Globally, mangroves also face emerging threats such as ~~from~~ coastal ocean acidification with unknown consequences for carbon sequestration (Widdicombe et al., 2023). The relative rise in sea level is expected to vary across oceanic regions (IPCC 2018) and responses of mangroves can vary. While mangrove loss is happening globally as highlighted in the ~~last World Ocean Assessment 2021~~WOA II, almost 50% of mangroves do not fall within the purview of loss alert system. As countries work towards Nationally Determined Contributions (NDCs) under the Paris Agreement 2015, among others, natural climate solutions (NCS) can help achieve these targets. Mangroves, as part of the coastal blue carbon ecosystems (CBCE) and NCS, can capture carbon although can vary regionally ~~(up to 15% of C_{org})~~, store and bring value to carbon credits (Friess et al., 2022). However, knowledge gaps and uncertainties exist for carbon credits, in addition to biodiversity credits including co-benefit sharing with I~~i~~ndigenous ~~communities~~Peoples (Faridah-Hanum et al., 2018; Stankovic et al., 2023). There has been improvement in limiting mangrove loss but human induced activities, in particular shrimp farming and coastal developments, are cumulatively magnifying diminishing trends of global coverage.

References

Arifanti VB, Kauffman JB, Subarno, Ilman M, Tosiani A, Novita N. 2021. Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia. Global Change Biology, 28, 4523-4538.

Allard, S.M., Costa, M.T., Bulseco, A.N,, Helfer, V., Wilkins, L.G.E., Hassenrück, C., Zengler, K., Zimmer, M., Erazo, N., Mazza Rodrigues, J.L., Duke, N., Melo, V.M.M., Vanwonterghem, I,, Junca, H., Makonde, H.M., Jiménez, D.J., Tavares, T.C.L., Fusi, M., Daffonchio, D., Duarte, C.M., Peixoto, R.S., Rosado, A.S., Gilbert, J.A., Bowman, J. (2020) Introducing the mangrove microbiome initiative: identifying microbial research priorities and approaches to better understand, protect, and rehabilitate mangrove ecosystems. mSystems 5, e00658-20.

Bardou, R., Friess, D. A., Gillespie, T. W., Cavanaugh, K. C. (2024). Assessing mangrove cover change in Madagascar (1972–2019): Widespread mangrove deforestation is slowing down. Global Ecology and Conservation, 53, e03022.

Bhargava, R., Friess, D.A., (2020) Previous shoreline dynamics determine future susceptibility to cyclone impact in the Sundarban mangrove forest. Frontiers in Marine Science, 9, 2022.

Blanco-Sacristán, J., Johansen, K., Duarte, C.M., Daffonchio, D., Hoteit, I., McCabe, M.F. (2022). Mangrove distribution and afforestation potential in the Red Sea. Science of the Total Environment, 843, 157098.

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R.M., Thomas, N., Tadono, T., Worthington, T.A., Spalding, M., Murray, N.J., Rebelo, L.-M., (2022) Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. Remote Sensing, 14, 3657.

Cameron, C., Maharaj, A., Kennedy, B., Tuiwawa, S., Goldwater, N., Soapi, K., Lovelock, C. E. (2021). Landcover change in mangroves of Fiji: Implications for climate change mitigation and adaptation in the Pacific. Environmental Challenges, 2, 100018.

Caribbean Biodiversity Fund, https://caribbeanbiodiversityfund.org/our-priorities/, Accessed on 5th January, 2025.

Chaiklang, P., Karthe, D., Babel, M., Giessen, L., Schusser, C. (2024). Reviewing changes in mangrove land use over the decades in Thailand: Current responses and challenges. Trees, Forests and People, 100630.

Chua, E. K. (2010). Wetlands in a city: The Sungei Buloh Wetland Reserve. Singapore: Simply

Diniz, C., Cortinhas, L., Nerino, G., Rodrigues, J., Sadeck, L., Adami, M., Souza-Filho, P. W. M. (2019). Brazilian mangrove status: Three decades of satellite data analysis. Remote Sensing, 11, 808.

Dubey, S. (2023) From conflict to co-existence: incorporation of mangrove in aquaculture. In Indian Sundarban at Crossroads: A World Mangrove Day Special Volume pp 83-99, Sundarbans Biosphere Reserve

Duke, N.C. (2020). A systematic revision of the vulnerable mangrove genus *Pelliciera* (Tetrameristaceae) in equatorial America. Blumea, 65, 107120.

Duke, N.C., Virly, S., Tracey. D. (2023). New Caledonian mangroves. A treasure to protect. Currumbin, Queensland Australia, James Cook University & MangroveWatch Publications, 210 pp.

Erftemeijer, P., de Boer, M., Hilarides, L. (2022). Status of mangroves in the Western Indian Ocean Region. Wetlands International, 1-67.

~~Etemadi, H., Smoak, J.M., Abbasi, E. (2021). Spatiotemporal pattern of degradation in arid mangrove forests of the Northern Persian Gulf. Oceanologia, 63, 99-114.~~

Ferreira, A. C., Borges, R., de Lacerda, L. D. (2022). Can sustainable development save mangroves?. Sustainability, 14, 1263.

Friess, D.A., Yando, E.S., Abuchahla, G.M.O., Adams, J.B., Cannicci, S., Canty, S.W.J, Cavanaugh, K.C., Connolly, R.M., Cormier, N., Dahdouh-Guebas. F., Diele, K., Feller, I.C., Fratini, S., Jennerjahn, T.C., Lee, S.Y., Ogurcak, D.E., Ouyang, X., Rogers, K., Rowntree, J.K., Sharma, S., Sloey, T.M., Wee, A.K.S. (2020) Mangroves give cause for conservation optimism, for now. Current Biology, 30, R153-R154.

Friess, D.A., Howard, J., Huxham, M., Macreadie, P.I., Ross, F. (2022). Capitalizing on the global financial interest in blue carbon. PLoS Climate, 1, e0000061.

~~Ghaemi, M., Bhadury, P., Gholmipur, S. (2024) Patterns of carbonate chemistry in mangroves of the Northern Persian Gulf. Regional Studies in Marine Science, 77, 103652.~~

Ghosh, A. Bhadury, P. (2020) Exploring biogeographic patterns of bacterioplankton communities across global estuaries. MicrobiologyOpen, 8, e00741.

Ghosh A, Woodward EMS, Nelson CE, Saha R and Bhadury P (2022) Nitrogen driven niche differentiation in bacterioplankton communities of northeastern coastal Bay of Bengal. Environmental Research Communications, 4, 035006.

Hagger, V., Worthington, T.A., Lovelock, C.E., Adame, M.F., Amano, T., Brown, B.M., Friess, D.A., Landis, E., Mumby, P.J., Morrison, T.H., O'Brien K.R., Wilson, K.A., Zganjar, C., Saunders, M.I. (2022) Drivers of global mangrove loss and gain in social-ecological systems. Nature Communications, 13, 6373.

https://www.iucnrle.org/ Accessed on 5th January, 2025)

Ghosh, A. Bhadury, P. (2018) Exploring biogeographic patterns of bacterioplankton communities across global estuaries. MicrobiologyOpen, 10, e741.

Gorman, D. (2018). Historical losses of mangrove systems in South America from human-induced and natural impacts. In Threats to Mangrove Forests, Hazards, Vulnerability, and Management (Eds Makowski, C., Finkl, C.W.), Springer, pp 155 - 171.

Goulding, T.C., Dayrat, B., 2023. The Coral Triangle and Strait of Malacca are two distinct hotspots of mangrove biodiversity. Scientific Reports, 13, 15793.

Hamza, A. J., Esteves, L. S., Cvitanovic, M., Kairo, J. (2020). Past and present utilization of mangrove resources in Eastern Africa and drivers of change. Journal of Coastal Research, 95, 39-44.

Faridah-Hanum, I., Rawat, G. S., Yahara, T., Abi-Said, M., Corlett, R. T., Courchamp, F., Dai, R., Freitag, H., Haryoko, T., Hewitt, C. L., Hussain, T., Kadoya, T., Maheswaran, G., Miyashita, T., Mohan Kumar, B., Mohapatra, A., Nakashizuka, T., Piggott, J. J., Raghunathan, C., Rawal, R., Sheppard, A., Shirayama, Y., Son, Y., Takamura, N., Thwin, S., Yamakita, T., Febria, C. M., Niamir, A. Chapter 3: Status, trends and future dynamics of biodiversity and ecosystems underpinning nature's contributions to people. In IPBES (2018): The IPBES regional assessment report on biodiversity and ecosystem services for Asia and the Pacific. Karki, M., Senaratna Sellamuttu, S., Okayasu, S., Suzuki, W. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on

Biodiversity and Ecosystem Services, Bonn, Germany, pp.175-264. Zenodo. https://doi.org/10.5281/zenodo.3237374

IPCC. (2018). Special report: Global warming of 1.5C. Inter-governmental Panel on Climate Change.

IPCC. (2021) In: Masson-Delmotte V, Zhai P, Pirani SL et al (eds) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jenoh, M.E., Bosire J.O., Cannicci, S., Koedam, N., Dahdouh-Guebas, F. (2024). Mangrove dieback due to massive sedimentation and its impact on associated biodiversity. Kenya Aquatica Journal, 9, 45-59.

Kairo, J. G., Mangora, M. M., Network, W. I. O. M., Western Indian Ocean Marine Science Association. (2020). Guidelines on Mangrove Ecosystem Restoration for the Western Indian Ocean Region-Western Indian Ocean Ecosystem Guidelines and Toolkits.

Kumar, R., Sinha, R., Rakib, M.R.J., Padha S., Ivy, N., Bhattacharya, S., Dhar, A., Sharma, P. (2022). Microplastics pollution load in Sundarban delta of Bay of Bengal. Journal of Hazardous Materials Advances, 7, 100099

Kusmana, C. (2014) Distribution and current status of mangrove forest in Indonesia. In: Hanum IF, Hakeem ALKR, Ozturk M (eds) Mangrove ecosystems of Asia: status, challenges, and management strategies. Springer, New York, pp 37–60.

Longépée, E., Ahmed Abdallah, A., Jeanson, M., Golléty, C. (2021). Local ecological knowledge on mangroves in Mayotte Island (Indian Ocean) and influencing factors. Forests, 12, 53.

Macamo C.C.F., Massuanganhe, E., Nicolau D.K., Bandeira S.O., Adams, J.B. (2016). Mangrove's response to cyclone Eline (2000): What is happening 14 years later. Aquatic Botany, 134, 10-17

Mandal, A., Ghosh. A., Kumar, G., Bhadury, P. (2025) Dataset of benthic foraminiferal community structure from sediment eDNA of Sundarbans mangrove ecosystem. Data in Brief, 60, 111554.

Moore, A.C., Hierro, L., Mir, N., Stewart, T. (2022) Mangrove cultural services and values: current status and knowledge gaps. People and Nature, 4, 1083-1097.

Ministry of Environment and Forestry Republic of Indonesia. The State of Indonesia's Forests 2020. Nurbaya S, Efransjah, Murniningtyas S, Erwinsyah, Damayanti EK, editors. The State of the World's Forests 2020. Jakarta, Indonesia: Ministry of Environment and Forestry, Republic of Indonesia; 2020.

Elinasi, M., Mangora, M.M., Mayunga, J.S. (2024). Mangrove cover change detection in the Rufiji Delta in Tanzania. WIO Journal of Marine Science, 17, 1-10

Morocho, R., González, I., Ferreira, T. O., Otero, X. L. (2022). Mangrove forests in Ecuador: A two-decade analysis. Forests, 13, 656.

Murillo-Sandoval, P. J., Fatoyinbo, L., Simard, M. (2022). Mangroves cover change trajectories 1984-2020: The gradual decrease of mangroves in Colombia. Frontiers in Marine Science, 9, 892946.

Naderloo, R., Shahdadi, A., Rahimian, H., Shojaei, M.G., & Nasrolahi, A. (2023). Atlas of Sensitive Marine Ecosystems of the Persian Gulf and Gulf of Oman. Tehran University Press.

Nyangoko, B. P., Shalli, M. S., Mangora, M. M., Gullström, M., Berg, H. (2022). Socioeconomic determinants of mangrove exploitation and management in the Pangani River Estuary, Tanzania. Ecology and Society, 27,

Nurbaya, S., Efransjah, Murniningtyas S, Erwinsyah, Damayanti, E.K., editors. The State of the World's Forests 2020. Jakarta, Indonesia: Ministry of Environment and Forestry, Republic of Indonesia.

Omar, H., Misman, M. A., Ismail P. Status of Mangroves in Malaysia. 2020. Rahman, Lokollo, F. F., Manuputty, G. D., Hukubun, R. D., Krisye, Maryono, ... Wardiatno, Y. (2024). A review on the

biodiversity and conservation of mangrove ecosystems in Indonesia. Biodiversity and Conservation, 33, 875-903.

https://www.pewtrusts.org/en/research-and-analysis/articles/2021/07/26/costa-rica-ensures-future-for-its-mangrove-forests accessed on 5th January, 2025.

Ray, K., Basak, S.K., Giri, C.K., Kotal, H.N., Mandal, A., Chatterjee, K., Saha, S., Biswas, B., Mondal, S., Das, I., Ghosh, A., Bhadury, P. (2024) Ecological restoration at pilot-scale employing site-specific rationales for small-patch degraded mangroves in Indian Sundarbans. Scientific Reports 14, 12952.

Ramarokoto, S., Raharijaona, L., Ravonjimalala, H. R., Randriamalala, J. (2024). Relative importance of local and regional/global drivers of mangrove degradation and deforestation in Madagascar. Regional Environmental Change 24(2):1-12 DoI: 10.1007/s10113-024-02247-y

Rémi, B., Friess, D.A., Gillespie, T.W., Cavanaugh, K.C. (2024). Assessing mangrove cover change in Madagascar (1972–2019): Widespread mangrove deforestation is slowing down. Global Ecology and Conservation, 53, e03022

Reis-Filho, J.A., Harvey, E.S., Giarrizzo, T. (2019). Impacts of small-scale fisheries on mangrove fish assemblages, ICES Journal of Marine Science, 76, 153–164.

Rull, V. (2022). Responses of Caribbean mangroves to Quaternary climatic, eustatic, and anthropogenic drivers of ecological change: a review. Plants, 11, 3502.

Sasmito, S.D., Basyuni, M., Kridalaksana, A., Saragi-Sasmito, M.F., Lovelock, C.E., Murdiyarso, D. (2023) Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. Nature Ecology and Evolution, 7, 62-70.

Samanta, S., Hazra, S., Mondal, P. P., Chanda, A., Giri, S., French, J. R., Nicholls, R. J. (2021). Assessment and attribution of mangrove forest changes in the Indian Sundarbans from 2000 to 2020. Remote Sensing, 13, 4957.

Stankovic, M., Mishra, A.K., Rahayu, Y.P., Lefcheck, J., Murdiyarso, D., Friess, D.A., Corkalo, M., Vukovic, T., Vanderklift, M.A., Farooq, S.H., Gaitan-Espitia, J.D. (2023). Blue carbon

assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. Science of the Total Environment, 904, 166618.

State of the Ocean Report (2024). Eds Enevoldsen, H., Isensee, K., Jie, L.Y., International Oceanographic Commission Technical Series, 190, 88 pp.

The First World Ocean Assessment (2016) United Nations Office of Legal Affairs, pp 570

The Second World Ocean Assessment (2021) United Nations Office of Legal Affairs, pp 1086

The State of the World's Mangroves 2024 (2024). Eds Leal, M., Spalding, M.D. Global Mangrove Alliance, pp 71

Trégarot, E., Caillaud, A., Cornet, C. C., Taureau, F., Catry, T., Cragg, S. M., Failler, P. (2021). Mangrove ecological services at the forefront of coastal change in the French overseas territories. Science of the Total Environment, 763, 143004.

Troche-Souza, C.H., Velázquez-Salazar, S., Cruz-López, M.I., Rodríguez-Zúñiga, M.T., Alcántara-Maya, J.A., Vázquez-Balderas, B., Valderrama-Landeros, L., Villeda-Chávez, E. Ressl, R. (2023). Comments on Acosta-Velázquez et al. changes in mangrove coverage classification criteria could impact the conservation of mangroves in Mexico. Land Use Policy, 2023, 129, 106651. *Land Use Policy*, 134, 106883.

UN-REDD https://www.un-redd.org/ accessed on 10th January, 2025

Yudha, R. P., Sugito, Y. S., Sillanpää, M. Nurvianto, S. (2021). Impact of logging on the biodiversity and composition of flora and fauna in the mangrove forests of Bintuni Bay, West Papua, Indonesia. Forest Ecology and Management, 488, 119038.

Zöckler, C. Aung, C. (2019). The mangroves of Myanmar. Sabkha Ecosystems: Volume VI: Asia/Pacific, 253-268.

Section 4

Sub-chapter 5i: Salt marshes

Contributors: Judith S. Weis[1] (coordinating author), Yuan Li[2], Luís Pinheiro[3], and Katherine E. A. Segarra[4],

1. Rutgers University, Newark NJ. U.S.

2. Yantai Inst. Of Coastal Zone Research, Chinese Academy of Sciences

3. University of Algarve, Portugal

4. U. S. Department of the Interior, United States.

1 Keynotes

- Salt marshes are extremely valuable ecosystems that continue to be lost worldwide, due primarily to sea level rise and development.
- Techniques are being developed to restore and rehabilitate marshes; some have shown encouraging results.
- Salt marshes are also damaged by pollution and invasive species.

2 Introduction

Salt marshes are among the most valuable ecosystems on Earth (Costanza et al., 1997), providing ecosystem services, including habitat for many species, protection from storms and flooding, "blue carbon" and nitrogen storage. They face many stressors, including sea level rise (SLR) and development, and are in global decline. Currently, only 21.8% of global salt marshes are inside marine protected areas (MPAs) (Figure 1) (Mcowen et al., 2017), where human activities are restricted, with about 7.5% included in UNESCO's Marine World Heritage sites (Fu et al., 2024a). Worthington et al. (2024) estimated their global extent in 2020 to be 52,880 km^2 distributed across 120 countries and territories with 45% in the temperate Northern Atlantic region. There have been some recent reviews about their status (Armitage 2021, Petillon et al, 2023, He et al, 2025.

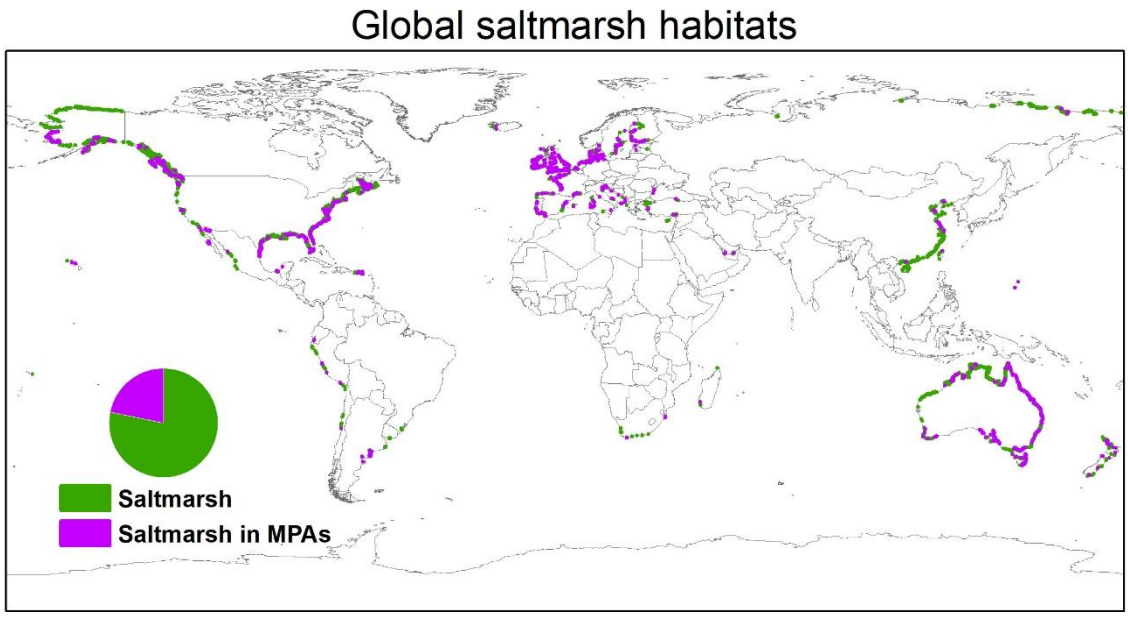


Figure 1. Global distribution of salt marsh ecosystems, including those in marine protected areas (MPAs).

2.1 Climate Change

Climate change poses the most severe threat to salt marshes worldwide. Marshes must either increase elevation at a greater rate than SLR or move inland, which is possible only when there is open land behind them. In developed areas with roads and buildings, marshes cannot move inland and are subject to "coastal squeeze," eventually being submerged. Nicholls et al. (1999) estimated that 1 meter of SLR would eliminate 46% of the world's coastal wetlands.

Rates of SLR are exacerbated in regions with considerable subsidence (Ohenhen et al. 2024) increasing relative SLR and reducing marsh ability to elevate fast enough. Some marshes have inadequate sediment supply (Ensign et al., 2023) or limited landward migration because of steep slopes (Thorne et al., 2018). It is further hindered by sea walls, groins, etc.

It has been recently realized that historical farming practices cause problems, especially when associated with SLR. Straight lines of flood-tolerant *Spartina alterniflora* have appeared in the high marsh. These lines may criss-cross each other, forming a network, inside which are "waffle pools" in which water does not drain. Adamowicz et al. (2020) realized that past agricultural practices of ditching and berms, combined with SLR, were responsible; tidal water now floods the high marsh plants which die and are replaced with shallow pools that expand into "megapools."

2.2 Development

Tidal wetlands have been filled for agriculture and urban development without regard for their ecological value. "Reclamation" involves dike installation blocking entry of tidal water, allowing land to dry out and be developed. A recent increase of 18.7% in China's coastal salt marsh area between 2010 and 2019, driven by stricter reclamation policies adopted in 2018, has begun to reverse a long-term net loss of 23.7% from 1985 to 2019 (Chen et al., 2022).~~The areal extent of salt marsh in China decreased from the 1980s to 2010s, with an overall 59% decline in area (Gu et al., 2018) and in native salt marsh grasses (Chen et al., 2022).~~ These reductions were attributed to SLR, pollution, and conversion to agriculture, aquaculture, salt pans, and urban development (Gu et al., 2018; Chen et al., 2022; Fu et al., 2024a). Similar losses to development are seen in Europe and America.

2.3 Bioturbation

The purple marsh crab *Sesarma reticulatum* causes extensive marsh damage by herbivory and bioturbation and causes loss in carbon stocks in US east coast marshes (Wittyngham et al., 2024). *Sesarma* "fronts" reduce elevation causing a transition from high to low marsh (Vu et al., 2017). Martinez-Soto and Johnson (2023) found that in the northern range into which fiddler crabs expanded, *Spartina* biomass was reduced when they were present. Studies in the native range also find negative effects: Smith and Green (2015) found fiddler crab bioturbation caused sediment loss, as excavated sediments on the surface wash away with outgoing tides. Raposa et al. (2018) found negative effects of burrows near creekbanks, where erosion increased.

2.4 Protecting and rehabilitating marshes

Efforts to protect and restore salt marshes are effective in reducing decline or even increasing areal extent. Billah et al. (2022) reviewed publications from 1990-2021 on restoration techniques and success indicators in North America, Europe, China, and Oceania. They found the most common techniques are recovery of tidal exchange, managed realignment, creation of marshland with dredged material, and control of invasive grasses. Indicators of success included structural diversity, ecosystem functions, physical condition, and species composition. They stressed that soil and plant succession functions may recover in weeks to years while carbon storage capacity may take up to a century to recover. Raposa et al. (2024) investigated if removing upland vegetation behind marshes facilitates marsh migration. One-time removal provided little benefit; they suggested that repeated removals might be required.

Applications of thin layers of sediment over marsh (Thorne et al., 2019) can improve plant health and recruitment. As canopy density grows, sediment trapping increases and might become self-maintaining. Adequate sediment supply is essential for sustaining habitats and may promote

accumulation of mineral-associated carbon (Fu et al., 2024b; Li et al., 2023). In Poplar Island, Chesapeake Bay US, where sediments had been added, Staver et al. (2024) used > 10 years of data and found that elevation change in the low marsh was double the high marsh rate and exceeded the natural reference marsh and relative SLR. The increase was due mostly to belowground biomass, which contributed more than surface sediment. By stimulating organic matter production and elevation change, the substrate apparently offset the low supply of sediment. Adding sediments to increase elevation is essential to long-term sustainability.

It is possible to create marshes where they previously did not exist. Stewart et al. (2024) observed recession in about half the marsh creation projects in British Columbia, Canada, representing 9.3% of the created marsh surveyed. They attributed losses to boat wake erosion and goose herbivory. Greater recession was found upriver, as was reduced dominance of native species. These remedies are much less effective than creating policies to stop filling in marshes for development.

2.5 Invasive Species (S4.C6sub1) The common reed, *Phragmites australis* (Saltonstall, 2002) arrived on the East Coast of North America over a century ago and invaded many brackish and freshwater marshes. It has become a dominant species in North America, reducing plant diversity, altering patterns of water flow, and causing sediment accumulation (Windham and Lathrop, 1999). It also is beneficial in sequestering contaminants (Zhang et al. 2023) and enabling marshes to increase their elevation. It is more likely to establish at low salinity and sites where rhizomes are buried in well-drained marsh areas (Bart et al., 2006). Millions of dollars are spent annually to remove it, but it inevitably returns.

As a mirror-image, since its introduction to coastal China in the 1960s, *Spartina alterniflora* has thrived remarkably, covering a latitudinal span of about 21 degrees from 40°47'N to 19°46'N along the coastline. By 2020, it had expanded across 519.70 km^2 (Li et al., 2022) reducing biodiversity and posing threats to artisanal fisheries and tourism (Qi and Chmura, 2023). By 2023, China had initiated nearly 200 projects to manage *S. alterniflora*, utilizing technologies like “mowing + flooding”, “mowing + plowing” and “mowing + shading.”

Salt marshes may also be damaged by non-native animals. Hogs in southeastern U.S. marshes reduce soil carbon storage and alter community structure (Persico et al. 2017; Hensel et al. 2021, Fischman et al. 2024). In addition to disturbing cordgrass by severing roots, creating wallows, and overturning grass and soil clumps, hogs consume mussels (Hensel et al. 2021b). In Ireland, cessation of cattle grazing was associated with an increase in salt marsh invertebrate biodiversity (Lynch 2022).

2.6 Pollution (S4.C6.sub5)

Marsh plants take up high concentrations of toxic metals from contaminated sediments. Metals of concern include mercury (Hg), cadmium (Cd), lead (Pb), and copper (Cu), which can bioaccumulate and cause toxicity. Metals in marsh sediments are affected by the presence of different plant species. Their concentrations in bare sediments were lower than vegetated "rhizosediment" in the Swartkops Estuary, South Africa (Nel et al., 2022).

Oil can have long term effects on salt marshes once it sinks down below the surface and cannot "weather." Effects can persist decades after a spill (Culbertson et al. 2007).

Large amounts of debris accumulate in tidal wetlands and other shorelines coming from both water (fishing gear, abandoned boats) and land (garbage, litter). In Brazil marshes, Pinheiro et al. (2021) found more litter in the high marsh where the water rarely reaches, than the middle and low marsh. Most items were plastic, from food packaging, fishery and shipping activities, and personal use. Plastics in coastal wetland sediments reach 156.7 items kg^{-1}, 200 times higher than in the water column (Ouyang et al., 2022). Variation depends on climatic and geographic zones, season, population density, and waste management. Tidal wetlands contain very high concentrations of microplastics, with greater amounts in urbanized areas (Lloret et al., 2021).

3 The environmental change since WOAII

3.1 Changes in the overall status

Since the last World Ocean Assessment, marshes continued to lose ground, though reported rates vary. A NASA satellite study (Campbell et al., 2022) found overall global loss equivalent to two soccer (football) fields per hour or 0.28 % per year (Figure 2). In contrast, a study of tidal wetlands (salt marshes, tidal flats and mangroves) found a net loss of only 4000 km^2 over two decades (Murray et al., 2024). Coastal erosion and hurricanes accelerate marsh loss. Observed substantial reductions were primarily attributed to sea level rise, pollution, and conversion to agriculture, aquaculture, salt pans, and urban development (Gu et al., 2018; Chen et al., 2022).

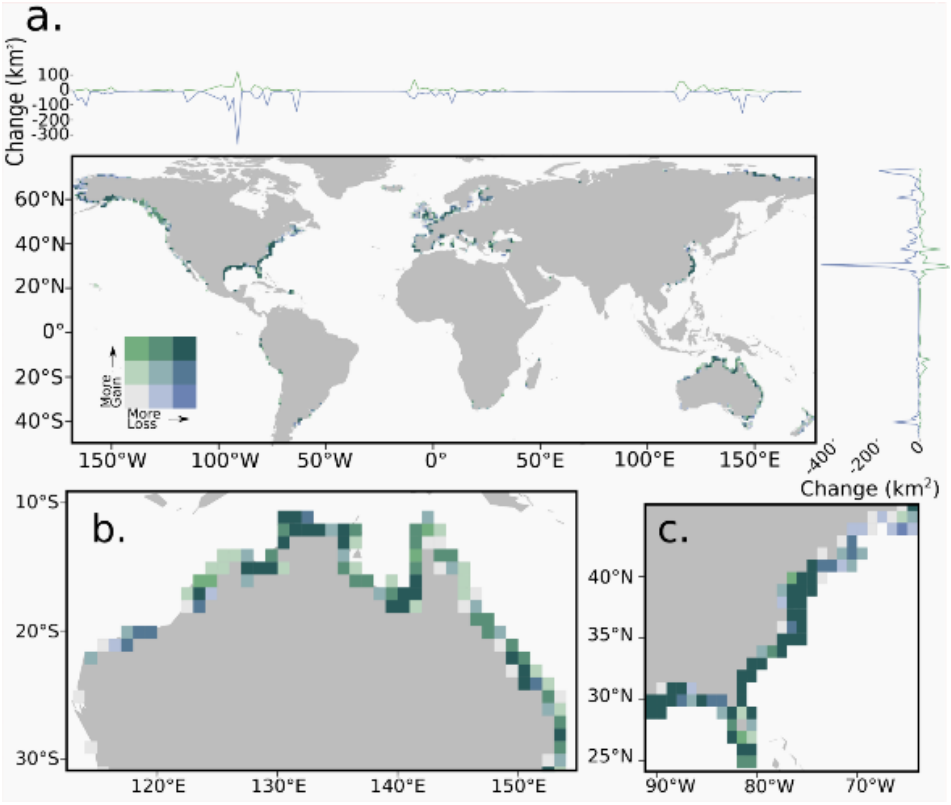


Figure 2. **a**, Global salt marsh loss and gain map between 2000–2019 visualized with a three-quantile bivariate colour ramp. Line plots of gain and loss (km^2) by longitude and latitude. **b**, Salt marsh gain and loss in Northern Australia. **c**, Salt marsh gains and losses across the Atlantic coast and the Gulf of Mexico.

4 Region-specific changes

4.1 The Arctic Ocean

Arctic salt marshes occur west of the Alaska Peninsula along the Bering Sea coastline and extend across Alaska's Coastal Plain and the Arctic coastline of Canada. They are under pressure from climate change, coastal erosion, severe storms, changes in sea ice, and increased industrial activities offshore, including oil-drilling. From 2015 - 2019, there were 279.4 ± 35.9 km^2 and 5.6 ± 1.0 km^2 of salt marsh loss and gain in Russia, respectively (Campbell et al., 2022). Lack of knowledge and mapping prevents accurate quantification and leads to underestimating global soil organic carbon stocks, estimated at 1.44 Pg C in the top meter of tidal marsh soils globally. Ward (2020) found low carbon stocks in salt marshes in Norway, likely due to historical isostatic uplift and sediment accretion outpacing sea level rise.

4.2 The European Baltic Sea, Northeast Atlantic Ocean, Mediterranean Sea and Black Sea

Salt marsh loss is attributed mostly to reclamation. The area lost, primarily in the European region, 2015-2019 was 103.2 ± 13.3 km^2 which was offset by 64.2 ± 11.3 km^2 of gain (Campbell et al., 2022)

4.3 The South Atlantic Ocean and the Wider Caribbean

Salt marshes in South America are mostly on the Atlantic coast, with over 95% of them in Argentina (Martinetto et al. 2023). These authors also found that these marshes store about 42.43 mg $OC \cdot ha^{-1}$ (40.74 belowground) and bury about 47.62 g $OC \cdot m^{-2} \cdot yr^{-1}$. In South Africa, approximately 43% of salt marsh has been lost to development and agriculture from 1930-2018 (Adams, 2020). At their equatorial end, salt marshes are losing ground to mangroves (S4.C5h) which are moving north due to climate change (Santilan et al., 2013). Mangroves may provide increased storm protection and carbon storage (Doughty et al., 2016; Dontis et al., 2020) but may also cause decline in habitat for some animals.

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf, Strait of Malacca and the South China Sea

Salt marsh extent in India is estimated as 290 km^2 (Viswanathan et al., 2020) and are considered an Ecologically Sensitive Area under the Coastal Regulation Zone with some designated as Ramsar Sites. Although salt marshes are present in the Arabian Sea (Almahasheer, 2021, there are currently no area estimates for the region.

4.5 The North Pacific Ocean

Chen et al (2022) found salt marshes in China declined from 151,324 ha in 1985 to 115,397 ha in 2019, a drop of 23.7%. During the last decade, Chinese socioeconomic reforms and stricter environmental regulations have significantly decreased the contributions of anthropogenic metals in saltmarshes (Fu et al., 2023). The contribution of black carbon derived from fossil fuel combustion (mean 80%) to the total organic carbon in saltmarsh soils is as high as 20% (Li et al., 2021).

4.6 The South Pacific Ocean

Salt marshes in Oceania showed a net loss of 32.1 km^2 from 2015-2019, primarily due to reclamation for agriculture and urban development in Australia.

4.7 The Southern Ocean

Salt marshes are not found in Antarctica.

5 Remaining key knowledge and capacity changes and any new gaps

Salt marshes are being lost worldwide due to sea level rise and continued development. There are ways to adapt to rising sea levels and preserve marshes with engineering practices (living shorelines, thin-layer deposition), and restore or create new marshes, but legal and policy changes are needed to curtail development (Weis et al., 2021).

Roads or houses immediately upland of a marsh prevent migration and cause "coastal squeeze." These houses are likely to be frequently flooded; some homeowners will be ready to move. In such situations, marsh migration pathways could be created, opening space for the marsh. This can be facilitated by agreements to move away via easements, land acquisition, buyouts, etc., where people receive compensation. Such agreements could be with whole neighborhoods; success will require efforts by planners and social workers, since people may be low income, feel attached to their neighborhood, and want to stay despite the risks (van Dolah et al., 2020).

As marsh edges erode, losses can be reduced by placing hard structures, such as oyster reefs or rocks near the eroding edge, making a "living shoreline." Challenges include site-specific factors (marshes are not all the same), weather (Currin et al., 2017), performance standards (Sutton-Grier et al., 2015), and regional norms (Zhu et al., 2020; Morris et al., 2019). Living shorelines generally succeed if they can persist past their initial stages. Thin channels ("runnels") can be dug to connect pools to tidal creeks to drain them, provided the creek has lower elevation than the pool (Watson et al., 2022).

More work is needed to understand effects of increased temperature on marsh structure and function (Duarte et al 2021). While oil and chemical contaminants are decreasing due to environmental policies, plastic pollution continues unabated. If marshes are to continue through this century, nations should take proactive steps to preserve and protect them. To reduce plastics, nations should ban single-use plastics, restrict plastic uses, put the burden of disposal and recycling on the plastic industry, not on government or individuals (Brander et al., 2024).

6 References

Adamowicz, S., Wilson, G., Burdick, D, Ferguson, W., Hopping, R. 2020. Farmers on the Marsh: Lessons from History and Case Studies for the Future. Wetland Science and Practice, 37, 183-195, ISSN 19436254. https://issuu.com/societyofwetlandscientists/docs/july_2020_wsp.

Adams, J. (2020). Salt marsh at the tip of Africa: Patterns, processes and changes in response to climate change. Estuarine, Coastal and Shelf Science, V. 237, 106650. https://doi.org/10.1016/j.ecss.2020.106650

Almahasheer, H. (2021). Assessment of coastal salt marsh plants on the Arabian Gulf region. Saudi Journal of Biological Sciences 28, 5640–5646. https://doi.org/10.1016/j.sjbs.2021.06.002

Armitage, A.R. 2021. Perspectives on Maximizing Coastal Wetland Restoration Outcomes in Anthropogenically Altered Ecosystems. *Estuaries and Coasts* **44**, 1699–1709. https://doi.org/10.1007/s12237-021-00907-4

Bart, D., Burdick, D., Chambers, R., Hartman, J.M. 2006. Human facilitation of invasions in tidal marshes: A review and synthesis. Wetlands Ecology and Management, 14, 53–65. https://doi.org/10.1007/s11273-005-2566-z.

Billah, M.M., Bhuiyan, M.K.A., Islam, M.A., Das, J., Hoque, A.R. 2022. Salt marsh restoration: an overview of techniques and success indicators. Environmental Science and Pollution Research, 29, 15347-15363. https://doi.org/10.1007/s11356-021-18305-5.

Brander, S. M., Senathirajah, K., Fernandez, M. O., Weis, J. S. et al. 2024. The time for ambitious action is now: Science-based recommendations for plastic chemicals to inform an effective global plastics treaty. Science of The Total Environment, 949, 174881. https://doi.org/10.1016/j.scitotenv.2024.174881.

Campbell, A., Fatoyimbo, L., Goldberg, L., Lagomasino D. 2022. Global hotspots of salt marsh loss and carbon emissions. Nature, 612, 701-706. https://doi.org/10.1038/s41586-022-05355-z.

Chen, G., Jin, R., Ye, Z., Li, Q., Gu, J., Luo, M., Luo, Y., Christakos, G., Morris, J., He, J., Li, D., Wang, H., Song, L., Wang, Q., Wu, J. 2022. Spatiotemporal mapping of salt marshes in the intertidal zone of China during 1985–2019. Journal of Remote Sensing, 2022, 9793626. https://doi.org/10.34133/2022/9793626.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., et al. 1997. The value of the world's ecosystem services and natural capital. Nature, 387, 253-260. https://doi.org/10.1038/387253a0.

Culbertson, J., Valiela, I., Peacock, E., Reddy, C et al. 2007. Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. Mar poll Bull 54 : 955-962. https://doi.org/10.1016/j.marpolbul.2007.02.015

Currin, C., Davis, J., Malhotra, A. 2017. Response of salt marshes to wave energy provides guidance for successful living shoreline implementation. In: Living Shorelines: The Science and Management of Nature-Based Coastal Protection. Bilkovic D., Mitchell, M., La Peyre, M., Toft, J.(eds.) CRC Press Boca Raton FL. https://doi.org/10.1201/9781315151465.

Duarte, B.; Carreiras, J.; Caçador, I. 2021. Climate change impacts on salt marsh blue carbon, nitrogen and phosphorous stocks and ecosystem Services. Appl. Sci. 11, https://doi.org/10.3390/ app11041969

Ensign, S.H., Halls, J.N., Peck, E.K. 2023. Watershed sediment cannot offset sea level rise in most US tidal wetlands. Science, 382, 1191-1195. https://doi.org/10.1126/science.adj0513.

Fischman, H.S., Smyth, A.R. & Angelini, C. Invasive consumers provoke ecosystem-wide disruption of salt marsh functions by dismantling a keystone mutualism. Biol Invasions 26, 169–185 (2024). https://doi.org/10.1007/s10530-023-03167-4

Fu, C., Steckbauer, A., Mann, H., Duarte, C.M. 2024a. Achieving the Kunming–Montreal global biodiversity targets for blue carbon ecosystems. Nature Reviews Earth & Environment, 5, 538-552. https://doi.org/10.1038/s43017-024-00566-6.

Fu, C., Li, Y., Zeng, L., Tu, C., Wang, X., Ma, H., Xiao, L., Luo, Y. 2024b. Climate and mineral accretion as drivers of mineral-associated and particulate organic matter accumulation in tidal wetland soils. Global Change Biology, 30, e17070. https://doi.org/10.1111/gcb.17070.

Fu, C., Li, Y., Tu, C., Hu, J., Zeng, L., Qian, L., Christie, P., Luo, Y. 2023. Dynamics of trace element enrichment in blue carbon ecosystems in relation to anthropogenic activities. Environment International, 180, 108232. https://doi.org/10.1016/j.envint.2023.108232.

Gu, J., Luo, M., Zhang, X., Christakos, G., Agusti, S., Duarte, C.M., Wu, J. 2018. Losses of salt marsh in China: Trends, threats and management. Estuarine, Coastal and Shelf Science, 214, 98-109. https://doi.org/10.1016/j.ecss.2018.09.015.

He, Q., Li, Z., Daleo, P. *et al.* 2025. Coastal wetland resilience through local, regional and global conservation. Nature Reviews Biodiversity **1**, 50–67. https://doi.org/10.1038/s44358-024-00004-x

Hensel MJS, Silliman BR, Hensel E, Byrnes JEK (2021a) Feral hogs control brackish marsh plant communities over time. Ecology. https://doi.org/10.1002/ecy.3572

Lang, M., Ingebritsen, J., Griffin, R. 2024. Status and trends of wetlands in the coterminous United States 2009-2029. U.S. Dept. of the Interior, Fish and Wildlife Service, Washington DC pp43.

Li, H., Mao, D., Wang, Z., Huang, X., Li, L., Jia, M. 2022. Invasion of *Spartina alterniflora* in the coastal zone of mainland China: Control achievements from 2015 to 2020 towards the Sustainable Development Goals. Journal of Environmental Management, 323, 116242. https://doi.org/10.1016/j.jenvman.2022.116242.

Li, Y., Fu, C., Zeng, L., Zhou, Q., Zhang, H., Tu, C., Li, L., Luo, Y. 2021. Black Carbon Contributes Substantially to Allochthonous Carbon Storage in Deltaic Vegetated Coastal Habitats. Environmental Science & Technology, 55, 6495−6504. https://doi.org/10.1021/acs.est.1c00636.

Li, Y., Fu, C., Hu, J., Zeng, L., Tu, C., Luo, Y. 2023. Soil Carbon, Nitrogen, and Phosphorus Stoichiometry and Fractions in Blue Carbon Ecosystems: Implications for Carbon Accumulation in Allochthonous-Dominated Habitats. Environmental Science & Technology, 57, 5913−5923. https://doi.org/10.1021/acs.est.3c00012.

Lloret, J., Pedroso-Pamies, R., Vandal, N. Rorty, R., Ritchie, M., McGuire, C., Chenoweth, K., Valiela, I. 2021. Salt marsh sediments act as sinks for microplastics and reveal effects of current and historical land use changes. Environmental Advances, 4, 10060. https://doi.org/10.1016/j.envadv.2021.100060.

Lynch, K.E., Penk, M.R., Perrin, P.M. et al. Cattle Grazing of a Celtic Sea Saltmarsh Affects Invertebrate Community Composition and Biomass, but not Diversity. Wetlands 42, 125 (2022). https://doi.org/10.1007/s13157-022-01643-6

Martinetto, P., Alberti, J., Becherucci, M. et al. (2023). Nature Communications) 14, 8500. https://doi.org/10.1038/s41467-023-44196-w

Martinez-Soto K., Johnson, D. 2023. A fiddler crab reduces plant growth in its expanded range. Ecology, 105, e4203. https://doi.org/10.1002/ecy.4203.

Maxwell, T.L., Spalding, M.D., Friess, D.A. et al. (2024). Soil carbon in the world's tidal marshes. Nature Communications 15, 10265. https://doi.org/10.1038/s41467-024-54572-9

Mcowen, C., Weatherdon, L.V., Bochove, J., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C.S., Spalding, M., Fletcher, S. 2017. A global map of saltmarshes (v6.1). Biodiversity Data Journal, 5, e11764. Paper DOI: https://doi.org/10.3897/BDJ.5.e11764; Data DOI: https://doi.org/10.34892/07vk-ws51.

Morris, R., Bilkovic, D., Boswell, M., Bushek, D., et al. 2019. The application of oyster reefs in shoreline protection: Are we over-engineering for an ecosystem engineer? Journal of Applied Ecology, 56, 1703-1711. https://doi.org/10.1111/1365-2664.13390.

Murray, N., Worthington, T., Bunting, P., Duce, S. et al. 2022. High resolution mapping of losses and gains of Earth's tidal wetlands. Science, 376, 744-749. https/doi.org/10.1126/science.abm9583.

Nel, M., Rubidge, G., Adams, J., Human, L. 2022. Contributions of wetland plants on metal accumulation in sediment. Sustainability, 14, 3679. https://doi.org/10.3390/su14063679.

Ohenhen, L., Shirzaei, M., Barnard, P. 2024. Slowly but surely: Exposures of communities and infrastructure to subsidence on the US East Coast. PNAS Nexus, 3, pgad426. https://doi.org/10.1093/pnasnexus/pgad426.

Ouyang, X., Duarte, C., Cheung, S.G., Tam, N.F.Y., Cannicci, S., Martin, C., Lo, H.S., Lee, S.Y. 2022. Fate and effects of macro- and microplastics in coastal wetlands. Environmental Science & Technology, 56, 4, 2386–2397. https://doi.org/10.1021/acs.est.1c06732.

Persico E, Sharp S, Angelini C (2017) Feral hog disturbance alters carbon dynamics in southeastern US salt marshes. Mar Ecol Prog Ser 580:57–68. https://doi.org/10.3354/meps12282

Petillon, J., McKinley, E., Alexander, M. et al. 2023. Top ten priorities for global saltmarsh research, conservation, and ecosystem service research. Science of the Total Environment 898, 165444 https://doi.org/10.1007/s12237-021-00907-4

Pinheiro, L., Carvalho, I.V., Agostini, V.O., Martinez-Souza, G., Galloway, T.S., Pinho, G.L. 2021. Litter contamination at a salt marsh: An ecological niche for biofouling in South Brazil. Environmental Pollution, 285, 117647. https://doi.org/10.1016/j.envpol.2021.117647.

Qi, X., Chmura, G.L. 2023. Invasive *Spartina alterniflora* marshes in China: a blue carbon sink at the expense of other ecosystem services. Frontiers in Ecology and the Environment, 21, 182-190. https://doi.org/10.1002/fee.2611.

Raposa, K.B., McKinney, R.A., Wigand, C., Hollister, J.W., et al. 2018. Top-down and bottom-up controls on southern New England salt marsh crab populations. Peer J, 6, e4876. https://doi.org/10.7717/peerj.4876.

Raposa, K.B., Weber, R., Durant D. Mitchell, J.C., Rasmussen, S., McKinney, R.A., Wigand, C. 2024. Upland vegetation removal as a potential tool for facilitating landward salt marsh migration. Restoration Ecology, e14242. https://doi.org/10.1111/rec.14242.

Saltonstall, K. 2002. Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America. Proceedings of the National Academy of Science, 99, 2445–2449. https://doi.org/10.1073/pnas.032477999.

Smith, S.M., Green, C.W. 2015. Sediment suspension and elevation loss triggered by Atlantic Mud Fiddler Crab (*Uca pugnax*) bioturbation in salt marsh dieback areas of Southern New England. Journal of Coastal Research, 31, 88-94. https://doi.org/10.2112/JCOASTRES-D-12-00260.1.

Staver, L.W., Morris, J.T., Cornwell, J.C., Stevenson, J.C., Nardin, W., Hensel, P., Owens, M.S., Schwark, A. 2024. Elevation changes in restored marshes at Poplar Island, Chesapeake Bay, MD: 1. Trends and drivers of spatial variabiity. Estuaries and Coasts, 47, 1784–1798. https://doi.org/10.1007/s12237-023-01319-2.

Sutton-Grier, A., Wowk, K., Bomford, H. 2015. Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environmental Science & Policy, 51, 137-148. https://doi.org/10.1016/j.envsci.2015.04.006.

Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., Freeman, C., Janousek, C., Brown, L., Rosencranz, J., Holmquist, J. 2018. US Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances, 2018, 4, eaao3270. https://doi.org/10.1126/sciadv.aao3270.

Thorne, K.M., Freeman, C.M., Rosenkranz J.A., Ganju, N.K., Guntenspergen, G.R. 2019. Thin-layer sediment addition to an existing salt marsh to combat sea-level rise and improve endangered species habitat in California USA. Ecological Engineering, 136, 197-208. https://doi.org/10.1016/j.ecoleng.2019.05.011.

Van Dolah, E.R., Miller Hesed, C.D., Paolisso, M.J. 2020. Marsh migration, climate change, and coastal resilience: human dimensions considerations for a fair path forward. Wetlands, 40, 1751–1764. https://doi.org/10.1007/s13157-020-01388-0.

Viswanathan, C., Purvaja, R., Joyson Joe Jeevamani, J. et al. (2020). Salt marsh vegetation in India: Species composition, distribution, zonation pattern and conservation implications. Estuarine, Coastal and Shelf Science, V. 242, 106792. https://doi.org/10.1016/j.ecss.2020.106792

Vu, H.D., Więski, K., Pennings, S.C. 2017. Ecosystem engineers drive creek formation in salt marshes. Ecology, 98, 162–174. https://doi.org/10.1002/ecy.1628.

Ward, R.D. 2020. Carbon sequestration and storage in Norwegian Arctic coastal wetlands: Impacts of climate change. Science of the Total Environment, 748, 141343. https://doi.org/10.1016/j.scitotenv.2020.141343.

Watson, E.B., Ferguson, W., Champlin L.K., White, J. D., Ernst, N., Sylla, H. A., Wilburn, B.P., Wigand, C. 2022. Runnels mitigate marsh drowning in microtidal salt marshes. Frontiers in Environmental Science: Section on Conservation and Restoration Ecology, 10, 987246. https://doi.org/10.3389/fenvs.2022.987246.

Weis, J.S., Watson E.B., Ravit, B., Harman, C., Yepsen, M. 2021. The status and future of tidal marshes in New Jersey faced with sea level rise. Anthropocene Coasts, 4, 168-192. https://doi.org/10.1139/anc-2020-0020.

Windham, L., Lathrop, R.G. 1999. Effects of *Phragmites australis* (common reed) invasion on aboveground biomass and soil properties in brackish tidal marsh of the Mullica River, New Jersey. Estuaries, 22, 927–935. https://doi.org/10.2307/1353072.

Wittyngham S., Johnson D., Chen, Y., Kirwan, M. 2024. A grazing crab drives saltmarsh carbon storage and recovery. Ecology, 105, e4385. https://doi.org/10.1002/ecy.4385.

Worthington, T., Spalding, M., Landis, E, Maxwell, T.L., Navarro, A., Smart, L.S., Murray, N.J. 2024. The distribution of global tidal marshes from earth observation data. Global Ecology and Biogeography, 33, e13852. https://doi.org/10.1101/2023.05.26.542433.

Xie, B., Han, G. 2023. Control of invasive plant *Spartina alterniflora*: Concept, technology and practice. Bulletin of Chinese Academy of Sciences, 38, 1924-1938. https://doi.org/10.16418/j.issn.1000-3045.20230921001 (in Chinese).

Zhang, Ni-chen, et al. "Mechanism of polycyclic aromatic hydrocarbons degradation in the rhizosphere of *Phragmites australis:* Organic acid co-metabolism, iron-driven, and microbial response." *Environmental Pollution* 327 (2023): 121608.

Zhu, L., Chen, Q., Wang, H., Capurso, W., Niemoczynski, L., Hu, K., Snedden, G. 2020.Field Observations of Wind Waves in Upper Delaware Bay with Living Shorelines. Estuaries and Coasts, 43, 739–755. https://doi.org/10.1007/s12237-019-00670-7.

Section 4

Sub-chapter 5j: Continental slopes and submarine canyons

M. Canals*, C. Creese, M.-C. Fabri, F. Galgani, V.A.I. Huvenne, J. Martin, A. Pusceddu, J.A. Trotter, M. Haghi, K. Ismail, N. Merchant, Y. Sun.

* Coordinating author, miquelcanals@ub.edu

Keynote Points

- Continental slopes and submarine canyons are increasingly affected by direct anthropogenic impacts, and by climate change.
- Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, placement of seafloor infrastructures, noise generation, and tourism appear as the most impacting human activities.
- Submarine canyons are highly valuable biodiversity hotspots, including corals, sponges, and cetaceans.
- Little is known about the capability and time scales of continental slopes and submarine canyons to recover after disturbance, but they are generally much slower compared to shallow waters. The recovery of habitats affected by bottom trawling can take decades while key ecosystem engineers rebuild.
- Despite substantial advances in slope and canyon knowledge, conservation, and management, many of the gaps identified in WOA II remain.
- Most continental slope and submarine canyon habitats remain unexplored, and mid- to long-term data is limited, making it difficult to assess changes over the past 5-10 years.

1. Introduction

The continental slope represents the seafloor province extending from the shelf edge (100-1,000 m depth or more) to the upper limit of the continental rise (1,000-4,000 m or more). Continental slopes vary in width, gradient, and length, covering 19.6 million km^2,or 5.2% of the global ocean floor, and are often incised by submarine canyons (Anell, 2024), which are slope dissecting steep-walled valleys varying in shape, length, and configuration. Canyons serve as drainage networks conveying sediments, organic matter, and pollutants from shallow to deep (Canals and others, 2006; Zhong and Peng, 2021; Jones and others, 2022). Intense hydrodynamic processes may occur in canyons eventually involving different water masses. Over 10,000 submarine canyons are known, with more yet to be mapped in underexplored oceanic regions.

2. Developments in understanding of continental slopes and submarine canyons

2.1. Functioning

The continental slope is a depocenter where sedimentary and organic particles can accumulate and be buried due to a hydrodynamic regime weaker than that on the shelf (Bianchi and others, 2018; Ausín and others, 2021). Longshore hydrographic fronts, and the balance between the horizontal pressure gradient and Coriolis force, create major water flows along isobaths. By promoting the slow, long-term sorting and redeposition of seafloor sediments, these currents create large deposits (contourite drifts) (Thran and others, 2018; Wilckens, 2023), that can trap substantial amounts of organic carbon (Yin and others, 2024).

Submarine canyons enhance the connectivity between coastal and deep realms (Maier and others, 2019), and accelerate the transfer of material from the shelf to deep waters, which promotes carbon sequestration (Baker and others, 2024). Canyon dynamics can encompass strong and deep tidal currents, local upwelling, bringing nutrients into the euphotic zone enhancing primary production (Saldías and others, 2021; Brun and others, 2023), and deep upwelling that can contribute to global diapycnal mixing (Wynne-Cattanach and others, 2024). Canyons also channel dense waters that cascade down continental slopes, enhancing cross-margin export of matter (Luneva and others, 2020; Durrieu de Madron and others, 2023). At high latitudes, shoreward cross-isobath flows may transport warm currents to the continental shelf, thus easing the melting of sea-terminating glaciers (Wynne-Cattanach and others, 2024; Donda and others, 2024). Marine heat waves can reach upper continental slope and submarine canyon depths (Amaya et al., 2023).

Submarine canyons are also loci for the reflection and refraction of internal waves and tides that could exceed 100 meters in amplitude, leading to increased energy focusing and dissipation, resuspension, and mixing (Hall and others, 2017; McPhee-Shaw and others, 2021; Tian and others, 2024), thereby affecting resident benthic communities (Pearman and others, 2023).

Episodic gravitational processes, some of which could generate tsunamis, help shaping continental slopes and canyons. Land-detached canyons can be as active (Heijnen and others, 2022) as those connected to the biggest river systems on Earth (Azpiroz-Zabala and others, 2017).

2.2. Effects of climate change

Canyon inhabitants are vulnerable to climate change given they often live near their tolerance limits of temperature, aragonite saturation, oxygen concentration, and nutrient levels. By 2100, significant increases in temperature with decreases in pH, dissolved oxygen, and particulate organic carbon in canyons and continental slope areas are projected under the high CO_2 emissions scenario RCP8.5 especially, with atmospheric CO_2 at ~940 ppm and mean global temperature ~3.7°C above pre-industrial levels (Levin, 2018, 2019; Bindoff and others, 2019). However, the heterogeneous, synergistic, and compounding effects of climate change related processes will be highly variable, spatially defined, and species-dependent.

Anthropogenic CO_2 has already descended canyon intermediate water depths (Trotter and others, 2019; Fontela and others, 2020). Climate velocity models have now identified the mesopelagic zone as highly susceptible to major shifts in biogeography (Brito-Morales and others, 2020). Since corals underpin deep-water reef ecosystems and local biodiversity hotspots, large reductions in coral habitat suitability predicted by 2100 (e.g., >79% in the North Atlantic) will have major ecological ramifications (Morato and others, 2020) (cf. S4.C5e). In deep waters, ingress of CO_2 via overturning ocean circulation has caused shoaling of the carbonate compensation depth (CCD), Canyons in the southwest Atlantic are deemed most vulnerable where substrates below the CCD have doubled since pre-industrial times (Harris and others, 2023b).

The Mediterranean Sea is at the forefront of climate change as it is warming faster than the global ocean. While invertebrate mass mortality events have occurred across the continental shelf, abrupt temperature increases and intensified oligotrophic conditions around canyons are now threatening deeper water communities (Bahamon and others, 2020). Globally, limited experimental and in-situ data show deep-water taxa are variably sensitive to warming at different life stages, thus reduced metabolic function, increased mortality, and latitudinal or depth migration is expected under higher temperature conditions (Bindoff and others, 2019; Simões and others, 2021; Lang and others, 2023; Scanes and others, 2024). Together with Antarctic warming, sea-ice retreat will reduce nutrient-rich zones and biomass in canyons (FAO, 2018; Bindoff and others, 2019). Krill, a keystone species of marine food webs, have already responded by their poleward contraction (Atkinson and others, 2019; Kawaguchi et al., 2024); thus, canyons in lower latitudes may serve as future refuges for krill (Santora and others, 2018).

At oxygen minima zones (e.g. African margins), where colonial corals appear hypoxia-tolerant (Wienberg and others, 2023) (cf. S4.C5e), greater sensitivities are expected in organisms living close to their metabolic thresholds. As these zones expand, the consequent impacts on mortality, reproduction, and other physiological impairments, will restructure or potentially decimate canyon and slope ecosystems.

3. Value as biodiversity hotspots

Continental slopes and submarine canyons can be biodiversity hotspots (De Leo and Puig, 2018; Ismail and others, 2018). Compared to continental slopes, canyons feature complex and dynamic environments with higher spatial heterogeneity and a wider range of habitats and communities.

Coral and sponge hotspots. Sediment-rich continental slopes host extensive soft coral communities, like bamboo corals, sea pens, and sponge grounds that provide crucial habitats for invertebrates and fish (Santín and others, 2018; Compaire and others, 2021; Grinyó and others, 2021). Highly dynamic, nutrient-rich and morphologically complex canyons support hard corals and sponges, and attract fish (Corbera and others, 2019; Saunders and others, 2021; Guy and Metaxas, 2022). Recent studies of the distribution of deep-sea habitats reveal new locations of cold-water corals (Bo and others, 2023; Trotter and others, 2019, 2022), soft-corals (Long and others, 2020), and biodiversity hotspots (Moccia and others, 2019, 2021; Gayá-Vilar and others, 2024), as well as changes in priority habitats (Moura and others, 2020; Nestorowicz and others, 2021). These discoveries show how depth, relief, local hydrodynamics and substratum collectively impact habitat distribution, and emphasize the need for further exploration and extensive conservation (cf. S4.C5e).

Recent discoveries of new deep-sea species (e.g., sponges, gastropods, octocorals and corals) including 111 unique taxa off the Western Antarctic Peninsula (Friedlander and others, 2020), highlight the need for ongoing taxonomic reviews (Addamo and others, 2024) (cf. S4.C5e).

***Cetacean hotspots*.** Submarine canyons, due to their complex topography and enhanced nutrient cycling provide productive conditions for marine mammals, whereas continental slopes serve are important feeding grounds and corridors for migratory cetaceans (Cannaby and others, 2023; Loutrage and others, 2023; Ransier and others, 2024). Temperature and productivity influence cetacean distribution (Granata and others, 2020; Salgado Kent and others, 2021), and their higher diversity in canyons (Hodge and others, 2022), highlighting their importance for cetacean conservation. The use of Species Distribution Models (SDMs) (Feyrer and others, 2024) and environmental DNA (eDNA) (Boldrocchi and others, 2024; Jeunen and others, 2024) has improved habitat characterization for various cetacean species along continental slopes.

4. Natural resources and ecosystem services

Continental slopes and submarine canyons sustain many supporting, provisioning, regulating and cultural services that are crucial to human well-being. These include: (i) seafood (Fanelli and others, 2018; De Leo and Puig, 2018; Clavel-Henry and others, 2020); (ii) non-renewable resources, in particular oil and gas, and possibly gas hydrates and deep-sea minerals in the future (Miller et al.,

2018; Weaver and Billett, 2019; Zhang and others, 2019); (iii) bioactive compounds from prokaryotes (Wang and others, 2020), fungi (Ogaki and others, 2020; Varrella and others, 2021) and invertebrates, especially octocorals and demosponges (Zhang and others, 2024); (iv) space for offshore energy and communication infrastructure (Bosch and others, 2018; Danovaro and others, 2024); (v) carbon sequestration (Graves and others, 2022); (vi) nutrient cycling (Chen and others, 2022); (vii) biodiversity enhancement (De Leo and others, 2020; Ramirez-Llodra, 2020); and (viii) ecological refuges and habitats for spawning of commercial species (Ramirez-Llodra, 2020).

High-resolution data from continental slopes and canyons has identified new functions and services, some already threatened. Fisheries have deepened, with documented impacts on single species and whole ecosystems (Oberle and others, 2018; Paradis and others, 2018, 2021; Taviani and others, 2023), even if new regional regulations limit their effects, such as the Commission implementing regulation of the European Union leading to the total closure of 87 sensitive zones between 400 and 800 m depth in the North-East Atlantic (European Union, 2022). Increasing anthropogenic impairment of the services provided by slopes and canyons, exacerbated by climate change, has prompted research on environmental management issues (Thiele, 2019; Baker and others, 2020; Amon and others, 2022).

5. Human activities and associated impacts

Loss of seafloor integrity and associated impacts. Continental slope and canyon floor integrity refers to the maintenance of the characteristic functioning of natural ecosystem processes and spatial connectedness, including the physical structure and biotic composition of the benthic community (Rice and others, 2010). Many human activities impact the seafloor and associated communities, causing disturbance or physical loss (ICES, 2019), and compromising the provision of ecosystem services. Loss involves sealed (e.g., pipelines, cables) or unsealed (e.g., bottom trawling) disappearance of the natural seafloor, which can occur over different time intervals (Buhl-Mortensen and Buhl-Mortensen, 2018). Other harmful activities include mining of hydrothermal sulphide fields, crusts and phosphates on continental slope settings (Curric, 2016; Carver, 2019; Galley and others, 2020; Jones and others, 2020; van Putten and others, 2023). The International Seabed Authority (ISA) has discussed on the draft regulations on exploitation of mineral resources in the Area —which might include continental slope settings beyond the limits of national jurisdiction— in order to ensure effective protection for the marine environment from harmful effects which may arise from such activities.

Fishing. Bottom trawling is the most significant human activity on continental margins and in canyons (Tiano and others, 2024). It disrupts benthic habitats by destroying them and resuspending

and overturning sediments, with impacts far surpassing natural processes like currents, particularly at greater depths (Puig and others, 2012; Schönke and others, 2022). Effects extend beyond fishing grounds, as resuspended particles spread impacts across large areas, including canyon axes (Pusceddu and others, 2014; Daly and others, 2018; Bradshaw and others, 2021).

***Waste dumping*.** Deep submarine canyons and adjacent continental slopes used for domestic and industrial waste disposal are "out of sight, out of mind" (Vare and others, 2018; Vogt and Skei, 2018; Pierdomenico and others, 2020). Canyons near populated and industrial areas especially can become conduits for land-sourced waste (Fabri and others, 2017; Bouchoucha and others, 2019). Industrial waste can spread well beyond the initial discharge site (Fontanier and others, 2020).

***Oil and gas exploration and exploitation*.** The oil and gas industry has continued its expansion into continental slopes (Zhang and others, 2019; Wen and others, 2023). Incidents with oil spills from drilling rigs and seabed pipelines (e.g., the Deepwater Horizon disaster) continue to pose severe environmental threats (Girard and Fisher, 2018; Kujawinski and others, 2020; Cavcic, 2023). Sediment resuspension, burial from anchoring and pipeline installation, and discharges of drilling muds and produced water typically affect areas within 100 to 2,000 m (Cordes and others, 2016). Hard structures, like pipelines, can become growing substrata for organisms, which should be considered during decommissioning (Rouse and others, 2019; McLean and others, 2022).

***Submarine cables*.** The submarine communication cable industry is growing, driven by increasing demand for content and data transmission, carrying over 95% of worldwide communications. Most new installations focus on mid and low latitudes (https://subtelforum.com/online-map), often connecting data centre hubs rather than traditional population centres (Submarine Telecoms Forum, 2024). Power cables are mostly installed in rather shallow waters, with some deep-water examples mostly in the Mediterranean Sea (Ardelean and Minnebo, 2015; https://cyprus-mail.com/2022/10/14/euroasia-interconnector-ready-for-construction-historic-day-president-says/). Power cables often incorporate fiber optics for communication purposes. Cable routes in deep-water are chosen to minimize environmental impact and avoid geohazard-prone areas (e.g., landslides and canyons) (Clare and others, 2023; https://www.internetsociety.org/resources/doc/2024/2024-west-africa-submarine-cable-outage-report/). Disused cables are increasingly recovered for recycling (cf. WOA II report).

***Noise*.** Human-driven underwater noise pollution modifies marine soundscapes (Bayrakci and Klingelhoefer, 2024), impacting marine organisms across various trophic levels (Duarte and others, 2021). Shipping, geophysical surveys, drilling, and military sonars are major sources of this pollution. While monitoring efforts are increasing, particularly for impulsive noise sources like seismic surveys

(Merchant and others, 2020), data on continuous noise from shipping are limited (Jalkanen and others, 2022).

Litter and plastic pollution. Seafloor litter accumulates in submarine canyons, being greatest near populated coastlines and tourism hotspots (Canals and others, 2021; Hernandez and others, 2022; Pierdomenico and others, 2023). These include mainly single-use plastics, microplastics, and lost fishing gear, which are transported by canyon hydrodynamics (Galgani and others, 2022; Harris and others, 2023a). Plastic degrades into micro/nanoplastics, threatening marine life and ecosystems, with accumulations in deep-sea sediments and biota showing alarming increases (Fossi and others, 2018; Kane and others, 2024). The persistence timescales of litter depend on composition, with those of plastics unknown but likely longest in deep-sea environments (Ward and Reddy, 2020), posing serious concerns for canyon ecosystems (Pierdomenico and others, 2019).

Tourism. Dolphin and whale-watching along the continental margins is a booming industry that supports local economies, but it can also negatively impact marine mammals. Other wildlife species can also be ~~impacted~~affected ~~as well~~ by boat-based and in-water tourist~~ic~~ activities (CMS Secretariat, 2025). Boat presence, noise pollution, and close encounters can disrupt the behaviour of cetaceans ~~behaviour~~ and other species, causing stress, altering feeding and socializing patterns, and even leading to habitat abandonment (Schuler and others, 2019; Sprogis and others, 2020). However, efforts are underway to promote more sustainable and ecologically respectful tourism practices (Amerson and Parsons, 2018; Suárez-Rojas and others, 2023) (cf. 5A.4). It is of the utmost importance to ensure that wildlife interactions driven by tourism are conducted sustainably (CMS Secretariat, 2025).

Recovery from disturbance. While evidence of anthropogenic impacts on continental slopes and submarine canyons is growing, little is known about the recovery of these habitats. Studying deep waters is challenging, and repeat surveys at impacted sites are scarce. Habitat recovery affected by bottom trawling, for example, can take decades while key ecosystem engineers like cold-water corals or sponges rebuild (Huvenne and others, 2016; Clark and others, 2022; Goode and others, 2024) (cf. S4.C5e). However, once impacts are removed and conditions are favourable, recolonisation by species can occur (Strong and others, 2023).

Submarine canyons, naturally prone to disturbances (e.g., slope failures and sediment flows), offer insights into natural recovery processes. The meiofauna of the Kaikoura Canyon nearly completely recovered within four years after the 2016 M_w 7.8 earthquake, nematode communities still differed from pre-earthquake conditions, and complete megafauna recovery is projected between 4.5 and 12 years (Bigham and others, 2023, 2024).

6. Future trends and need for conservation

Most continental slope and submarine canyon habitats remain unexplored, and mid- to long-term data is limited, making it difficult to assess changes over the past 5-10 years. Natural disturbances and those derived from human activities can have immediate and widespread effects, but recovery and shifts in these deep-sea ecosystems are generally much slower compared to shallow waters (Da Ros and others, 2019).

Evidence of climate change-induced shifts in marine species is emerging. Tropicalization of demersal megafauna along the Brazilian Meridional Margin has occurred since 2013 (Alvarez Perez and Sant'Ana, 2022). European Seas (e.g., the Mediterranean, Black, and Baltic seas), have been warming since the 1980s, leading to tropicalization and deborealization (Chust and others, 2024), and the expansion of non-indigenous species (Galil and others, 2018, 2021). Sea pens and shrimps are expected to shift to higher latitudes, while most cold-water corals will move to lower latitudes in the Atlantic (Morato and others, 2023) (cf. S4.C5e).

Improved waste management and recycling could reduce the amount of waste reaching coastal areas and nearby canyon heads (Willis and others, 2022; Bruemmer and others, 2023). Greater enforcement of and amendments to international agreements aim to curb marine pollution (https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx; https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx).

However, debate continues over the disposal of hazardous waste like radioactive materials (Buser and others, 2020; Dabrowska and others, 2021). Conservation efforts have advanced with many continental slopes and canyons now within Exclusive Economic Zones (EEZs), and cross-boundary agreements aiming to extend conservation efforts into international waters (Fernandez-Arcaya and others, 2017).

Despite substantial advances in slope and canyon knowledge, conservation, and management, many of the gaps identified in WOA II remain. With new technologies, coordinated funding initiatives, and new regulatory frameworks, major progress is anticipated to better understand canyon processes (Demopoulos and others, 2024; Wynne-Cattanach and others, 2024), quantify ecosystem functioning and services, and better predict ecosystem adaptations under climate change (Sweetman and others, 2017). Marine litter and pollution research is shifting from identifications and inventories to investigations into ecotoxicological and species behavioural effects (Bruemmer and

others, 2023). The expansion and increased accessibility of new technologies (e.g. AUVs, ROVs) and AI-based data analysis, together with increased time series observations (Chauvet and others, 2018), will further support evidence-based management of continental margins.

7. Knowledge and capacity building gaps

The major imbalance in data availability and access to key observational equipment and research capacity still hampers our progress to fully understand the world's continental slopes and submarine canyons. Research efforts remain focused on only a limited number of study sites, mostly within the EEZs of developed nations. The ten most prominent institutions in submarine canyon research are based in the US, Spain, France, The Netherlands, and the United Kingdom. The most studied canyons are all along the continental margins of North America (6 canyons), southern Europe (4) and Taiwan (1) (Matos and others, 2018). Specialised vocational and university training is closely connected to marine research, industrial development, and management capabilities. While there are diverse strategies and initiatives to address these imbalances (e.g., greater access to the best universities, research centres, and modern infrastructure), challenges remain (Barnhill and others, 2023; Howell and others, 2020; Roberts and others, 2023).

Ocean literacy campaigns are also important for societies to understand the benefits of, and provide support to, deep sea research, which is especially critical given the general lack of interest in protecting the deep sea (Carlesi and others, 2023), despite scientists increasingly advocating their importance (Niner and others, 2018; Da Ros and others, 2019; Fanelli and others, 2021).

8. References

Addamo, Anna M. and others. Unravelling the relationships among *Madrepora* Linnaeus, 1758, *Oculina* Lamark, 1816 and *Cladocora* Ehrenberg, 1834 (Cnidaria: Anthozoa: Scleractinia). Invertebrate Systematics, vol. 38, No. 4, 2024.

Alvarez Perez, Jos A., and Rodrigo Sant'Ana. Tropicalization of demersal megafauna in the western South Atlantic since 2013. Communications Earth & Environment, vol. 3, 227, 2022.

Amaya, Dillon J., and others. Bottom marine heatwaves along the continental shelves of North America. Nature Communications, vol. 14, 1038, 2023.

Amerson, Alicia, and Edward C.M. Parsons. Evaluating the sustainability of the gray-whale-watching industry along the pacific coast of North America. Journal of Sustainable Tourism vol. 26, No. 8, pp. 1362–1380, 2018.

Amon, Diva J., and others. Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. Marine Policy, vol. 138, 105006, 2022.

Anell, Ingrid. The fourth slope: A fundamental new classification of continental margins. Basin Research, vol. 36, e12863, 2024.

Ardelean, Mircea, and Philip Minnebo. HVDC Submarine Power Cables in the World — State-of-the-Art Knowledge. JRC Technical Reports, European Commission, 2015.

Atkinson, Angus, and others. Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. Nature Climate Change, vol. 9, pp. 142–147, 2019.

Ausín, Blanca, and others. Controls on the abundance, provenance and age of organic carbon buried in continental margin sediments. Earth and Planetary Science Letters, vol. 558, 116759, 2021.

Azpiroz-Zabala, Maria, and others. Newly recognized turbidity current structure can explain prolonged flushing of submarine canyons. Science Advances, vol. 3, e1700200, 2017.

Bahamon, Nixon, and others. Stepped coastal water warming revealed by mb multiparametric monitoring at NW Mediterranean fixed stations. *Sensors,* vol. 20, No. 9, 2658, 2020.

Baker, Megan L., and others. Globally significant mass of terrestrial organic carbon efficiently transported by canyon-flushing turbidity currents. Geology, vol. 52, No. 8, pp. 631–636, 2024.

Baker, Maria, and others, eds. Natural capital and exploitation of the deep ocean. Oxford: Oxford University Press, 2020.

Barnhill, Kelsey A., and others. Ship-to-shore training for active deep-sea capacity development. ICES Journal of Marine Science, vol. 80, No. 6, pp. 1619–1628, 2023.

Bayrakci, Gaye, and Frauke Klingelhoefer, eds.. Noisy oceans. Monitoring seismic and acoustic signals in the marine environment. Geophysical Monograph Series, Hoboken, New Jersey: American Geophysical Union – John Wiley & Sons, Inc., 2024.

Bianchi, Thomas S., and others. Centers of organic carbon burial and oxidation at the land-ocean interface. Organic Geochemistry, vol. 115, pp. 138-155, 2018.

Bigham, Katharine T., and others. Recovery of deep-sea meiofauna community in Kaikōura Canyon following an earthquake-triggered turbidity flow. PeerJ, vol. 12, e17367, 2024.

Bigham, Katharine T. and others. Deep-sea benthic megafauna hotspot shows indication of resilience to impact from massive turbidity flow. Frontiers in Marine Science, vol. 10, 1180334, 2023.

Bindoff, Nathaniel L. and others. “Changing ocean, marine ecosystems, and dependent communities”, in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, Hans-Otto Pörtner and others, eds. (Cambridge and New York, Cambridge University Press, 2019).

Bo, Marzia, and others. The cold-water coral province of the eastern Ligurian Sea (NW Mediterranean Sea): historical and novel evidences. Frontiers in Marine Science, vol. 10, 1114417, 2023.

Boldrocchi, Ginevra, and others. Cuvier's beaked whale (*Ziphius cavirostris*) detection through surface-sourced eDNA: A promising approach for monitoring deep-diving cetaceans. Ecological Indicators, vol. 161, 111966, 2024.

Bosch, Jonathan, and others. Temporally explicit and spatially resolved global offshore wind energy potentials. Energy, vol. 163, pp. 766–781, 2018.

Bouchoucha, Marc, and others. Trace element contamination in fish impacted by bauxite red mud disposal in the Cassidaigne canyon (NW French Mediterranean). Science of the Total Environment, vol. 690, pp. 16-26, 2019.

Bradshaw, Clare, and others. Physical disturbance by bottom trawling suspends particulate matter and alters biogeochemical processes on and near the seafloor. Frontiers in Marine Science, vol. 8, 683331, 2021.

Brito-Morales, Isaac, and others. Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. Nature Climate Change, vol. 10, pp. 576–581, 2020.

Bruemmer, Alice L., and others. Marine litter-fauna interactions: a standardised reporting framework and critical review of the current state of research with a focus on submarine canyons. Frontiers in Marine Science, vol. 10, 1225114, 2023.

Brun, Lénaig, and others. Strong hydrodynamic processes observed in the Mediterranean Cassidaigne submarine canyon. Frontiers in Marine Science, vol. 10, 1078831, 2023.

Buhl-Mortensen, Pal, and Lene Buhl-Mortensen. Impacts of bottom trawling and litter on the seabed in Norwegian waters. Frontiers in Marine Science, vol. 5, 42, 2018.

Buser, Marcos, and others. Deep geological radioactive and chemical waste disposal: where we stand and where we go. ATW International Journal for Nuclear Power, vol. 65, . 6/7, pp. 311–316, 2020.

Canals, Miquel, and others. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environmental Research Letters, vol. 16, 023001, 2021.

Canals, Miquel, and others. Flushing submarine canyons. Nature, vol. 444, pp. 354-357, 2006.

Cannaby, Heather, and others. Environmental controls on macrozooplankton and fish distributions over diurnal to seasonal time scales in the northern Barents Sea. Progress in Oceanography, vol. 219, 103159, 2023.

Carlesi, Lorenzo, and others. Estimating preferences for Mediterranean deep-sea ecosystem services: A discrete choice experiment. Marine Policy, vol. 151, 105593, 2023.

Carver, Rosanna. Resource sovereignty and accumulation in the blue economy: the case of seabed mining in Namibia. Journal of Political Ecology, vol. 26, pp. 323-465, 2019.

Cavcic, Melisa. 2022 in review: Some of the major incidents related to offshore oil & gas. Offshore Energy, 2023 (https://www.offshore-energy.biz/2022-in-review-some-of-the-major-incidents-related-to-offshore-oil-gas/).

Chauvet, Pauline, and others. Annual and seasonal dynamics of deep-sea megafaunal epibenthic communities in Barkley Canyon (British Columbia, Canada): A response to climatology, surface productivity and benthic boundary layer variation. Progress in Oceanography, vol. 168, pp. 89-105, 2018.

Chen, Zhiyon, and others. Organic carbon remineralization rate in global marine sediments: A review. Regional Studies in Marine Science, vol. 49, 102112, 2022.

Chust, Guillem, and others. Cross-basin and cross-taxa patterns of marine community tropicalization and deborealization in warming European seas. Nature Communications, vol. 15, pp. 21-26, 2024.

Clare, Mike A., and others. Climate change hotspots and implications for the global subsea telecommunications network. Earth-Science Reviews, vol. 237, 104296, 2023.

Clark, Malcolm R., and others. Seamount recovery: analysis of 20 years of time-series data from the Graveyard Knolls, Chatham Rise, New Zealand. New Zealand Aquatic Environment and Biodiversity Report 292, 2022.

Clavel-Henry, Morane, and others. Modeling the spatiotemporal distribution of the deep-sea shrimp *Aristeus antennatus* (Crustacea: Decapoda) on the northwestern Mediterranean continental margin crossed by submarine canyons. Journal of Marine Systems, vol. 209, 103372, 2020.

CMS Secretariat. International Guidelines for sustainable marine wildlife interactions: Boat-based and in-water activities. CMS Technical Series Publication 49, 69 p., 2025 (https://www.cms.int/en/publication/international-guidelines-sustainable-marine-wildlife-interactions-boat-based-and-water).

Compaire, Jesus C., and others. Connectivity of coastal and neritic fish larvae to the deep waters. Limnology and Oceanography, vol. 66, No. 6, pp. 2423-2441, 2021.

Corbera, Guillem, and others. Ecological characterisation of a Mediterranean cold-water coral reef: Cabliers Coral Mound Province (Alboran Sea, western Mediterranean). Progress in Oceanography, vol. 175, pp. 245-262, 2019.

Cordes, Erik E., and others. Environmental impacts of the deep-water oil and gas industry: A review to guide management strategies. Frontiers in Environmental Sciences, vol. 4, 58, 2016.

Curric, Jock. Brief overview of potential ecosystem impacts of marine phosphate mining in the Western Cape, South Africa. Prepared for WWF South Africa, 17 p., 2016 (https://cer.org.za/wp-

content/uploads/2016/08/Potential-Ecosystem-Impacts-of-Marine-Phosphate-Mining-in-the-Western-Cape-South-Africa.pdf).

Dabrowska, Jolanta, and others. Marine waste — Sources, fate, risks, challenges and research needs. International Journal of Environmental Research and Public Health, vol. 18, 433, 2021.

Daly, Eoghan, and others. Bottom trawling at Whittard Canyon: Evidence for seabed modification, trawl plumes and food source heterogeneity. Progress in Oceanography, vol. 169, pp. 227-240, 2018.

Danovaro, Roberto, and others. Making eco-sustainable floating offshore wind farms: Siting, mitigations, and compensations. Renewable and Sustainable Energy Reviews, vol. 197, 114386, 2024.

Da Ros, Zaira, and others. The deep sea: The new frontier for ecological restoration**.** Marine Policy, vol. 108, 103642, 2019.

De Leo, Fabio C., and Puig, Pere. Bridging the gap between the shallow and deep oceans: The key role of submarine canyons. Progress in Oceanography, vol. 169, pp. 1-5, 2018.

De Leo, Fabio C., and others. "Continental slope and submarine canyons: Benthic biodiversity and human impacts", in *Brazilian Deep-Sea Biodiversity. Brazilian Marine Biodiversity*, Paulo Y.G. Sumida and others, eds. (Cham, Springer, 2020).

Demopoulos, Amanda, W.J., and others. Consumer isoscapes reveal heterogeneous food webs in deep-sea submarine canyons and adjacent slopes. Progress in Oceanography, vol. 223, 103231, 2024.

Donda, Federica, and others. Footprint of sustained poleward warm water flow within East Antarctic submarine canyons. Nature Communications, vol. 15, 6028, 2024.

Duarte, Carlos M., and others. The soundscape of the Anthropocene ocean. Science, vol. 371, 583, 2021.

Durrieu de Madron, Xavier, and others. Impact of dense water formation on the transfer of particles and trace metals from the coast to the deep in the northwestern Mediterranean. Water, vol. 15, 301, 2023.

European Union. Commission implementing regulation determining the existing deep-sea fishing areas and establishing a list of areas where vulnerable marine ecosystems are known to occur or are likely to occur. Official Journal of the European Union, Regulation 2022/1614, 141 p., 2022.

Fabri, Marie-Claire, and others. Cold-water coral ecosystems in Cassidaigne Canyon: An assessment of their environmental living conditions. Deep Sea Research Part II: XX, vol. 137, pp. 436-453, 2017.

Fanelli, Emanuela, and others. Deep-sea mobile megafauna of Mediterranean submarine canyons and open slopes: Analysis of spatial and bathymetric gradients. Progress in Oceanography, vol. 168, pp. 23-34, 2018.

Fanelli, Emanuela, and other. Identifying priorities for the protection of deep Mediterranean Sea ecosystems through an integrated approach. Frontiers in Marine Science, vol. 8, 698890, 2021.

FAO. “Deep-ocean climate change impacts on habitat, fish and fisheries”, in *FAO Fisheries and Aquaculture Technical Paper 638*, Lisa Levin and others, eds. (Rome, FAO, 2018).

Fernandez-Arcaya, Ulla, and others. Ecological role of submarine canyons and need for canyon Ccnservation: A review. Frontiers in Marine Science, vol. 4, 5, 2017.

Feyrer, Laura, J., and others. Identifying important habitat for northern bottlenose and Sowerby's beaked whales in the western North Atlantic. Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 34, No. 1, e4064, 2024.

Fontanier, Christophe, and others. Deep-sea benthic foraminifera at a bauxite industrial waste site in the Cassidaigne Canyon (NW Mediterranean): Ten months after the cessation of red mud dumping. Comptes Rendus – Géoscience, vol. 352, No. 1, pp. 87-101, 2020.

Fontela, Marcos, and others. The Northeast Atlantic is running out of excess carbonate in the horizon of cold-water corals communities. Scientific Reports, vol. 10, 14714, 2020.

Fossi, Maria C., and others. A review of plastic-associated pressures: Cetaceans of the Mediterranean Sea and eastern Australian shearwaters as case studies. Frontiers in Marine Science, vol. 5, 173, 2018.s

Friedlander, Allan M., and others. Spatial patterns of continental shelf faunal community structure along the Western Antarctic Peninsula. PLoS ONE, vol. 15, 10, 2020.

Galgani, François, and others. “Marine litter, plastic, and microplastics on the seafloor”, in *Plastics and the Ocean: Origin, Characterization, Fate, and Impacts*, Anthony L. Andrady, ed. (John Wiley & Sons, Inc., 2022).

Galil, Bella S., and others. Invasive biota in the deep-sea Mediterranean: an emerging issue in marine conservation and management. Biological Invasions, vol. 21, pp. 281–288, 2018.

Galil, Bella S., and others. Non-indigenous species along the Israeli Mediterranean coast: tally, policy, outlook. Hydrobiologia, vol. 848, pp. 2011–2029, 2021.

Galley, Christopher G., and others. Magnetic imaging of subseafloor hydrothermal fluid circulation pathways. Science Advances, vol. 6, eabc6844, 2020.

Gayá-Vilar, Alberto, and others. High-resolution density assessment assisted by deep learning of *Dendrophyllia cornigera* (Lamarck, 1816) and *Phakellia ventilabrum* (Linnaeus, 1767) in rocky circalittoral shelf of Bay of Biscay. PeerJ, vol. 12, e17080, 2024.

Girard, Fanny, and Charles R. Fisher. Long-term impact of the Deepwater Horizon oil spill on deep-sea corals detected after seven years of monitoring. Biological Conservation, vol. 225, pp. 117-127, 2018.

Goode, Savannah L., and others. Early signs of recovery suggested by changes in the structure and function of deep-sea megabenthic communities on a seamount 19 years after fishing. Deep Sea Research Part I: Oceanographic Research Papers (preprint), 2024.

Granata, Antonia, and others. Vertical distribution and diel migration of zooplankton and micronekton in Polcevera submarine canyon of the Ligurian mesopelagic zone (NW Mediterranean Sea). Progress in Oceanography, vol. 183, 102298, 2020.

Graves, Carolyn A., and others. Sedimentary carbon on the continental shelf: Emerging capabilities and research priorities for Blue Carbon. Frontiers in Marine Science, vol. 9, 926215, 2022.

Grinyó, Jordi, and others. Megabenthic assemblages on bathyal escarpments off the west Corsican margin (Western Mediterranean). Deep Sea Research Part I: Oceanographic Research Papers, vol. 171, 103475, 2021.

Guy, Graeme, and Anna Metaxas.. Recruitment of deep-water corals and sponges in the Northwest Atlantic Ocean: implications for habitat distribution and population connectivity. Marine Biology, vol. 169, No. 8, 107, 2022.

Hall, Rob A., and others. Partly standing internal tides in a dendritic submarine canyon observed by an ocean glider. Deep Sea Research Part I: Oceanographic Research Papers, vol. 126, pp. 73-84, 2017.

Harris, Peter T., and others. A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution. Continental Shelf Research, vol. 255, 104947, 2023a.

Harris, Peter T., and others. Rising snow line: Ocean acidification and the submergence of seafloor geomorphic features beneath a rising carbonate compensation depth. Marine Geology, vol. 463, 107121, 2023b.

Heijnen, Maarten S., and others. Challenging the highstand-dormant paradigm for land-detached submarine canyons. Nature Communications, vol. 13, 3488, 2022.

Hernandez, Ivan, and others. Marine litter in submarine canyons: A systematic review and critical synthesis. Frontiers in Marine Sciences, vol. 9, 965612, 2022.

Hodge, Brooke C., and others. Identifying predictors of species diversity to guide designation of marine protected areas. Conservation Science and Practice, vol. 4, No. 5, e12665, 2022.

Howell, Kerry L., and others. A blueprint for an inclusive, global deep-sea ocean decade field program. Frontiers in Marine Science, vol. 7, 584861, 2020.

Huvenne, Veerle A.I., and others. Effectiveness of a deep-sea cold-water coral Marine Protected Area, following eight years of fisheries closure. Biological Conservation, vol. 200, pp. 60-69, 2016.

ICES. Workshop on scoping of physical pressure layers causing loss of benthic habitats D6C1–methods to operational data products (WKBEDLOSS). ICES Scientific Reports, vol. 1, no. 15, 2019.

Ismail, Khaira, and others. Quantifying spatial heterogeneity in submarine canyons. Progress in Oceanography, vol. 169, pp. 181-198, 2018.

Jalkanen, Jukko-Pekka, and others. Underwater noise emissions from ships during 2014–2020. Environmental Pollution, vol. 311, 110766, 2022.

Jeunen, Gert-Jan, and others. Characterizing Antarctic fish assemblages using eDNA obtained from marine sponge bycatch specimens. Reviews in Fish Biology and Fisheries, vol. 34, No. 1, pp. 221-238, 2024.

Jones, Daniel O.B. and others. "Deep-sea mining: processes and impacts". In *Natural Capital and Exploitation of the Deep Ocean*. Maria Baker, Eva Ramirez-Llodra and others, eds. (Oxford University Press, 2020).

Jones, Ellie S., and others. Distributions of microplastics and larger anthropogenic debris in Norfolk Canyon, Baltimore Canyon, and the adjacent continental slope (Western North Atlantic Margin, U.S.A.). Marine Pollution Bulletin, vol. 174, 113047, 2022.

Kane, Ian A., and others. Large volumes of microplastics are transported to the deep sea by turbidity currents. Science, vol. 368, pp. 1140–1145, 2024.s

Kawaguchi, So, and others. Climate change impacts on Antarctic krill behaviour and population dynamics. Nature Reviews Earth & Environment, vol. 5, pp. 43–58, 2024.

Kujawinski, Elizabeth B., and others. The first decade of scientific insights from the Deepwater Horizon oil release. Nature Reviews Earth & Environment, vol. 1, pp. 237-250, 2020.

Lang, Bethan J., and others. Impacts of ocean warming on echinoderms: A meta-analysis. Ecology and Evolution, vol. 13, e10307, 2023.

Levin, Lisa A.. Manifestation, drivers, and emergence of open ocean deoxygenation. Annual Review of Marine Science, vol. 10, pp. 229–260, 2018.

Levin, Lisa A. Sustainability in deep water: The challenges of climate change, human pressures, and biodiversity conservation. Oceanography, vol. 32 (2), pp. 170–180, 2019.

Long, Stephen, and others. Identification of a soft coral garden candidate vulnerable marine ecosystem (VME) using video imagery, Davis Strait, West Greenland. Frontiers in Marine Science, vol. 7, 460, 2020.

Loutrage, Liz, and others. The nocturnal distribution of deep-pelagic fish on the continental slope of the Bay of Biscay. Progress in Oceanography, vol. 216, 103070, 2023.

Luneva, Maria V., and others. Hotspots of dense water cascading in the Arctic Ocean: Implications for the Pacific Water pathways. Journal of Geophysical Research: Oceans, vol. 125, e2020JC016044, 2020.

Maier, Katherine L., and others. Sediment and organic carbon transport and deposition driven by internal tides along Monterey Canyon, offshore California. Deep Sea Research Part I: Oceanographic Research Papers, vol. 153, 103108, 2019.

Matos, Fábio L., and others. Canyons pride and prejudice: Exploring the submarine canyon research landscape, a history of geographic and thematic bias. Progress in Oceanography, vol. 169, pp. 6-19, 2018.

Miller, Kathryn A., and others. An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. Frontiers in Marine Science, vol. 4, 418, 2018.

McLean, Dianne L., and others. Influence of offshore oil and gas structures on seascape ecological connectivity. Global Change Biology, vol. 28, No. 11, pp. 3515-3536, 2022.

McPhee-Shaw, Erika E., and others. Submarine canyon oxygen anomaly caused by mixing and boundary-interior exchange. Geophysical Research Letters, vol. 48, e2021GL092995, 2021.

Merchant, Nathan D., and others. Impulsive noise pollution in the Northeast Atlantic: Reported activity during 2015–2017. Marine Pollution Bulletin, vol. 152, 110951, 2020.

Moccia, Davide, and others. New sites expanding the "Sardinian cold-water coral province" extension: A new potential cold-water coral network? Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 2, No. 1, pp. 153-160, 2019.

Moccia, Davide, and others. Spatial distribution and habitat characterization of marine animal forest assemblages along nine submarine canyons of Eastern Sardinia (central Mediterranean Sea). Deep Sea Research Part I: Oceanographic Research Papers, vol. 167, 103422, 2021.

Morato, Telmo, and others. Climate-induced changes in the suitable habitat of cold- water corals and commercially important deep-sea fishes in the North Atlantic. Global Change Biology, vol. 26, pp. 2181–2202, 2020.

Morato, Telmo, and others. Models of VME taxa and functional traits distribution: Maps demonstrating the outcomes of Atlantic-wide VME taxa and functional traits distribution modeling. Deliverable D2.2, iAtlantic Project, 2023.

Moura, Teresa, and others. Assessing spatio-temporal changes in marine communities along the Portuguese continental shelf and upper slope based on 25 years of bottom trawl surveys. Marine Environmental Research, vol. 160, 105044, 2020.

Nestorowicz, Iga-Maria, and others. Identifying habitats of conservation priority in the São Vicente submarine canyon in Southwestern Portugal. Frontiers in Marine Science, vol. 8, 672850, 2021.

Niner, Holly, J., and others. Deep-sea mining with no net loss of biodiversity — An impossible aim. Frontiers in Marine Science, vol. 5, 53, 2018.

Oberle, Ferdinand K.J., and others. "Fishing activities", in *Submarine Geomorphology*, Aaron Micallef and others, eds.. (Cham, Springer Geology, Springer, 2018).

Ogaki, Mayara B., and others. Cultivable fungi present in deep-sea sediments of Antarctica: taxonomy, diversity, and bioprospecting of bioactive compounds. Extremophiles, vol. 24, No. 2, pp. 227-238, 2020.

Paradis, Sarah, and others. Evidence of large increases in sedimentation rates due to fish trawling in submarine canyons of the Gulf of Palermo (SW Mediterranean). Marine Pollution Bulletin, vol. 172, 112861, 2021.

Paradis, Sarah, and others. Spatial distribution of sedimentation-rate increases in Blanes Canyon caused by technification of bottom trawling fleet. Progress in Oceanography, vol. 169, pp. 241-252, 2018.

Pearman, Tabitha R.R., and others. Spatial and temporal environmental heterogeneity induced by internal tides influences faunal patterns on vertical walls within a submarine canyon. Frontiers in Marine Science, vol. 10, 1091855, 2023.

Pierdomenico, Martina, and others. Transport and accumulation of litter in submarine canyons: a geoscience perspective. Frontiers in Marine Science, vol. 10, 1224859, 2023.

Pierdomenico, Martina, and others. Massive benthic litter funnelled to deep sea by flash-flood generated hyperpycnal flows. Scientific Reports, vol. 9, 5330, 2019.

Pierdomenico, Martina, and others. The key role of canyons in funnelling litter to the deep sea: A study of the Gioia Canyon (Southern Tyrrhenian Sea). Anthropocene, vol. 30, 100237, 2020.

Puig, Pere, and others. Ploughing the deep seafloor. Nature, vol. 489, pp. 286-290, 2012.

Pusceddu, Antonio, and others. Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. Proceedings of the National Academy of Sciences, vol. 111, No. 24, pp. 8861-8866, 2014.

Ramirez-Llodra, Eva. "Deep-sea ecosystems: Biodiversity and anthropogenic mpacts", in *The law of the seabed – Acces, uses and protection of seabed resources*, Catherine Banet, ed. Publications on Ocean Development, vol. 90, pp. 36-60, 2020.

Ransier, Krista T., and others. Electronic tags reveal high migratory diversity within the largest Atlantic halibut (*Hippoglossus hippoglossus*) stock. Canadian Journal of Fisheries and Aquatic Sciences, vol. 81, No. 7, pp. 828-846, 2024.

Rice, Jake, and others. Marine Strategy Framework Directive - Task Group 6 Report Seafloor integrity. Luxembourg, Office for Official Publications of the European Communities, 2010.

Roberts, John M., and others. A blueprint for integrating scientific approaches and international communities to assess basin-wide ocean ecosystem status. Communications Earth & Environment, vol. 4, 12, 2023.

Rouse, Sally, and others. Benthic conservation features and species¡ associated with subsea pipelines: Considerations for decommissioning. Frontiers in Marine Science, vol. 6, 200, 2019.

Saldías, Gonzalo S., and others. Circulation and upwelling induced by coastal trapped waves over a submarine canyon in an idealized eastern boundary margin. Geophysical Research Letters, vol. 48, e2021GL093548, 2021.

Salgado Kent, Chandra, and others. Seasonal productivity drives aggregations of killer whales and other cetaceans over submarine canyons of the Bremer Sub-Basin, south-western Australia. Australian Mammalogy, vol. 43, No. 2, pp. 168-178, 2021.

Santín, Andrew, and others. Sponge assemblages on the deep Mediterranean continental shelf and slope (Menorca Channel, Western Mediterranean Sea). Deep Sea Research Part I: Oceanographic Research Papers, vol. 131, pp. 75-86, 2018.

Santora, Jarrod A., and others,. Submarine canyons represent an essential habitat network for krill hotspots in a Large Marine Ecosystem. Scientific Reports, vol. 8, 7579, 2018.

Saunders, Benjamin J., and others. Quantifying patterns in fish assemblages and habitat use along a deep submarine canyon-valley feature using a remotely operated vehicle. Frontiers in Marine Science, vol. 8, 608665, 2021.

Scanes, Elliot, and others. The long-lived deep-sea bivalve *Acesta excavata* is sensitive to the dual stressors of sediment and warming. Marine Pollution Bulletin, vol. 202, 116323, 2024.

Schönke, Mischa, and others. Quantifying the physical impact of bottom trawling based on high-resolution bathymetric data. Remote Sensing, vol. 14, No. 12, 2782, 2022.

Schuler, Alicia R., and others. Humpback whale movements and behavior in response to whale-watching vessels in Juneau, AK. Frontiers in Marine Science, vol. 6, 710, 2019.

Simões, Marianna V.P., and others. Environmental matching reveals non-uniform range-shift patterns in benthic marine Crustacea. Climatic Change, vol. 168, 31, 2021.

Sprogis, Kate R., and others. Vessel noise levels drive behavioural responses of humpback whales with implications for whale-watching. eLife, vol. 9, e56760, 2020.

Strong, James A., and others. Recovery and restoration potential of cold-water corals: experience from a deep-sea marine protected area. Restoration Ecology, vol. 31, No. 8, e13970, 2023.

Suárez-Rojas, Chaitanya, and others. Sustainability in whale-watching: A literature review and future research directions based on regenerative tourism. Tourism Management Perspectives, vol. 47, 101120, 2023.

Submarine Telecoms Forum. Industry report 2023-2024. Submarine Telecoms Forum, Inc., 2024.

Sun, Kai, and others. Review of underwater sensing technologies and applications. *Sensors, vol. 21, No.* 23, 7849, 2021.

Sweetman, Andrew K., and others. Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene, vol.* 5, 4, 2017.

Taviani, Marco, and others. First assessment of anthropogenic impacts in submarine canyon systems off southwestern Australia. Science of the Total Environment, vol. 857, 159243, 2023.

Thiele, Torsten. “Deep-sea natural capital: Putting deep-sea economic activities into an environmental context”, in *Environmental Issues of Deep-Sea Mining*, Rahul Sharma, ed. (Cham, Springer, 2019).

Thran, Amanda C., and others. Controls on the global distribution of contourite drifts: Insights from an eddy-resolving ocean model. Earth and Planetary Science Letters, vol. 489, pp. 228-240, 2018.

Tian, Zhuangcai, and others. Suspension and transportation of sediments in submarine canyon induced by internal solitary waves. Physics of Fluids, vol. 36, No. 2, 022112, 2024.

Tiano, Justin, and others. Global meta-analysis of demersal fishing impacts on organic carbon and associated biogeochemistry. Fish & Fisheries, vol. 00, pp. 1–15, 2024.

Trotter, Julie A., and others. First ROV exploration of the Perth Canyon: Canyon setting, faunal observations, and anthropogenic impacts. Frontiers in Marine Science, vol. 6, 173, 2019.

Trotter, Julie A., and others. Unveiling deep-sea habitats of the Southern Ocean-facing submarine canyons of south-western Australia. Progress in Oceanography, vol. 209, 102904, 2022.

van Putten, Elizabeth I., and others. History matters: societal acceptance of deep-sea mining and incipient conflicts in Papua New Guinea. Maritime Studies, vol. 22, 32, 2023.

Vare, Lindsay L., and others. Scientific considerations for the assessment and management of mine tailings disposal in the deep sea. Frontiers in Marine Science, vol. 5, 17, 2018.

Varrella, Stefano, and others. Diversity, ecological role and biotechnological potential of Antarctic marine fungi. Journal of Fungi, vol. 7, No. 5, 391, 2021.

Vogt, Craig, and Jens Skei. "An emerging environmental issue: Marine discharge of mine tailings", in *Handbook on Marine Environment Protection - Science, Impacts and Sustainable Management*, Markus Salomon and Till Markus, eds. (Springer Int. Publ., 2018).

Wang, Ya-Nan, and others. Progress in research on bioactive secondary metabolites from deep-sea derived microorganisms. Marine Drugs, vol. 18, No. 12, 614, 2020.

Ward, Collin P., and Christopher M. Reddy. We need better data about the environmental persistence of plastic goods. Proceedings of the National Academy of Sciences, vol. 117, No. 26, pp. 14618–14621, 2020.

Weaver, Phillip P.E., and Billett, David. "Environmental impacts of nodule, crust and sulphide mining: An overview", in *Environmental Issues of Deep-Sea Mining - Impacts, Consequences and Policy Perspectives*, Rahul Sharma, ed. (Springer Cham, 2019).

Wen, Zhixin, and others. Analysis of the world deepwater oil and gas exploration situation. Petroleum Exploration and Development, vol. 50, No. 5, pp. 1060-1076, 2023.

Wienberg, Claudia, and others. "Cold-water coral reefs in the oxygen minimum zones off West Africa", in *Cold-Water Coral Reefs of the World. Coral Reefs of the World 19*, Erik Cordes and Furu Mienis, eds. (Cham, Springer, 2023).

Wilckens, Henriette. Contourite development: Analysing the interaction between bottom currents and sedimentary systems. PhD Thesis, University of Bremen, Germany, 2023.

Willis, Kathryn, and others. Local waste management successfully reduces coastal plastic pollution. One Earth, vol. 5, pp. 666-676, 2022.

Wynne-Cattanach, Bethan L., and others. Observations of diapycnal upwelling within a sloping submarine canyon. Nature, vol. 630, pp. 884–890, 2024.

Yin, Shaoru, and others. Efficient organic carbon burial by bottom currents in the ocean: A potential role in climate modulation. Geophysical Research Letters, vol. 51, e2024GL109444, 2024.

Zhang, Chuwen, and others. Deep-sea microbial genetic resources: new frontiers for bioprospecting. Trends in Microbiology, vol. 32, No. 4, pp. 321–324, 2024.

Zhang, Gongcheng, and others. Giant discoveries of oil and gas fields in global deepwaters in the past 40 years and the prospect of exploration. Journal of Natural Gas Geoscience, vol. 4, No. 1, pp. 1-28, 2019.

Zhong, Guangfa, and Xiaotong Peng. Transport and accumulation of plastic litter in submarine canyons—The role of gravity flows. Geology, vol. 49, No. 5, pp. 581–586, 2021.

https://cyprus-mail.com/2022/10/14/euroasia-interconnector-ready-for-construction-historic-day-president-says/: News on the Great Sea Interconnector (formerly EuroAsia Interconnector) power cable dated 14/10/2022.

https://subtelforum.com/online-map/: Submarine cables of the world viewer.

https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx: List of amendments, terms of reference and assessment frameworks, regulations and other matters relevant to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (pdfs for downloading).

https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx: General information on the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.

https://www.internetsociety.org/resources/doc/2024/2024-west-africa-submarine-cable-outage-report/: 2024 West Africa submarine cable outage report.

Section 4

Sub-chapter 5k: High-latitude ice

Coordinating Author: Walker O. Smith, Jr.

Authors: (alphabetical order)
Maksym, Ted; Massom, Robert A.; Sergienko, Olga V.; Smith, Walker O., Jr.; Stammerjohn, Sharon E.

---

1 Key points

- Loss of continental ice has accelerated from Greenland since the early 1990's and from Antarctic ice sheets since the late 1990s, contributing 21.0 mm to global sea-level rise from 1992-2020.
- ~~Arctic sea ice will continue to decline in the future , leading to model predictions of a sea ice-free Arctic Ocean during summer by 2050and,. according to models, lead to an ice-free Arctic during summer.~~
- Arctic sea ice will continue to decline in the future, leading to model predictions of occurrences of an ice-free Arctic Ocean during Septembers by mid-21st century
- The abrupt reduction in Antarctic sea ice extent and duration since 2016 may herald a fundamental change in the Southern Ocean.

2 Introduction

This chapter focuses on two key components of our planet's climate system - sea ice and ice sheets - and how they respond to climate change. It highlights the substantial changes occurring in high-latitude cryospheres of both polar regions and their influences on the ocean and atmosphere, particularly physical impacts, as biological impacts were treated previously (United Nations, 2022a,b). Sea ice forms from freezing seawater as the ocean cools each autumn-winter. Ice sheets, on the other hand, comprise glacial ice formed from snow accumulation over thousands of years which compacts and flows seaward under gravity. The mass loss from ice sheets injects large volumes of freshwater into the ocean and contributes to sea-level rise. Sea ice and ice sheets profoundly influence - and are strongly impacted by - the ocean and the atmosphere.

Interactions of the polar cryosphere with the ocean and atmosphere impact global circulation and lower-latitude atmospheric patterns. and influence global weather and climate, the ocean's freshwater budget, the uptake of anthropogenic heat and carbon, and

global sea level rise. Similarly, polar systems are influenced by atmospheric teleconnections to lower-latitudes and ocean variability there. At the same time, changes in the extent, mass, formation and melt, thickness and properties of polar ice can accelerate change via complex feedback processes (Goosse and others, 2018). As a thin veneer that lies between the ocean and atmosphere, sea ice reacts to change and variability in weather patterns and climate drivers at sub-daily, seasonal and decadal time scales. In contrast, the Antarctic and Greenland ice sheets respond over centuries to millennia, although more rapid changes are beginning to occur. In short, ice sheets and sea ice are both sensitive indicators and influencers of climate change and variability via highly coupled ocean-atmosphere-cryosphere processes ~~(IPCC, 2023)~~.

2.1 The Arctic and Antarctic Sea-Ice Systems

2.1.1 Similarities and Contrasts

Sea ice includes *pack ice* that is in constant motion due to winds and ocean currents, and *fast ice* that is attached to coastal margins. Each year, Earth's high-latitude oceans are transformed by the advance and retreat of sea ice driven by seasonal changes in ocean and atmosphere temperatures, wind patterns, and solar insolation. In the Arctic, sea-ice extent (SIE) varies between ~15 x 10^6 km^2 in March to ~6 x 10^6 km^2 in September (Fig. 1). The lowest Arctic SIE since the start of the satellite record in 1979 occurred in September 2012 (3.39 x 10^6 km^2). In contrast, Antarctic SIE varies between ~19 x 10^6 km^2 in September to ~3 x 10^6 km^2 in February (Fig. 2), with the lowest summer minimum on record being in 2023 (1.79 x 10^6 km^2). Sea ice greatly influences biological processes in both polar systems by impacting light, nutrients, and food availability and by forming habitats for the diverse biota (United Nations, 2017, 2022a).

There are distinct differences between the two polar sea-ice systems due to differences in their geographical settings, processes of sea-ice formation and decay, and ice-ocean-atmosphere interactions (Turner and Overland, 2009; Maksym, 2019). Arctic sea ice largely forms within the Arctic Ocean basin and is constrained by adjacent land masses (although sea ice in the Bering and East Greenland Seas is unconstrained). Large-scale sea-ice motion is dominated by an atmospheric high-pressure system in the Western Arctic, the oceanic Transpolar Drift Stream in the central Arctic and the Beaufort Gyre, the first two of which export sea ice into the North Atlantic via Fram Strait.

In contrast, Antarctic sea ice seasonally expands outward from (then retreats back to) the Antarctic continent, thereby buffering (then exposing) the coastal margins of the

Antarctic Ice Sheet (Reid and Massom, 2022). In winter, Antarctic sea ice extends to lower latitudes compared to the Arctic, while continually being exposed to the high winds and waves of the Southern Ocean (Massom and Stammerjohn, 2010). The overall configuration and motion of the Antarctic sea ice reflects large-scale patterns of atmospheric and ocean circulation (Holland and Kwok, 2012). Regional variations in these factors combine to create variations in timings of annual ice-edge advance, retreat, annual duration, and maximum and minimum SIE (Stammerjohn and others, 2008). Antarctic SIE displays high variability over temporal scales of days to weeks due to changing winds and temperatures associated with the passage of cyclones (Uotila and others, 2011). On seasonal and interannual timescales, SIE and the timings of sea-ice advance and retreat are influenced by modes of climate variability such as the El Niño-Southern Oscillation (Stammerjohn and others, 2008) and the Southern Annular Mode, the latter being a function of the surface pressure gradient between Antarctica and mid-latitudes (Marshall, 2003).

Sea-ice thickness strongly influences the heat and freshwater budgets of both polar oceans (Maksym and others, 2012). Historically, Arctic sea ice was substantially thicker, with maximum thickness reaching 6 m. In recent years much of the multiyear (MYI) has disappeared, and Arctic sea ice is now 1-2 m thick (Kwok, 2018) and largely first-year ice (FYI), thus being similar to the typical ~1 m thick Antarctic FYI (Worby and others, 1998). Fast ice is confined to narrow coastal bands a few kilometers to hundreds of kilometers wide in both the Antarctic and Arctic – depending on coastal configuration and bathymetry and the distribution of grounded icebergs – and can be annual or perennial (Mahoney, 2018; Fraser and others, 2021).

There are also differences in the oceanic settings of the two polar systems. Arctic water columns are strongly stratified, with low-salinity water at the surface underlain by a cold, salty halocline that insulates the sea ice from the warm, deeper Atlantic Water (Steele and Boyd, 1998). In the Antarctic, the upper water column is substantially saltier (although freshening in recent years; United Nations, 2022a), allowing mixing to greater depths, and a strong upward transfer of heat from warm Circumpolar Deep Water that limits the thermodynamic growth of Antarctic sea ice to ~70 cm (Martinson, 1990). Only during summer does the surface Southern ~~Antarctic~~ ocean become seasonally stratified by sea-ice melt (Haumann and others, 2016).

Due to its high reflectance and low thermal conductivity, snow that ~~accumulation~~ accumulates on sea ice substantially modifies the physical and optical properties and

growth/melt rates of the ice and its interactions with the ocean and atmosphere (Sturm and Massom, 2017). Snow depths on sea ice tend to be greater in the Antarctic than in the Arctic due to higher precipitation over the Southern Ocean (Webster and others, 2018). Sea ice alsoF seasonally limits solar heating of the upper ocean and also acts as an insulating barrier between the ocean and atmosphere that reduces exchanges of heat and gases (e.g., water vapor, carbon dioxide), as well as vertical mixing of the upper ocean. Seasonal sea-ice formation/decay releases vast volumes of brine/freshwater in winter/summer, respectively (Meredith and Brandon, 2017). In coastal regions in the Weddell Sea, Ross Sea, parts of East Antarctica, and in the Labrador and Greenland Seas, particularly high rates of sea-ice formation generate large volumes of dense brine, which sink to form Bottom Waters that drive the global thermohaline circulation (Abernathey and others, 2016).

2.1.2 Greenland and Antarctic Ice Sheets

Continent-wide estimates of ice-sheet mass budgets for both Greenland and Antarctica have been completed (Otosaka and others, 2023). The Greenland and Antarctic ice sheets together store ~68% of our planet's freshwater. The Greenland Ice Sheet (GIS) is ~1.7 x 10^6 km^2 in area, has a mean thickness of 1.67 km, and contains 2.9 x 10^6 km^3 of ice (equivalent to a 7.4 m rise in sea level if completely melted; Kulp and Strauss, 2019). It lies on bedrock above sea level and drains into fjords through outlet glaciers. The Antarctic Ice Sheet (AIS) covers ~14 x 10^6 km^2, has a mean thickness of 2.16 km, and contains 26.9 x 10^6 km^3 of ice (Fretwell and others, 2013), enough to raise sea level by 58 m if melted. The AIS has three components: the West and East Antarctic ice sheets (WAIS and EAIS), and the Antarctic Peninsula. Unlike the GIS and much of the EAIS, a large portion of the WAIS rests on bedrock that is below sea level and more vulnerable to climate change than those ice-sheet areas that are grounded above sea level. The EAIS is substantially higher and thicker than the WAIS (Morlighem and others, 2017) and its response to climate warming represents the largest unknown in projections of future sea-level rise (IPCC, 2023).

Ice sheets impact the ocean by releasing large volumes of freshwater as meltwater orvia icebergs. Direct freshwater input to the ocean occurs by fourfour processes (Straneo and others, 2019):

- surface meltwater runoff (extensive across Greenland and the Antarctic Peninsula in summer);
- discharge of sub-glacial meltwater (largely occurs in Greenland; Fig. 3); and

- basal melting of floating ice shelves through their contact with warm waters (predominantly for Antarctic ice shelves; Fig. 4); and
- iceberg calving.

2.1.3 Icebergs

Calving, the process by which ice mechanically fractures to form icebergs, is a natural and continuous process in the evolution of ice shelves and marine-terminating glaciers and has been estimated to account for half of the ice lost annually from both the AIS (Depoorter and others, 2013) and the GIS (Shiggins and others, 2023). Icebergs drift large distances, or ground on shallow banks where they reside for multiple years and influence coastal sea-ice processes (polynya and fast-ice formation) and in particular conditions around Antarctica (Barber and Massom, 2007). The AIS, with its seaward margin of numerous floating ice shelves and ice tongues, produces vast numbers of icebergs that vary greatly in size, with the largest tabular iceberg being >10,000 km^2 (Budge and Long, 2018). Greenland icebergs are typically small, with dimensions similar to the thickness of the source glacier front (Reeh and others, 2001).

2.2 Change and Variability in the Arctic Ocean-Cryosphere System

2.2.1 Arctic Sea Ice

The response of Arctic sea ice to ~~anthropogenic warming~~ climate change has been dramatic (all sea ice data are available from the NSIDC Sea Ice Index and the ESA Climate Change Initiative; Fig. 5). The current high rate of Arctic sea-ice loss and associated surface-ocean warming is unprecedented in the past 1,500 years (Osborne and others, 2017). Annual SIE has declined since 1979 (the start of the satellite record) but slowed since 2007, with losses being greatest in the East Siberian, Chukchi, Laptev, Barents and Kara Seas (Jahn and others, 2024). The September reduction in SIE is greatest in Beaufort and Chukchi Seas, but the greatest March reduction ~~was~~ has been in the Greenland and Barents Seas ~~https://climate.copernicus.eu/climate-indicators/sea-ice.~~

The Arctic SIE summer reduction has increased open-water duration and reduced~~tions in~~ sea-ice age (Kwok, 2018) and thickness (Petty and others, 2023). Prior to 1970, MYI covered most of the Arctic Ocean i.e., ~5.5 x 10^6 km^2 in winter. Thereafter, MYI area decreased to a minimum of 1.6 x 10^6 km^2 in 2017 (Kwok, 2018), and now the Arctic is largely covered by thinner FYI that is more vulnerable to seasonal melt (Stroeve and Notz, 2018). Climate models

project a continued decline, resulting in an ~~nearly~~ ice-free[20] ~~-free~~ end of summer Arctic Ocean ~~between 2030 and~~by 2050 (Kim and others, 2023; Jahn and others, 2024).

2.2.2 Greenland Ice Sheet

The mass loss of the GIS is the second largest contributor to sea-level rise after ocean thermal expansion (Zemp and others, 2019), contributing ~14±2 mm over 1992-2020 at a loss rate of 169 gigatons per year, representing a 645% increase relative to its historical contribution (from 1992-1996; Otosaka and others, 2023). The enhanced loss of ice from the GIS results from changes in atmospheric and oceanic forcing that drive increases in surface and submarine melting and calving (Hanna and others, 2024).

2.3 Change and Variability in the Antarctic Ocean-Cryosphere System

2.3.1 Southern Ocean Sea Ice

The circumpolar average of Antarctic SIE increased slightly from 1979-2015, reaching consecutive record-high winter SIEs in 2012, 2013 and 2014, but then decreased substantially in 2016, reaching consecutive record-low summer SIEs in 2017, 2022, 2023 and 2024. Extreme record-low winter SIEs occurred in 2023 and 2024. Since the winter of 2015, seasonal SIE has remained largely below the 1979-2024 mean (Fig. 6), potentially heralding a regime shift in the Southern Ocean (Hobbs and others, 2024). An observed shift to longer persistence of sea-ice anomalies, changed response to atmospheric forcing, and increases in the spatial coherence of anomalies (Hobbs and others, 2024, Schroeter and others, 2023) could indicate a fundamental change in the highly coupled sea ice-ocean-atmosphere system (Eayrs and others, 2021; Raphael and Handcock 2022; Purich and Doddridge 2023).

2.3.2 Antarctic Ice Sheet

Between 1992-2020, the AIS lost 2,671 gigatons of ice, equivalent to 7.4 mm of sea-level rise or nearly half of the GIS contribution. Antarctica's contribution to sea-level rise increased from 0.14 mm per year over 1992-1999 to 0.39 mm per year from 2010-2020 (Otosaka and others, 2023). Most of this loss has come from the WAIS, where major outlet glaciers (Pine Island and Thwaites) have undergone enhanced melting, thinning and retreat leading to

[20] The term 'ice-free' used here should not be confused with a formal navigational term 'ice-free' of the relevant UN-bodies (WMO, IMO). As icebergs will continue to be present within the domains of the Arctic and Southern Oceans, the term 'ice-free' navigationally is not applicable.

increased discharge of grounded ice (Jenkins and others, 2018). The Antarctic Peninsula has shed 13 gigatons per year, while East Antarctica remains near equilibrium. East Antarctica, however, constitutes the most uncertain component in future predictions of Antarctica's contribution to sea level rise (Fricker and others, 2025).

2.3.3 Antarctic Ice Shelves

Of paramount importance to the Antarctic ice sheet-ocean system is the ~~dynamics~~ structural integrity of ice shelves, which are far less common around the GIS (Bindschadler and others, 2011). Ice shelves play a crucial role in moderating the ice sheet's contribution to sea-level rise by buttressing the discharge of grounded ice mass into the ocean~~.~~, yet they ~~Ice shelves~~ are the most vulnerable part of the ice sheet system, with recent extensive thinning due to basal melting by the increased presence of warm ocean waters within ice shelf cavities (Verfaillie and others, 2022). Moreover, abrupt ice-shelf mechanical disintegration has occurred, caused by thinning, melting and increased exposure to wave forcing along ice shelf fronts e.g., on the Antarctic Peninsula (Massom and others, 2018) (Fig. 7). Rates of basal melting and calving vary regionally (Hanna and others, 2024) and are impacted by atmospheric and oceanic forcing. Iceberg calving is the largest factor affecting ice shelf area, whereas ice-front retreat and thinning are secondary factors (Greene and others, 2022). Large calving events (e.g., tabular iceberg B15) can disrupt Antarctic Bottom Water (AABW) formation by decreasing sea-ice production in coastal polynyas (areas of vigorous ice production driven by persistent off-ice winds; Tamura and others, 2012). Additionally, glacial meltwater inputs and ocean freshening can affect sea-ice production, and in certain areas (e.g., the Ross Sea) can also influence AABW production (Jacobs and Giulivi, 2010). There is substantial concern that various ice shelf and glacial response processes could lead to rapid ice loss (as characterized by the IPCC (2023) as a low-likelihood, high-impact, scenario for high rates of sea level rise), but the mechanisms for such collapse are uncertain (e.g. Sergienko, 2022, Morlighem and others, 2024).

3 Outlook

Under present emission rates of greenhouse gases, ice coverage and volume will continue to decrease, and the impacts of this reduction will increase markedly (Chown and others, 2022). With increased open water in both polar regions and the loss of a protective sea-ice buffer, erosion of coastal margins will accelerate due to predicted increased storms and wave heights. Increased ice discharge from ice sheets will result in a heightened sea level, endangering coastal communities globally. Increased shipping and other human activities (e.g., tourism) in both regions will undoubtedly result in greater

disturbance and release of pollutants, endangering regional biota. Loss of sea ice in both regions also has the potential to accentuate climate warming via complex feedback mechanisms (Goosse et al., 2018) which further accelerate ice loss.

4 Remaining key knowledge and capacity gaps

While significant advances have been made to understand processes driving cryospheric change in polar regions, further progress is urgently needed, given the global impacts of ice loss and the fact that climate models cannot as yet reliably predict future changes and their impacts. Specific gaps include:

- Understanding the recent abrupt declines in Antarctic sea ice (particularly those in autumn-winter) and potential future changes,
- Quantifying the thickness distributions of Antarctic sea ice and its snow cover and determining whether these are changing,
- Understanding subglacial processes under polar ice sheets that control ice discharge into surrounding oceans,
- Understanding processes such as supraglacial and subglacial hydrology and iceberg calving mechanisms,
- Quantifying processes impacting sea-level rise, and
- Reducing uncertainty in the timing of a ~~sea ice free~~open water Arctic.

5 References

Abernathey, Ryan, and others (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geosciences*, vol. 9, pp. 596–601. https://doi.org/10.1038/ngeo2749

Barber, David G., and Robert A. Massom (2007). The role of sea ice in Arctic and Antarctic polynyas. In Walker O. Smith and David G. Barber (Eds.), *Polynyas: Windows to the World's Oceans*, pp. 1-54. Elsevier, Amsterdam.

Bindschadler. Robert, and others (2011). Getting around Antarctica: new high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic ice sheet created for the International Polar Year. *The Cryosphere*, vol. 5, pp. 569-588. https://doi.org/10.5194/tc-5-569-2011

Budge, Jeffery S., and David G. Long (2018). A comprehensive database for Antarctic iceberg tracking using scatterometer data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* vol. 11, pp. 434–442.

Chown, Steven L., and others (Eds.) (2022) *Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action*. Scientific Committee on Antarctic Research, Cambridge, United Kingdom.

Depoorter, M. A. and others (2013). Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature,* vol. 502, pp. 89–92. https://doi.org/10.1038/nature12567

Eayrs, Clare, and others (2021). Rapid decline in Antarctic sea ice in recent years hints at future change. *Nature Geosciences,* vol. 14, pp. 460–464. https://doi.org/10.1038/s41561-021-00768-3

Fraser, Alexander D., and others (2021). Eighteen-year record of circum-Antarctic landfast sea ice distribution allows detailed baseline characterisation, reveals trends and variability. *The Cryosphere*, vol. 15, pp. 5061-5077. https://doi.org/10.5194/tc-15-5061-2021

Fretwell, Peter, and others (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryos*phere, vol. 7, pp. 375–393, https://doi.org/10.5194/tc-7-375-2013

Fricker, Helen A., and others (2025). Antarctica in 2025: Drivers of deep uncertainty in projected ice loss. *Science*, vol. 387, pp. 601-609. https://doi.org/10.1126/science.adt9619

Greene, Chad A., and others (2024). Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022. *Nature,* vol. 625, pp. 523–528. https://doi.org/10.1038/s41586-023-06863-2

Goosse, Hugues, and others (2018). Quantifying climate feedbacks in polar regions. *Nature Commun*ications, vol. 9, art. 1919. https://doi.org/10.1038/sHobbs41467-018-04173-0

Hanna, Edward, and others (2024). Short- and long-term variability of the Antarctic and Greenland ice sheets. *Nature Reviews Earth & Environment*, vol. 5, pp. 193-210. https://doi.org/10.1038/s43017-023-00509-7

Haumann, F. Alexander and others (2016). Sea-ice transport driving Southern Ocean salinity and its recent trends. *Natur*e, vol. 537, pp. 89–92. https://doi.org/10.1038/nature19101

Hobbs, Will, and others (2024). Observation evidence for a regime shift in summer Antarctic sea ice. *Journal of Climate,* vol. 37, pp. 2263-2275. https://doi.org/10.1175/JCLI-D-23-0479.1

Holland, Paul R., and Ron Kwok (2012). Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*, vol. 5, pp. 872-875. https://doi.org/10.1038/ngeo1627

ICCI. State of the Cryosphere 2023 – Two Degrees is Too High. International Cryosphere Climate Initiative (ICCI), Stockholm, Sweden. 62 pp.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115. https://doi:10.59327/IPCC/AR6-9789291691647.

Jacobs, Stanley S., and Claudia F. Giulivi (2010). Large multidecadal salinity trends near the Pacific-Antarctic continental margin. *Journal of Climate*, vol. 23, pp. 508–524. https://doi.org/10.1175/2010JCLI3284.1

Jahn, Alexandra, and others (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth & Environment*, vol. 5, pp. 164-176. https://doi.org/10.1038/s43017-023-00515-9

Jenkins, Adrian, and others (2018). West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. *Nature Geoscience*, vol. 11, no. 10, pp. 733–738. https://doi:10.1038/s41561-018-0207-4

Kim, Yeon-Hee, and others (2023). Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. *Nature Communications*, vol. 14, art. 3139. https://doi.org/10.1038/s41467-023-38511-8

Kulp, S.A., and Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, vol. 10, art. 4844. https://doi.org/10.1038/s41467-019-12808-z

Kwok , Ron (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958-2018). *Environmental Research Letters, vol.* 13, art. 105005, https://doi.org/10.1088/1748-9326/aae3ec

Mahoney, Andy (2018). Landfast ice in a changing Arctic, in *Arctic Report Card 2018*, https://arctic.noaa.gov/report-card/report-card-2018/landfast-sea-ice-in-a-changing-arctic/.

Maksym, Ted, and others (2012). Antarctic sea ice – a polar opposite. *Oceanography*, vol. 25, no. 3, pp. 140–51. http://www.jstor.org/stable/24861407.

Maksym, Ted (2019). Arctic and Antarctic sea ice change: contrasts, commonalities, and causes. *Annual Review of Marine Science*, vol. 11, pp. 187-213. https://doi.org/10.1146/annurev-marine-010816-060610

Marshall, Gareth (2003). Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate*, vol. 16, pp. 4134-4143. https://doi.org/10.1175/1520-0442

Martinson, Douglas G. (1990) Evolution of the Southern Ocean winter mixed layer and sea ice: open ocean deep water formation and ventilation. *Journal of Geophysical Research*, vol. 95, no. C7, pp. 11641-11654. https://doi.org/10.1029/JC095iC07p11641

Massom, Robert, and Sharon Stammerjohn (2010). Antarctic sea ice change and variability – physical and ecological implications, *Polar Science,* vol. 4, pp. 149-186, https://doi.org/10.1016/j.polar.2010.05.001

Massom, Robert, and others (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature*, vol, 558, pp. 383–389, https://doi.org/10.1038/s41586-018-0212-1

Meredith, Michael R., and Mark A. Brandon (2017). Oceanography and sea ice in the Southern Ocean, in *Sea Ice, 4th Edition*, Wiley, David Thomas, ed.

Morlighem, Mathieu, and others (2017). BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation, *Geophysical Research Letters*, vol. 44, pp. 11,051-11,061. https://doi.org/10.1002/2017GL074954

Morlighem, Mathieu and others (2024). The West Antarctic Ice Sheet may not be vulnerable to marine ice cliff instability during the 21st century. *Science Advances,* vol. 10, eado7794. https://doi.10.1126/sciadv.ado7794

Osborne, Emily, and others (2017). Palaeoceanographic perspectives on Arctic Ocean change, in *Arctic Report Card, 2017.* https://www.arctic.noaa.gov/Report-Card

Otosaka, Inès N., and others (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth Systems Science Data*, vol. 15, pp. 1597–1616. https://doi.org/10.5194/essd-15-1597-2023

Petty, Alek, and others (2023). Winter Arctic sea ice thickness from ICESat-2: upgrades to freeboard and snow loading estimates and an assessment of the first three winters of data collection. *The Cryosphere,* vol. 17, pp. 127-156, https://doi.org/10.5194/tc-17-127-2023

Purich, Ariaan, and Edward Doddridge (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. *Nature Communication Earth and Enviro*nment, vol. 4, art. 314. https://doi.org/10.1038/s43247-023-00961-9

Raphael, Marilyn, and Mark Handcock (2022). A new record minimum for Antarctic sea ice. *Nature Reviews Earth and Environ*ment, vol. 3, pp. 215–216. https://doi.org/10.1038/s43017-022-00281-0

Reeh, Niels, and others (2001). Sea ice and the stability of north and northeast Greenland floating glacier. *Annals of Glaciology*, vol. 33, pp. 474–480. https://doi:10.3189/172756401781818554

Reid, Phil E., and Robert A. Massom (2022). Change and variability in Antarctic coastal exposure, 1979–2020. *Nature Communications,* vol. 13**,** art. 1164. https://doi.org/10.1038/s41467-022-28676-z

Sergienko, Olga (2022). No general stability conditions for marine ice-sheet grounding lines in the presence of feedbacks. *Nature Commun*ications, vol. 13, art. 2265. https://doi.org/10.1038/s41467-022-29892-3

Shiggins, Conner J., and others (2023). Automated ArcticDEM iceberg detection tool: insights into area and volume distributions, and their potential application to satellite imagery and modelling of glacier–iceberg–ocean systems. *The Cryosphere*, vol. 17, pp. 15–32. https://doi.org/10.5194/tc-17-15-2023

Stammerjohn, Sharon E., and others (2008). Sea ice in the western Antarctic Peninsula region: Spatio-temporal variability from ecological and climate change perspectives. *Deep-Sea Research II*, vol. 55, pp. 2041-2058. https://doi:10.1016/j.dsr2.2008.04.026

Stammerjohn, Sharon E., and others (2012). Regions of rapid sea ice change: an interhemispheric seasonal comparison. *Geophysical Research Letters*, vol. 39, art. L06501. https://doi.org/10.1029/2012GL050874

Steele, Michael and Timothy Boyd (1998). Retreat of the cold halocline layer in the Arctic Ocean. *Journal of Geophysical Research Oceans*, vol. 103, pp. 10419–10435. https://doi.org/10.1029/98JC00580

Straneo, Fiametta, and others (2019). The case for a sustained Greenland Ice Sheet-Ocean Observing System (GrIOOS). *Froniers in Marine Science,* vol. 6, art. 138. https://doi:10.3389/fmars.2019.00138

Stroeve, Jullienne, and Dirk Notz (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, vol.13, art. 103001. https://doi.10.1088/1748-9326/aade56

Sturm, Matthew, and Robert Massom (2017). Snow in the sea ice system: friend or foe?, in *Sea Ice, 4th Edition*, Wiley, David Thomas, ed., 2017.

Tamura, Takeshi, and others (2012). Potential regime shift in decreased sea ice production after the Mertz Glacier calving. *Nature Communications,* vol. 3, art. 826 (2012). https://doi.org/10.1038/ncomms1820

Turner, John, and James Overland (2009). Contrasting climate change in the two polar regions. *Polar Research*, vol. *28*, pp. 146–164. https://doi.org/10.1111/j.1751-8369.2009.00128.x

United Nations (2017). Chapter 46: High-latitude ice and the biodiversity dependent on it. In *The First Global Integrated Marine Assessment: World Ocean Assessment I*. Cambridge: Cambridge University Press.

United Nations (2022a). Chapter 7K: High-latitude ice. In *The Second Global Integrated Marine Assessment: World Ocean Assessment iI*. Cambridge: Cambridge University Press.

United Nations (2022b). Chapter S4.C3: Trends in the physical and chemical state of the ocean. In *The Second Global Integrated Marine Assessment: World Ocean Assessment iI*. Cambridge: Cambridge University Press.

Uotila, Petteri, and others (2011). Relationships between Antarctic cyclones and surface conditions as derived from high-resolution numerical weather prediction data, *Journal of Geophysical Research,* vol. 116, art. D07109, https://doi:10.1029/2010JD015358

Verfaillie, Deborah, and others (2022). The circum-Antarctic ice-shelves respond to a more positive Southern Annular Mode with regionally varied melting. *Nature*

*Communications Earth and Environ*ment, vol. 3, art. 139, https://doi.org/10.1038/s43247-022-00458-x

Webster, Melinda and others (2018). Snow in the changing sea-ice systems. *Nature Climate Change,* vol. 8, pp. 946–953. https://doi.org/10.1038/s41558-018-0286-7

Zemp, Michael, and others (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature,* vol. 568, pp. 382–386. https://doi.org/10.1038/s41586-019-1071-0

Figure 1. Seasonal mean sea-ice extent in the Arctic and its variability. Mean (black line) calculated from data from 1979 – 2022; grey areas represent 1, 2 and 3 standard deviations (σ) around the mean for the same time period. Also shown are the data from 2023 to illustrate recent changes. Data from https://doi.org/10.7265/EFMZ-2T65.

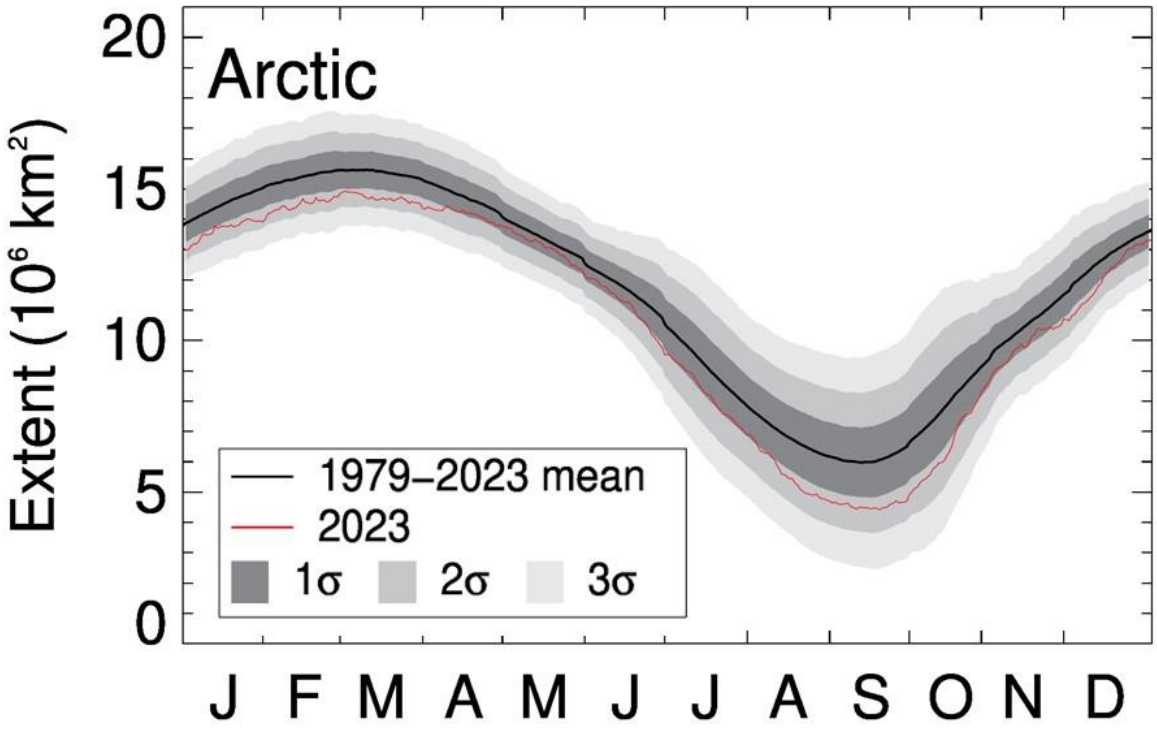


Figure 2. Seasonal mean sea-ice extent in the Antarctic and its variability. Mean (black line) calculated from data from 1979 – 2022; grey areas represent 1, 2 and 3 standard deviations (σ) around the mean for the same period. Also shown are the data from 2023 to illustrate recent changes. Data from https://doi.org/10.7265/EFMZ-2T65.

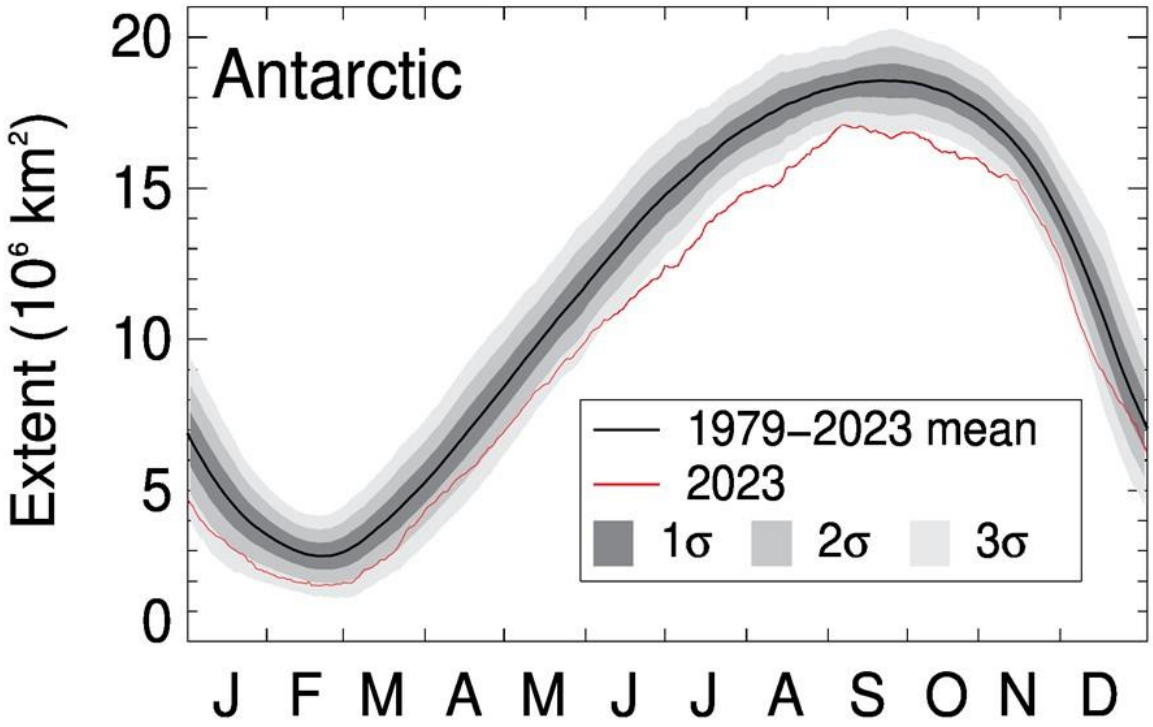


Figure 3. Processes responsible for changes in ice in the Greenland Ice Sheet (from Hanna and others, 2024).

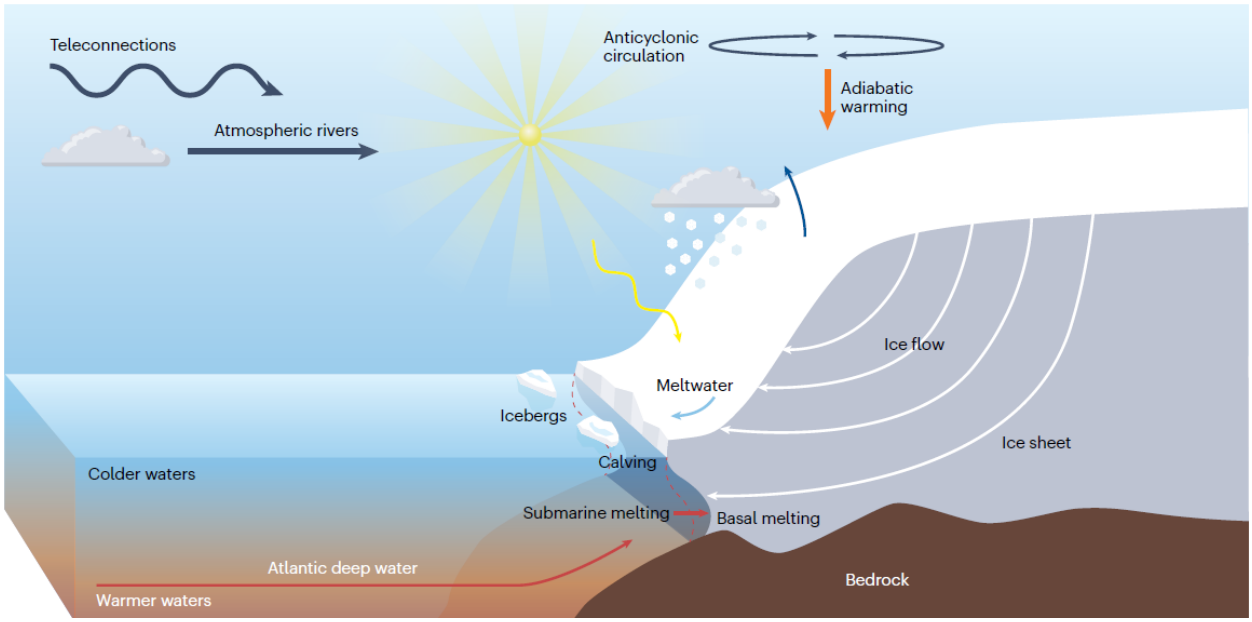


Figure 4. Processes responsible for changes in ice in Antarctic ice sheets (from Hanna and others, 2024).

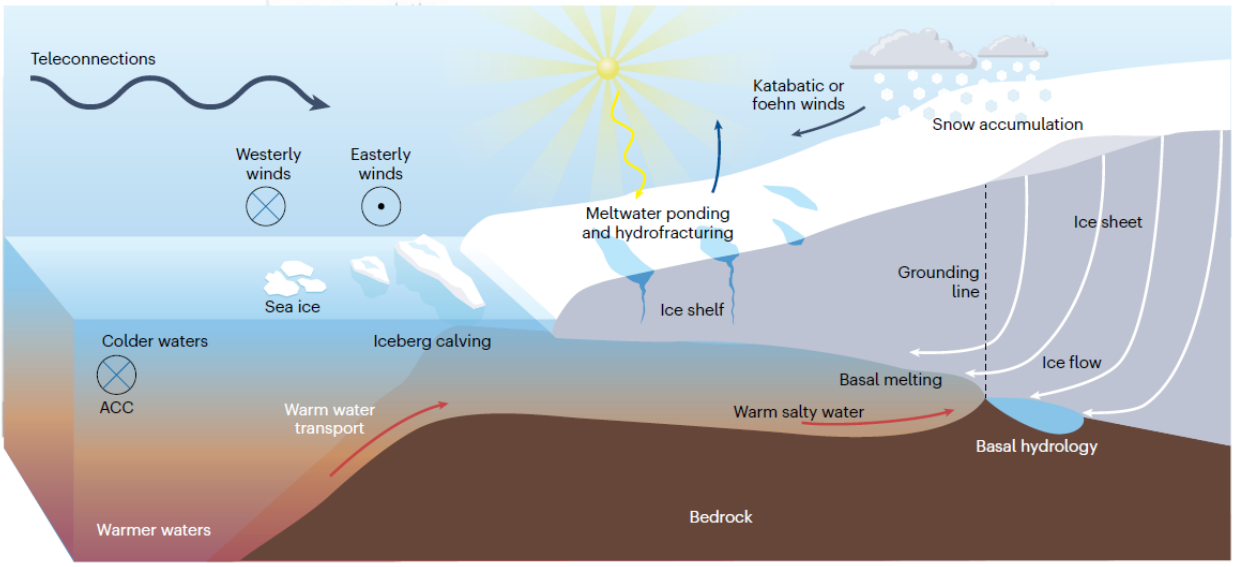


Figure 5. Annual Arctic sea-ice extent since 1979. Data from the NSIDC Sea Ice Index (https://doi.org/10.7265/EFMZ-2T65).

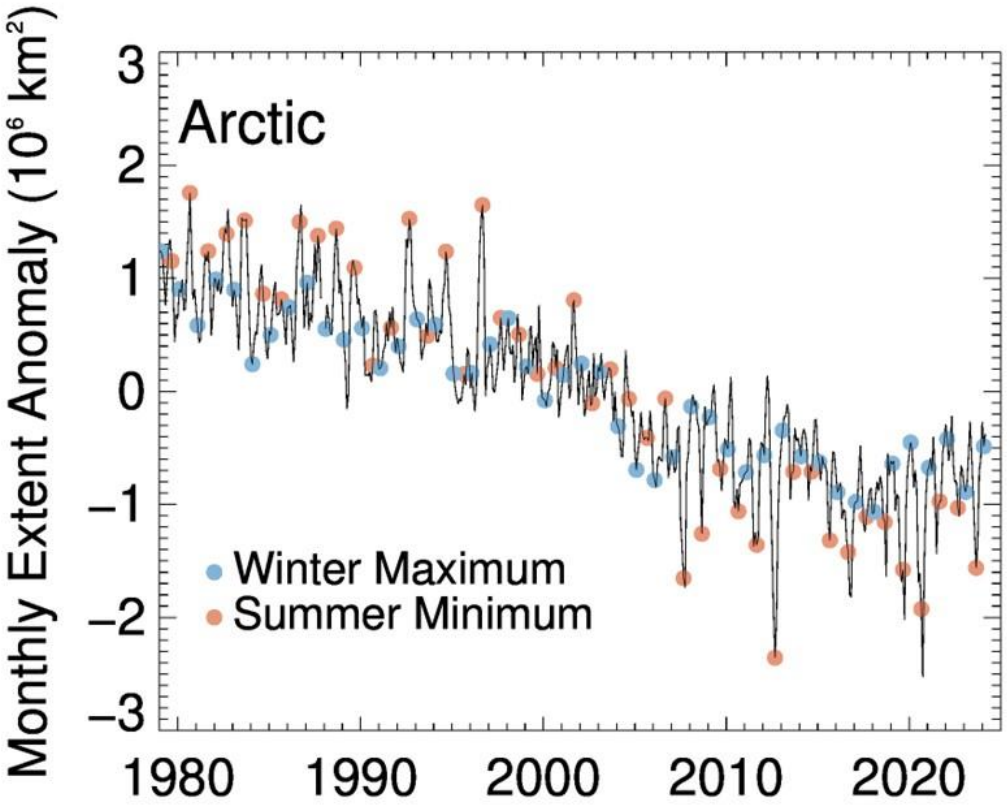


Figure 6. Annual Antarctic sea-ice extent since 1979. Data from the NSIDC Sea Ice Index (https://doi.org/10.7265/EFMZ-2T65).

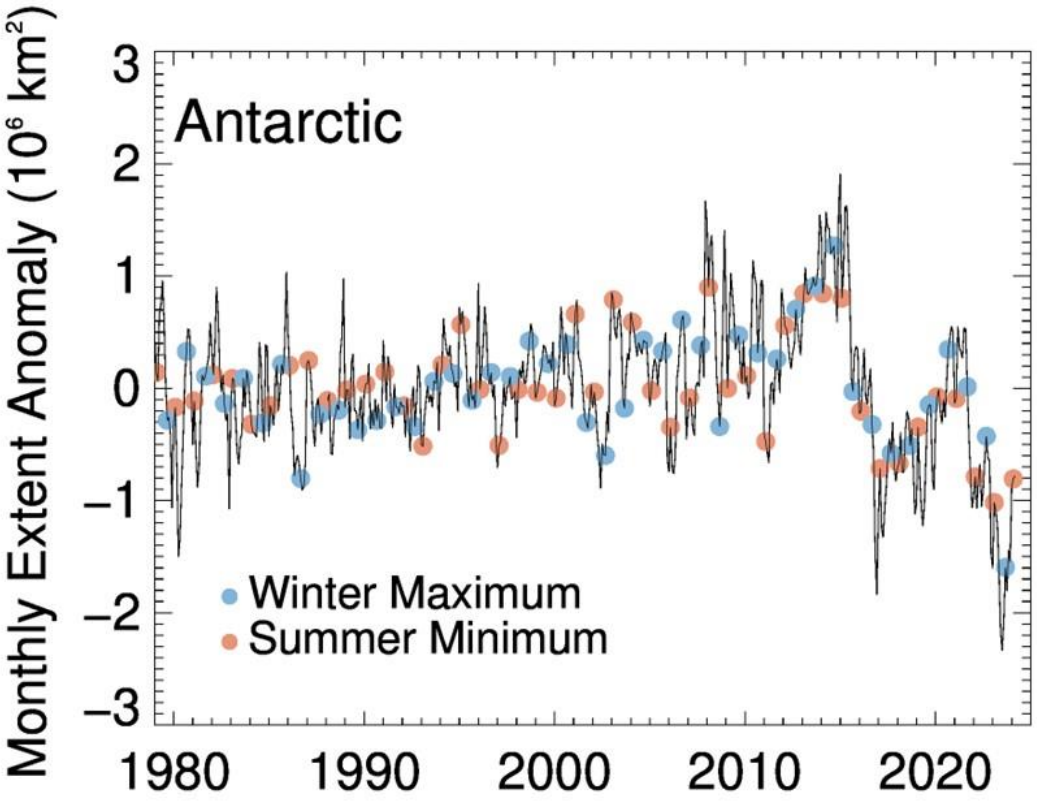
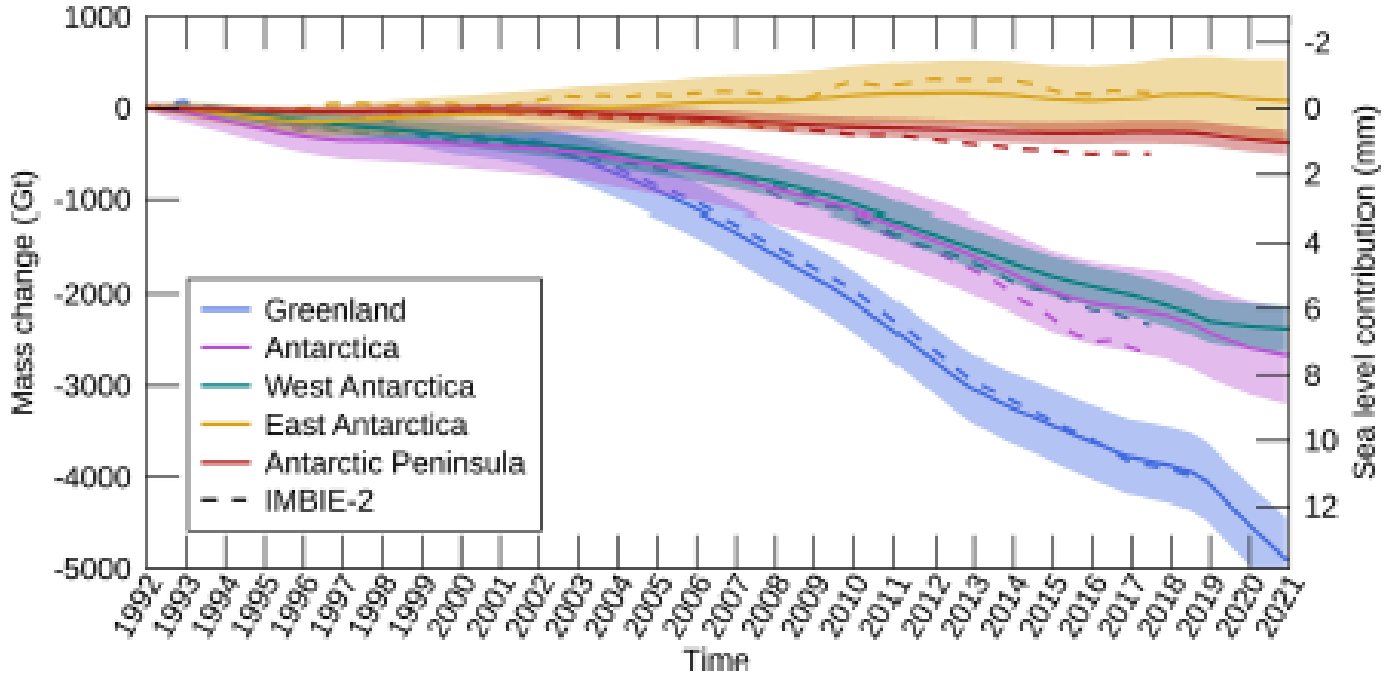


Figure 7. Cumulative ice sheet mass changes for ice sheets in Greenland and Antarctica. The shadings represent the associated uncertainties and are calculated according to Otosaka and others (2023). The dashed lines show the results from IMBIE Team (2020). From Otosaka and others (2023).



Section 4

Sub-chapter 5l: Seamounts and pinnacles

Contributors: Pavanee Annasawmy (convener and lead member), Amy R. Baco, Malcom R. Clark, Réka Domokos, Dannielle Eager, Jason M. Hall-Spencer, Astrid Leitner, Ariadna Mecho, Telmo Morato, Jose Angel Alvarez Perez, Yeqiang Shu, Junlong Zhang

Keynote points

- Increase in:
  - ❖ Seamount studies using novel and integrated approaches such as environmental DNA, camera systems, human-occupied or remotely operated vehicles, baited remote underwater videos, and machine learning.
  - ❖ Seamount pressures and impacts, including fishing, mining interests, ocean acidification and climate change effects.
  - ❖ Protection legislature

- While most studies in the global ocean report a seamount effect on the physical oceanographic environment and biological processes, a few found conflicting results when seamounts are studied on a case-by-case basis.
- Despite significant improvements, our understanding of abyssal seamounts, those found within areas beyond national jurisdictions (hereafter "ABNJs"), and connectivity of seamount fauna remains limited.

1. Introduction

Seamounts are underwater topographic features that rise at least 1,000 meters from the seabed~~rising to at least ~ 1000 m from the seabed~~, with small pillar-like features termed pinnacles (Leitner et al., 2021a). The number of predicted seamount locations has increased due to heightened interest and technical advances (Fig. 1; Yesson et al., 2021; Gevorgian et al., 2023).

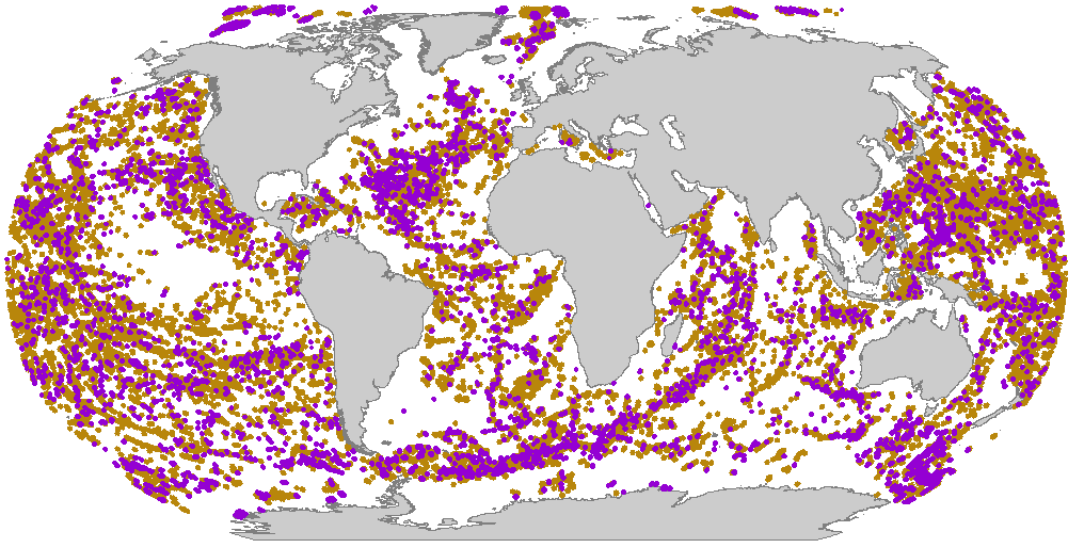


Fig. 1 Yesson et al. 2021; Source: https://doi.pangaea.de/10.1594/PANGAEA.921688. Credit: Pavanee Annasawmy.

The chapter reviews a non-exhaustive list of advancements in our understanding of seamount distributions, related physical processes, ecological patterns, and pressures, highlighting region-specific changes (Supplementary Tables 1 through to 8 accessible here: https://docs.google.com/document/d/1glyPlZQrvNqk6es_x80_aV5Q8Vr4rbLy/edit). The chapter does not include detailed scientific definitions or explanations.

2. Description of changes in knowledge since World Ocean Assessment II (WOAII)

Since WOAII, there has been an increase in seamount publications following re-analysis of archived data and recent multi-disciplinary surveys (Fig. 2), likely driven by increasing interest in exploration, species distribution and ecology for sustainable fisheries and conservation, human impacts, and the role of seamounts in the global carbon pump/sink (Tao et al., 2022).

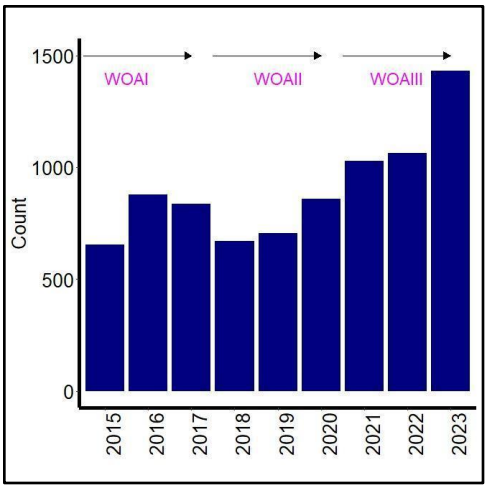


Fig. 2 Increase in seamount literature since WOAI. Source: https://openalex.org/; Accessed 14/06/2024; Credit: Pavanee Annasawmy

Data repository: https://drive.google.com/file/d/1OU0lxMvO-GI7vwzHLNZY3ZCtpVHgzKLk/view?usp=sharing

The following key differences are noted between WOAII and WOAIII (Table A).

Table A. Brief advances in seamount knowledge since WOAII.

Knowledge baseline (WOAII)	Progress in knowledge (WOAIII)
Limited seamount sampling	Enhanced sampling via multidisciplinary cruises, novel approaches, autonomous platforms, and improved seamount detection algorithms
Generalized seamount "ecological paradigms	Paradigms questioned through case-by-case studies
Few region-specific studies noted, especially in the Arctic, Southern, and Indian Oceans	Increased research in these regions
Climate change effects limited to oxygen concentration decline	Additional effects on trophic connections and species distributions
Few working groups limited to the Global North on seamount conservation and management	Seamount working group established in the Indian Ocean

Limited seamount legislature	Expanding seamount legislature

3. Region-specific changes

Global studies provided high-resolution habitat suitability models for deep-sea reef-forming hard corals, few soft coral species, and thorn/black corals (Yesson et al., 2017; Cordes et al., 2023; Tong et al., 2023).

Region-specific changes are summarised below and described in detail here:

https://docs.google.com/document/d/1glyPlZQrvNqk6es_x80_aV5Q8Vr4rbLy/edit?usp=drive_web&ouid=102665398611373187650&rtpof=true

3.1 Arctic

Similar to the WOAII period, recent research on Arctic seamounts (Fig. 3; Supplementary Table 1) focused on sediments and sponge communities, yielding the following key findings: sponge-dominated communities on the Schulz Bank vary by depth and the type of substrata (Meyer et al., 2023); the sedimentary cover on Mosby seamount dates from the middle Miocene or younger (Geissler et al., 2019); on Langseth Ridge, sponge life are associated with extinct seep life (von Jackwoski et al., 2023), and sponges play a role in pelagic-benthic coupling of microbial communities (Morganti et al., 2022); megafaunal densities and assemblage composition vary between seamounts of the Langseth Ridge (Stratmann et al., 2022).

Fig 3. Location of few Arctic seamounts. *Credit: Pavanee Annasawmy*

3.2 South Atlantic and the Wider Caribbean

Vulnerable Marine Ecosystems (hereafter referred to as "VMEs") are groups of species, communities or habitats that may be vulnerable to impacts from fishing activities (FAO, 2025). Areas hosting certain categories of organisms that may be classified as indicator species, such as seamounts, may be considered VMEs with subsequent management measures such as MPA designations to conserve those ecosystem attributes (Watling and Auster, 2021; Vinha et al., 2024). Deep-sea corals and sponges act as indicator species for VMEs (Watling & Auster 2020).

Seamounts of the Discovery rise were explored by an international effort to map VMEs (Fig. 4; Supplementary Table 2). Cold-water coral communities (scleractinians and gorgonians), 36 fish morphotypes (*Laemonema* sp., *Guttigadus* sp.), and 13 cephalopod flank/summit residents, classified in 5 morphotypes (*Moreteuthopsid ingens*, *Histioteuthis cf. atlantica*, *Opisthoteuthis cf. agassizii*) were uncovered. These records supported the maintenance of fishing closure areas within the South East Atlantic Fisheries Organisation (SEAFO) Convention Area (Perez et al., 2022).

Genetic connectivity of seamount populations of Bluenose Warehou (*Hyperoglyphe antarctica*) was reported between 4 seamounts within the Tristan da Cunha Exclusive Economic Zone (hereafter, "EEZ") (Heyworth et al., 2021). Latitude and depth were drivers of benthic assemblage composition, differentiating the 13 tropical and temperate seamounts and oceanic islands of Ascension Island, Saint Helena and Tristan da Cunha (Bridges et al., 2021). Seamounts were hotspots for fishes living below 200 m depth, and micronekton (crustaceans, fishes and cephalopods of 2 to 20 cm in size) over summits < 200 m (Campanella et al., 2021). VMES were described and protected within the boundaries of Marine Protected Areas (hereafter "MPAs") established in the island's EEZs.

The Fernando de Noronha and the Vitória-Trindade seamount chains and underlying currents drive the genetic diversity of the octopus, *Octopus insularis* (Lima et al., 2022).

Further research showed species connectivity between seamounts of the Fernando de Noronha Ridge (Tosetto et al., 2024), seismic activities at Roncador Bank (Idárraga-García & León, 2019), and factors influencing coral assemblage and communities at Anegada Passage (Quattrini et al., 2017; Auscavitch et al., 2020).

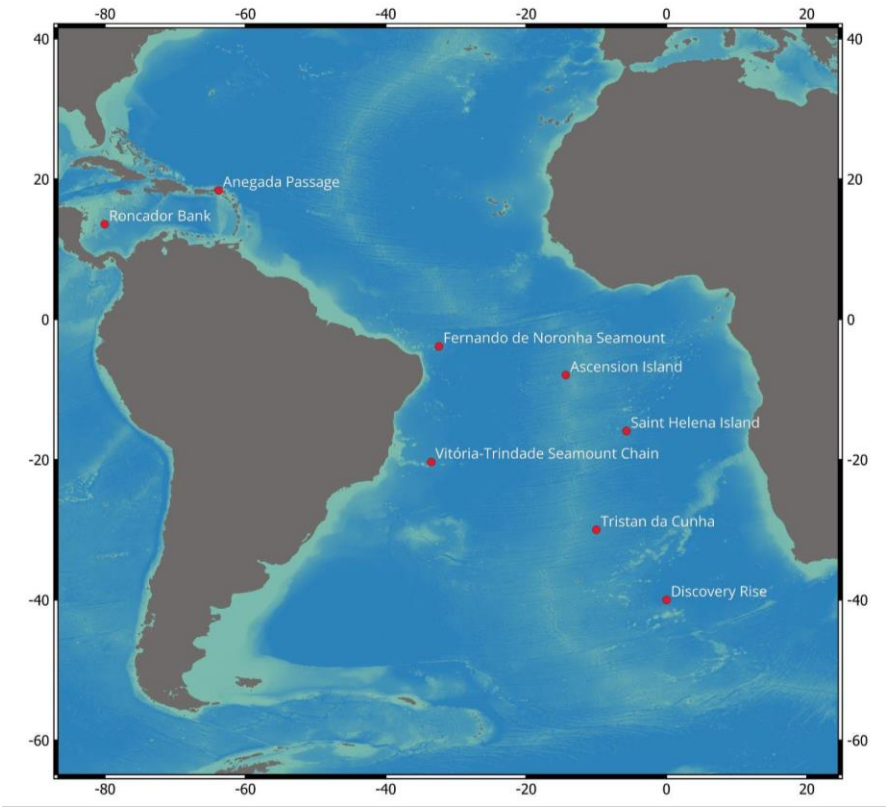


Fig. 4 Location of South Atlantic seamounts, islands, and other features. Credit: Ariadna Mecho.

3.3 North Atlantic

North Atlantic seamounts (Fig. 5; Supplementary Table 3) were investigated during recent expeditions by the USA and Germany. A science-based and participatory process shepherded by the regional government led to the creation of the largest MPA network (Azores Marine Protected Area Network; 287 000 km2) in Europe, 15% designated as fully protected, and 15% as highly protected. Positive effects of the Azores MPA archipelago were observed on resident, large bodied fishes, and higher fish abundance in deeper habitats (Afonso et al., 2018). The dynamic interactions between hydrology and seamount topography support enhanced food supply and presence of VME taxa at Cabo Verde seamounts (Vinha et al., 2024). Internal waves influenced local hydrology, potentially driving food and nutrient supply, and contributing to larval fish aggregations and higher trophic level predators at Senghor seamount (Denda et al., 2017; Mohn et al., 2021), coral larvae dispersal at Rosemary seamount (Stashchuk &Vlasenko, 2021), and supported benthic communities at Ormonde and Formigas seamount (Mosquera Giménez et al., 2019).

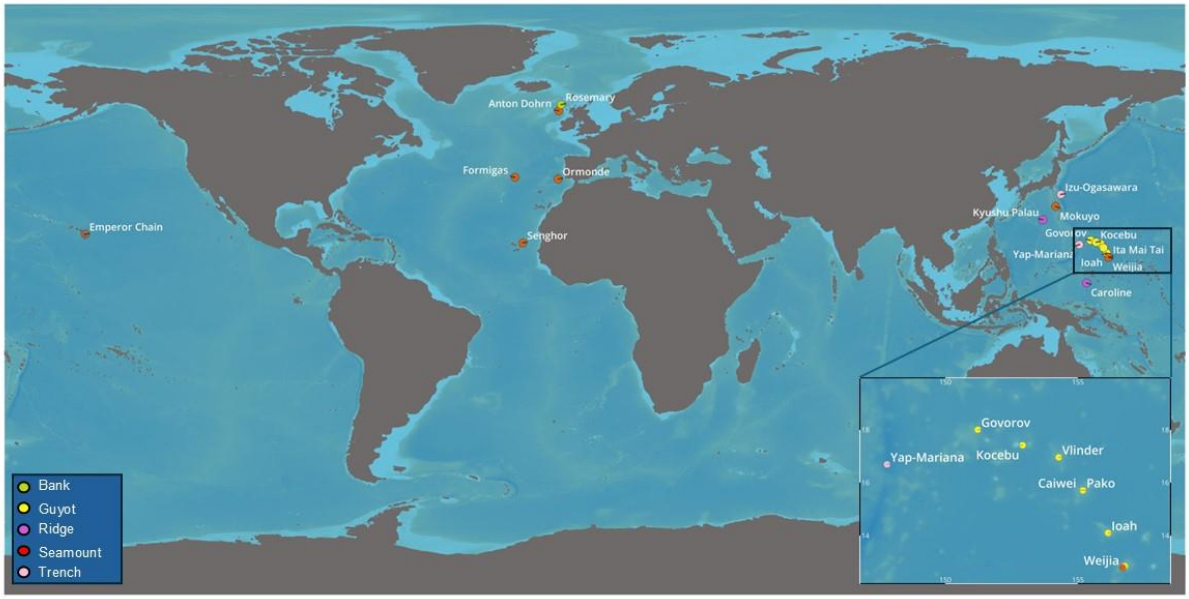


Fig. 5. Location of North Atlantic and Pacific bathymetric features. Credit: Ariadna Mecho.

3.4 North Pacific

North West, Central, and North East Pacific seamounts and pinnacles (Fig. 5) remain the most studied ones in the world's ocean. Recent studies by China, Russia, Canada, and the USA, and the use of autonomous and mobile technologies (useful for providing longer time series, allowing the mapping of seafloor habitats, greater sampling collection, and refined observations through real-time video footage), and machine learning (enhancing data processing and analyses), have enhanced our understanding of the formation and evolution, biodiversity and taxonomy, biogeochemistry, seamount effect on the physical oceanographic environment (e.g, presence of

anticyclonic caps, taylor columns, internal waves) impacting all trophic levels, from microbes to megafauna, and ecosystem research and management of these seamounts (Baco et al., 2017, 2023b, Domokos, 2022; Mejia-Mercado & Baco, 2022, 2023, Leitner et al., 2021a, b, c; Shu et al., 2022; Wang et al., 2024; Supplementary Table 4). Time series of the Mokuyo, Izu-Ogasawara Arc have shown shifts in vent communities (Chen et al., 2024).

Ecologically or Biologically Significant Marine Areas (hereafter "EBSA") are areas that hold special importance in terms of their ecological and biological characteristics (e.g., by providing essential habitats, food sources or breeding grounds for particular species). ABNJ seamounts of the NW Pacific qualify as EBSAs amidst existing or anticipated pressures linked to potential seabed mining and climate change (Du Preez et al., 2023).

The 2024 Seamount Science Summit – Ecological Insights Workshop gathered 26 experts who provided key recommendations for managing seamounts as VMEs under the United Nations General Assembly Resolution 59/25. To date, only the Northwest Atlantic Fisheries Organization has fully implemented these recommendations, designating all seamounts within its Regulatory Area as VMEs and prohibiting bottom-contact fishing (NPFC, 2024).

3.5 South East and West Pacific

Underexplored seamounts in the Southeast Pacific (SEP) basin (Fig. 6) are concentrated along 3 major ridges: the Salas y Gómez, Nazca, and Juan Fernández, hosting > 144 seamounts, 51 of which lie within Chile's EEZ, with summits ranging from 0 to 2000 m deep.

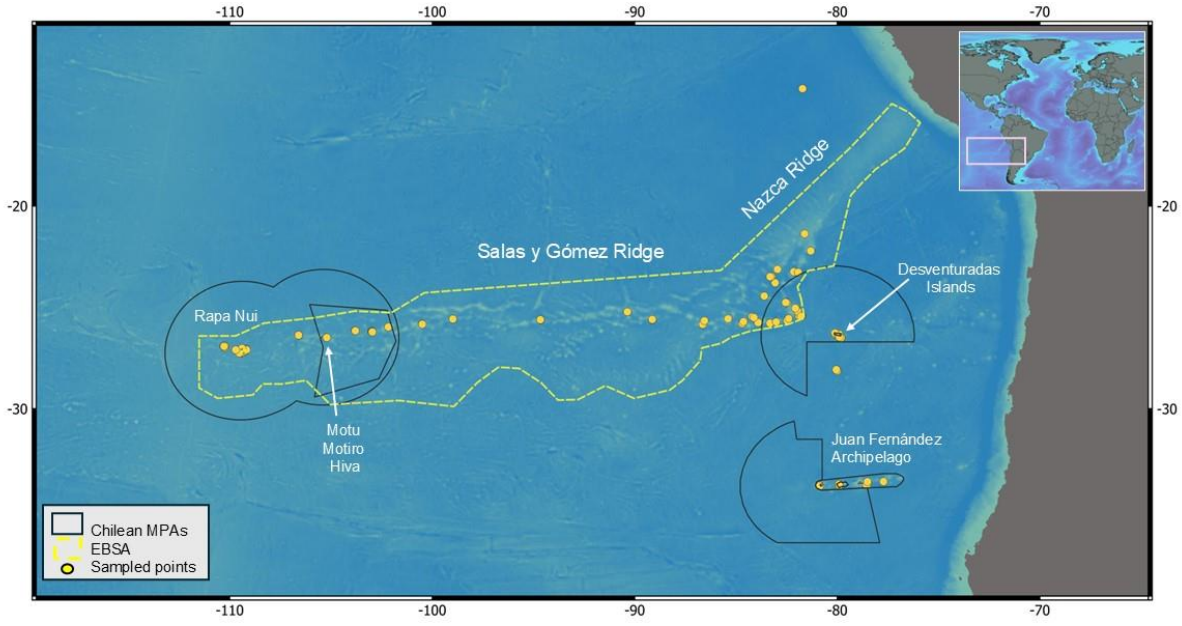


Fig. 6. South East Pacific basin. Credit: Ariadna Mecho.

Recent expeditions by the Schmidt Ocean Institute (SOI, USA), the Japan Agency for Marine-Earth Science and Technology, and the Center for Ecology and Sustainable Management of

Oceanic Islands (ESMOI, Chile) surveyed 32 seamounts, and discovered > 34 uncharted ones. SEP seamounts are recognized as biodiversity hotspots, featuring 150 new species from the SOI 2024 cruises, including habitat-forming, endemic species, and pristine ecosystems, earning the EBSA recognition. High ecological connectivity prevails in the region, supporting the resilience of marine populations across the Pacific.

Chile has established large-scale MPAs, covering the Rapa Nui and Desventuradas ecoregions. Peru has created an MPA located in the eastern Nazca Ridge. Over 73% of the ridges and associated seamounts still lie in ABNJ, vulnerable to human activities (i.e., fishing, potential deep-sea mining, floating plastic debris and microplastics). International stakeholders are working to establish the first "blue corridor" to protect and ensure the long-term health of biodiversity (Wagner et al., 2021; Delgado et al., 2022; Boteler et al., 2022; Chavez-Molina et al., 2023; Gaymer et al., 2025).

In the South West Pacific, recent research efforts shed light on benthic communities, megafauna, and biophysical coupling on seamounts off New Caledonia in the South West Pacific (Supplementary Table 5). In New Zealand, an updated database now includes nearly 3000 features (Fig. 7. Clark et al. 2022b).

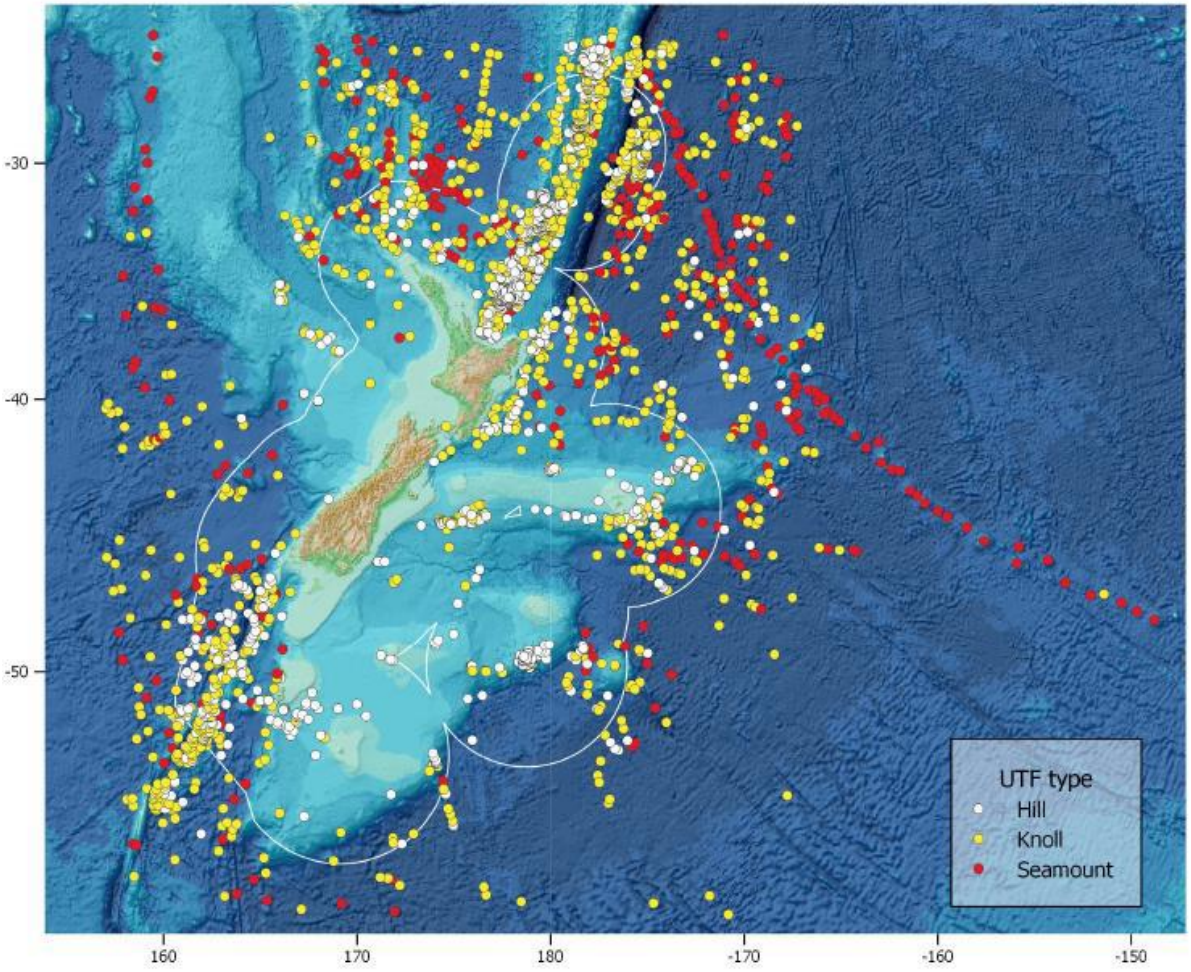


Fig. 7. Distribution of Underwater Topographic Features (UTFs) in the New Zealand region (Clark et al., 2022b).

3.6 Indian

The pelagic diversity, taxonomy, distribution, migration, ecotoxicology, trophic and biophysical interactions, connectivity, and observations of physical phenomena along the SouthWest Indian Ridge (SWIR), Sandes, La Pérouse, MAD-Ridge and Walters Shoal seamounts have been investigated since 2016 with French, German, British, and Norwegian research efforts (Fig. 8, 9; Laptikhovsky et al., 2017; Letessier et al., 2017; Read & Pollard, 2017; Rogers, 2018; Annasawmy et al., 2019; Annasawmy, 2019; Hosegood et al., 2019; Letessier et al., 2019; Annasawmy et al., 2020a, 2020b, 2024; Cherel et al., 2020; Harris et al., 2020; Marsac et al., 2020; Noyon et al., 2020; Roberts & Ternon, 2020; Rocke et al., 2020; Yesson et al., 2021; Diaz et al., 2023; Diaz, 2023; Swanborn et al., 2023; Yutsis et al., 2023; Eager, 2024; O'Hara, 2024; Robinson et al., 2024) (Supplementary Table 6).

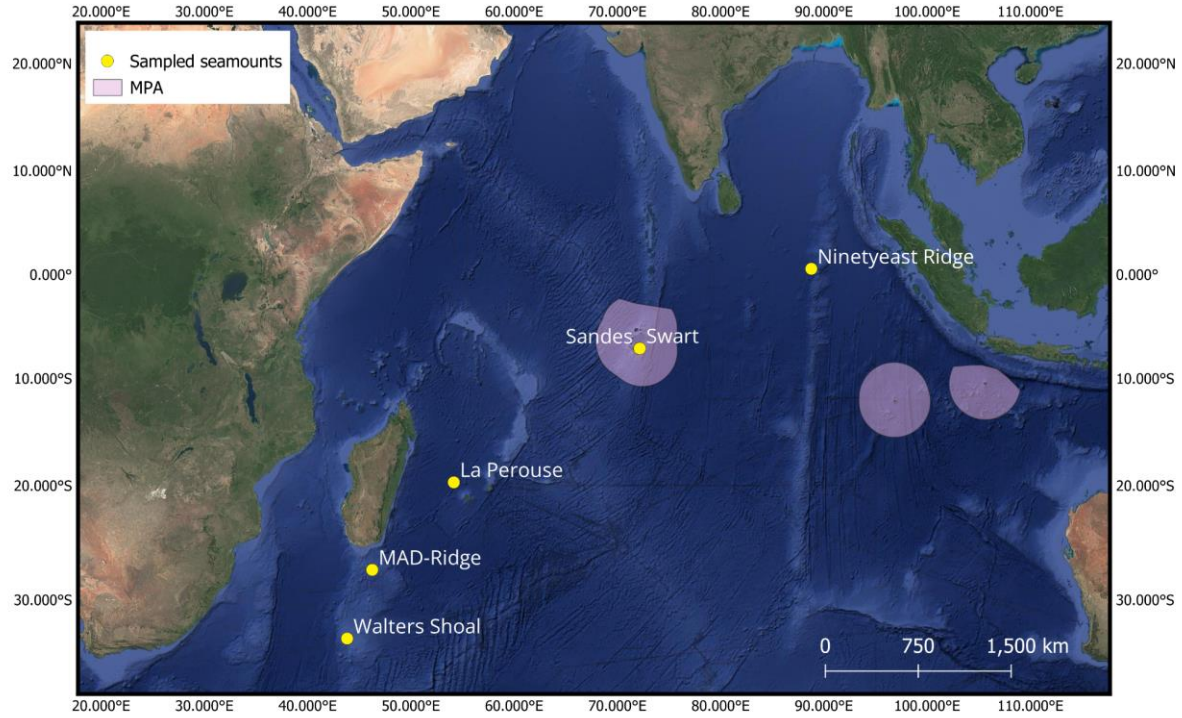


Fig. 8. Indian Ocean seamounts and MPAs. Credit: Dannielle Eager.

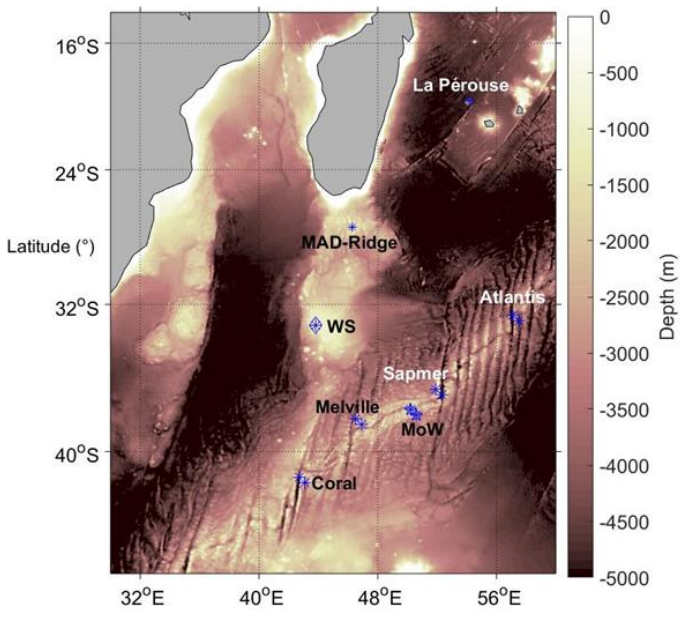


Fig. 9. South West Indian Ocean seamounts (Annasawmy, 2019).

Several seamount paradigms were questioned:

(1) the seamount oasis effect was observed on some SWIR seamounts and for specific taxa but was not widespread across Indian Ocean seamounts.

(2) lack of Taylor cap formation (trapped/enclosed circulations over seamount summits) under intense mesoscale eddies (rotating cyclonic or anticyclonic water masses) and over shallow seamounts.

(3) seamounts are not hotspots of micronekton diversity and densities (Annasawmy et al., 2019, 2020a, Marsac et al., 2020).

The lanternfish Diaphus suborbitalis, which is a key trophic link between plankton and top predators, and which contributes to the biological carbon pump by transporting carbon from the surface to deeper waters through diel vertical migration, has been observed exclusively at seamounts to date, and not in open ocean waters (Annasawmy et al., 2019; 2024; 2025; Cherel et al., 2020). Seamounts are distinct topographic barriers in the ocean, impacting the trophic connections between micronekton which feed on zooplankton, and which migrate from deeper waters to the top 200 m at night and those which do not migrate (Annasawmy et al., 2024).

The habitat preferences of key marine organisms at seamounts of the Indian Ocean are significant in the context of ecosystem health and potential conservation measures in the face of anthropogenic threats such as fishing and plastic pollution (Annasawmy, 2019). In 2022, the WIO N.O.I.S.E (Western Indian Ocean National Or International SEamounts, banks, submarine structures) network was launched, gathering regional researchers, students, policy makers and institutions interested in marine ecosystems' functioning, their exploitation, conservation and governance associated with seamounts and shallow topographic structures in national waters, continental shelves as well as in the high seas of the Western Indian Ocean.

3.7 Southern Ocean

A number of seamounts and ridges of the Southern Ocean have been sampled in recent years (Supplementary Table 7). The interaction of the Antarctic Circumpolar Current (ocean current flowing from west to east around Antarctica) with seamounts generates upward movements, facilitating iron injection, hence fuelling productivity which attracts megafauna (Sergi et al., 2020). Significant research has been made on sedimentary cover at Jiawang seamount, contributing to our understanding of the formation process of seafloor deposits (Cui et al., 2023). The first observation of thermophilic and hyperthermophilic microorganisms, important for biogeochemical processes such as iron oxide deposition (Emerson and Moyer, 2002), were made at Orca seamount (Rodrigo et al., 2018). Seamounts and ridges of the Ross Sea have also been surveyed.

4. Pressures

Seamounts of the global ocean are under intensive fishing pressures (Baco et al., 2019, 2020, 2023a, Morgan & Baco, 2020), plastic contamination affecting marine life (Fig. 10), and ocean acidification (Refer to Supplementary Table 8 for seamount locations). Mining exploration contracts (e.g., Fig. 11) are increasingly being issued in the global ocean which coincides with VME and conservation priority areas (Rogers, 2019).

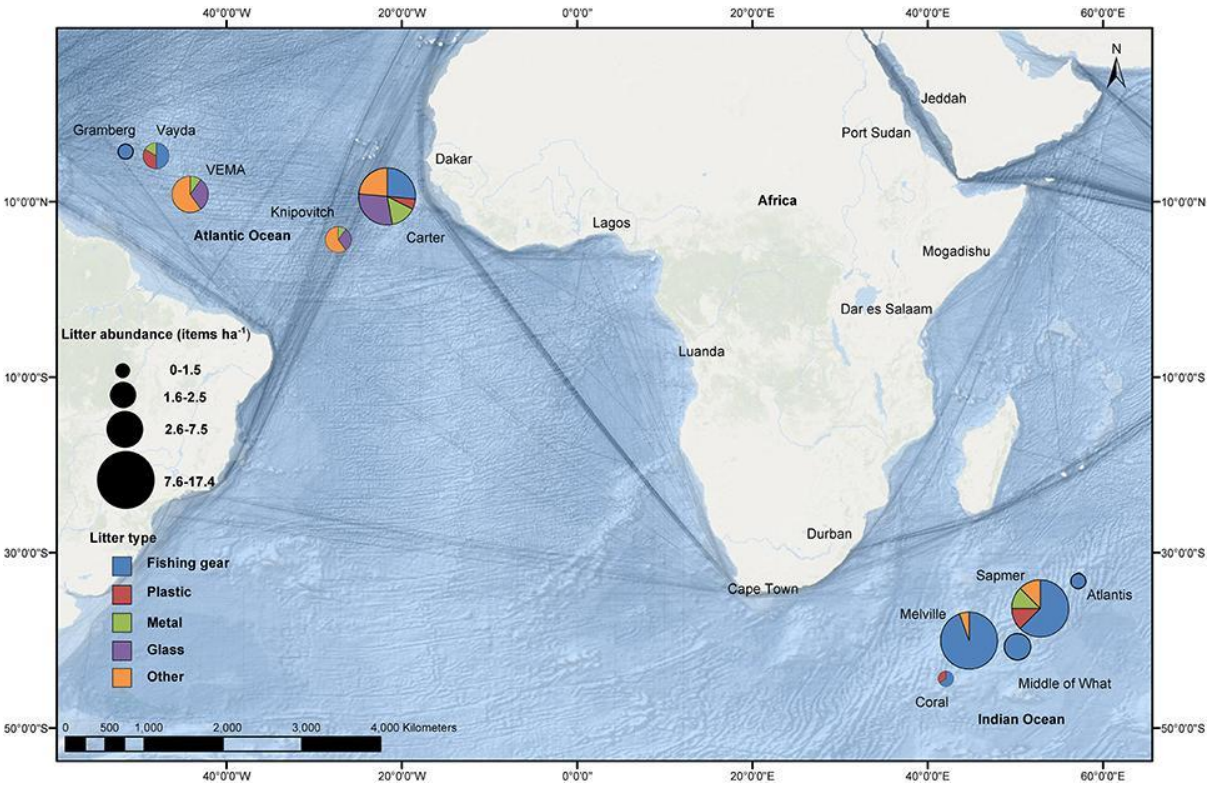


Fig. 10. Marine litter distribution at seamounts (Woodall et al., 2015).

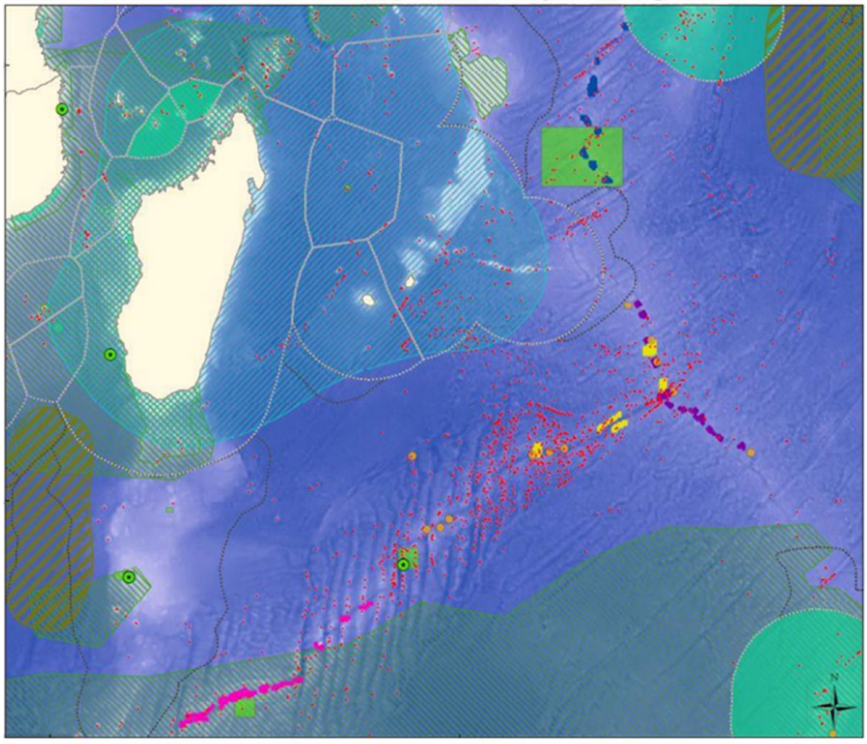


Fig. 11. Distribution of conservation areas and deep-sea mining exploration in the Indian Ocean. (Guduff et al., 2018).

Potential mining of cobalt rich crusts represents an important pressure facing seamounts in the coming years. Habitat removal and sediment plume effects are the top risk sources likely to affect community structure, biodiversity, reproductive capacity, trophic ecology, behavior, and population connectivity of seamount benthic, benthopelagic and pelagic communities. Seamount communities are highly vulnerable with possible impacts across ecological scales from species, single trophic levels, to the entire community. Recovery times are estimated to be over 100 years and the scale of impact is estimated between 1 km2 and~~to~~ 10 000 km2 (Washburn et al. 2019). The one existing study to date of impacts from a seamount mining test has found significant, sustained decreases in the density of mobile epifauna and highly mobile swimmers that persisted 1 month and 1 year after the disturbance in addition to dead and damaged sessile benthic megafauna that were crushed and/or removed by the excavator (Washburn et al. 2023).

The first comprehensive study of Indian Ocean seamounts has demonstrated the effects of a warmer ocean causing lower productivity levels, lower trophic values of pelagic organisms, and potential shifts in food web structure (Annasawmy et al., 2024). A decrease of 28% to 100% in suitable habitats, including seamounts, for cold-water coral species of the North Atlantic has been forecasted due to climate change (Morato et al., 2020).

Time series surveys off Tasmania and New Zealand highlighted the role of untrawled patches and unfished seamounts in post-fishing recruitment, with observations on Graveyard Knoll indicating the first signs of stony coral recovery 15 to 20 years after fishing ceased (Williams et al. 2020; Clark et al. 2021, 2022a). A 2022 NIWA (National Institute of Water and Atmospheric Research) survey following Tonga's Hunga volcanic eruption revealed benthic devastation from pyroclastic flows, except where the seamount features provided "shelter" for communities which were unaffected (Seabrook et al. 2023).

5. Remaining knowledge and capacity changes and any new gaps

Despite significant progress, key knowledge and geographical gaps remain about seamount ecology, bathyal ecosystems, seamount functioning, recruitment and connectivity within and between seamount communities, anthropogenic pressures (linked to pollution, fishing, ocean warming, expansion of oxygen minimum zones), and management in ABNJ, seamounts of the Arctic, Southern and Indian Oceans. Lack of global time series data introduces uncertainties in seamount observations, assumptions and conclusions. The knowledge gaps on seamount crusts are substantial and the lack of experimental data makes assessing the environmental risks of potential deep sea mining of seamounts challenging. The effect of multiple stressors on seamount disturbance and effectiveness of management actions still remain to be assessed. Although data and observations are increasingly findable, accessible, interoperable, and reusable, several years of embargo are generally placed on collected data, thereby reducing scientific progress and collaborations. Local, traditional and I~~i~~ndigenous Peoples' knowledges are~~is~~ still not taken into account in seamount research from many regions of the world's ocean.

6. Outlook

Individual seamounts exhibit unique characteristics that influence biophysical processes, and seamounts are interconnected to each other. Seamounts are facing significant and increasing anthropogenic pressures, making further study of these complex ecosystems a high priority. Integrating artificial intelligence into advanced technologies that monitor deep-sea seamount ecosystems on longer time scales is crucial, as limited research on seamount fauna hinders our understanding of their biogeography. Further exploration and data collection are needed for seamount detection, assessment, and protection. Initiatives such as the scientist ashore program implemented during the 2024 NA161-169 expeditions of North Pacific seamounts by the NOAA Ocean Exploration via the Ocean Exploration Cooperative Institute with > 800 ship-to-shore participants, > 55 000 live stream views, > 1 million social medial views, with full data access, facilitate global collaboration and will significantly build scientific and management capacity. While it is premature to fully assess the impacts of such initiatives, they are expected to enhance seamount research by accelerating discoveries, refining habitat models, increasing public

engagement, and providing insights into seamount ecosystems that may inform future management strategies. Cost-effective deep-sea research enhances large spatial-scale biodiversity data observation at seamounts (Fig. 12; Annasawmy et al., 2025). For a more holistic view of seamount ecosystems, local, traditional and Iindigenous Peoples' knowledges must be taken into account.

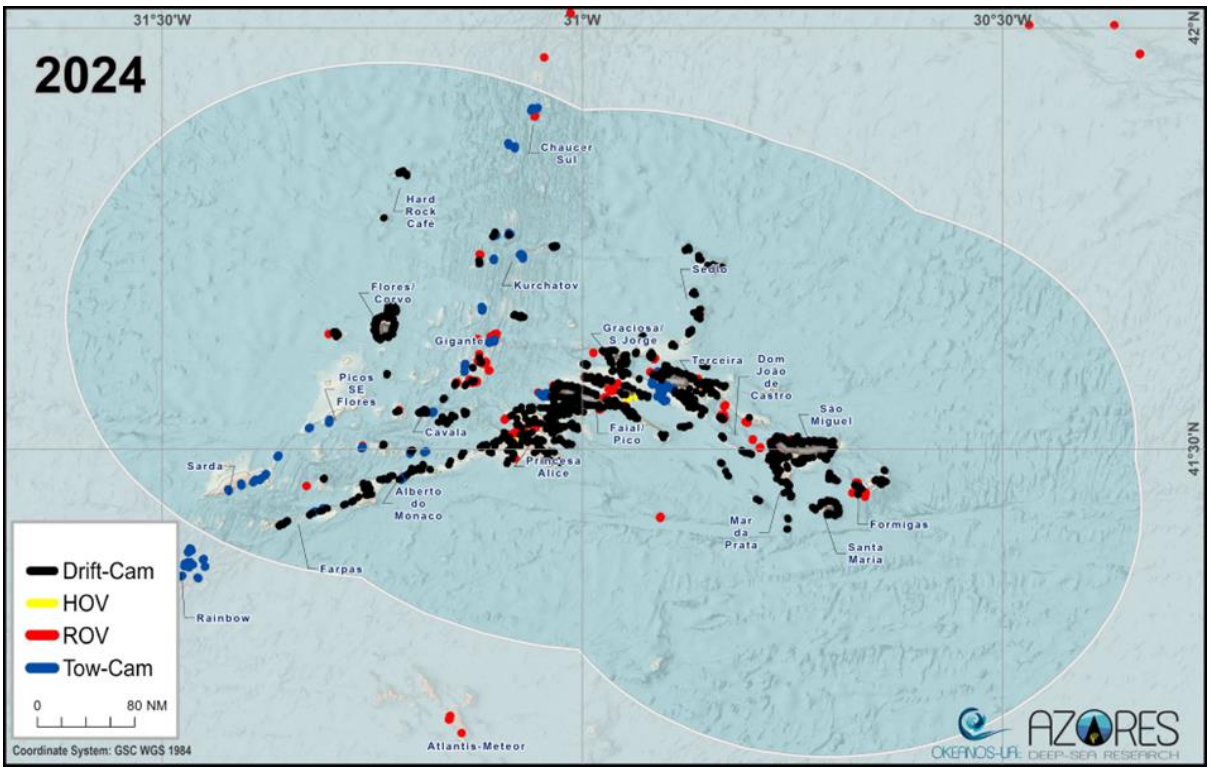


Fig. 12. Seamount observations in the Azores (North Atlantic) using cost-effective technologies (Drift-Cameras and Tow-Cameras, HOV (human-operated vehicles), ROV (remotely-operated vehicles) (Credit: Telmo Morato).

References

Adrianov, A. V., & Maiorova, A. S. (2024). The first Mud Dragons (Kinorhyncha) from the Emperor Seamount Chain (Northwestern Pacific) with notes on their biogeography and distribution patterns in the Pacific Deep-Sea. Deep Sea Research Part II: Topical Studies in Oceanography, 105430. https://doi.org/10.1016/j.dsr2.2024.105430

Afonso, P., Schmiing, M., Fontes, J., Tempera, F., Morato, T., & Santos, R. S. (2018). Effects of marine protected areas on coastal fishes across the Azores archipelago, mid-North Atlantic. Journal of Sea Research, 138, 34-47.

Annasawmy, P., G. Chandelier, and T. Le Mézo. 2025. Unraveling major questions in micronekton ecology and their role in the biological carbon pump through integrative approaches and autonomous monitoring. In Frontiers in Ocean Observing: Marine Protected Areas, Western Boundary Currents, and the Deep Sea. E.S. Kappel, V. Cullen, G. Coward, I.C.A. da Silveira, C. Edwards, P. Heimbach, T. Morris, H. Pillar, M. Roughan, and J. Wilkin, eds, Oceanography 38(Supplement 1), https://doi.org/10.5670/oceanog.2025e118.

Annasawmy, P., Ménard, F., Marsac, F., Ternon, J-F., Cherel, Y., Romanov, E., Le Loc'h, F., 2024. Environmental variability shapes trophic and resource partitioning between epipelagic and mesopelagic biomes in oceanic provinces: Implications in a globally changing ocean, Progress in Oceanography, 229: 103339. https://doi.org/10.1016/j.pocean.2024.103339

Annasawmy, P., Ternon, J-F., Lebourges-Dhaussy, A., Roudaut, G., Herbette, S., Ménard, F., Cotel., P., Marsac, F., 2020a. Micronekton distribution as influenced by mesoscale eddies, Madagascar shelf and shallow seamounts in the south-western Indian Ocean: an acoustic approach. Deep-Sea Res. II. https://doi.org/10.1016/j.dsr2.2020.104812

Annasawmy, P., Cherel, Y., Romanov, E.V., Le Loch, F., Ménard, F., Ternon, J-F., Marsac, F., 2020b. Stable isotope patterns of micronekton at two shallow seamounts of the south-western Indian Ocean. Deep-Sea Res. II. https://doi.org/10.1016/j.dsr2.2020.104804

Annasawmy, P., Ternon, J-F., Cotel, P., Demarcq, H., Cherel, Y, Romanov, E.V., Roudaut, G., Lebourges-Dhaussy, A., Ménard, F., Marsac, F., 2019. Micronekton distribution and assemblages at two shallow seamounts in the south-western Indian Ocean: Insights from acoustics and mesopelagic trawl data. Prog. Oceanogr. 178: 102161. https://doi.org/10.1016/j.pocean.2019.102161

Annasawmy, P., 2019. Patterns among micronekton communities in relation to the environmental conditions at two shalow seamounts in the south-western Indian Ocean. Thesis. University of Cape Town (South Africa) and Université de Montpellier. Available at: https://theses.fr/2019MONTG087

Auscavitch, S. R., Lunden, J. J., Barkman, A., Quattrini, A. M., Demopoulos, A. W., & Cordes, E. E. (2020). Distribution of deep-water scleractinian and stylasterid corals across abiotic environmental gradients on three seamounts in the Anegada Passage. PeerJ, 8, e9523. https://doi.org/10.7717/peerj.9523

Baco, A.R., Morgan, N.B., Roark, E.B., Biede, V. 2023a. Bottom contact fisheries disturbance and signs of recovery of precious corals in the Northwestern Hawaiian Islands and Emperor Seamount Chain. Ecological Indicators. 148: 110010. https://doi.org/10.1016/j.ecolind.2023.110010

Baco, A.R., Parrish, F.A., Auscavitch, S. (2023b) Deep-Sea Corals of the North and Central Pacific Seamounts. In: Cordes, E., Mienis, F. (eds) Cold-Water Coral Reefs of the World. Coral Reefs of the World, 19. Springer, Cham. https://doi.org/10.1007/978-3-031-40897-7-10

Baco, A.R., Morgan, N. B., and E. B. Roark. 2020. Observations of Vulnerable Marine Ecosystems and Significant Adverse Impacts on High Seas Seamounts of the Northwestern Hawaiian Islands and Emperor Seamount Chain. Marine Policy. 115: 103834. https://doi.org/10.1016/j.marpol.2020.103834

Baco, A.R., E. B Roark, Morgan. N.B., 2019. Amid Fields of Rubble, Scars, and Lost Gear, Signs of Recovery Observed on Seamounts on 30-40 year Time Scales. Science Advances. 5: eaaw4513. DOI: 10.1126/sciadv.aaw4513

Baco, A.R., N.B. Morgan, E.B. Roark, M. Silva, K. Shamberger, K. Miller. 2017. Defying dissolution, discovery of deep-sea scleractinian coral reefs in the North Pacific. Scientific Reports. 7: 5436 | DOI:10.1038/s41598-017-05492-w

Boteler, Ben, et al. "Borderless conservation: Integrating connectivity into high seas conservation efforts for the Salas y Gómez and Nazca ridges." Frontiers in Marine Science 9 (2022): 915983. https://doi.org/10.3389/fmars.2022.915983

Bridges, A.E.H., Barnes, D.K.A., Bell, J.B., et al. (2021) Benthic Assemblage Composition of South Atlantic Seamounts. Frontiers in Marine Science, 8, 660648. https://doi.org/10.3389/fmars.2021.660648

Campanella F, Collins MA, Young EF, Laptikhovsky V, Whomersley P and van der Kooij J (2021). First Insight of Mesoand Bentho-Pelagic Fish Dynamics Around Remote Seamounts in the South Atlantic Ocean. Front. Mar. Sci. 8:663278. doi: 10.3389/fmars.2021.663278

Chavez-Molina, Vasco, et al. "Protecting the Salas y Gomez and Nazca Ridges: A review of policy pathways for creating conservation measures in the international waters of the Southeast Pacific." Marine Policy 152 (2023): 105594. https://doi.org/10.1016/j.marpol.2023.105594

Chen, C., Methou, P., Yamamoto, D., Kayamori, M., Nomaki, H., 2024. There and there again: Hydrothermal vent communities at Mokuyo Seamount, 30 years apart. Ecological Research. https://doi.org/10.1111/1440-1703.12528

Cherel, Y., Romanov, E.V., Annasawmy, P., Thibault, D., Ménard, F., 2020. Micronektonic fish species over three seamounts in the southwestern Indian Ocean. Deep-Sea Res. II. https://doi.org/10.1016/j.dsr2.2020.104777

Clark, M.R.; Bowden, D.A.; Stewart, R.; Rowden, A.A.; Goode, S. (2022a). Seamount recovery: analysis of 20 years of time series seafloor image data from the Graveyard Knolls, Chatham Rise, New Zealand. New Zealand Aquatic Environment and Biodiversity Report No.292. 25 p.

Clark, M.R.; Wood, B.; Mackay, K.; Anderson, O.F.; Hart, A.; Rickard, G.; Rowden, A.A. (2022b). Underwater Topographic Features in the New Zealand region: development of an updated 'SEAMOUNT' database and information on the extent and intensity of deep-sea trawl fisheries on them. New Zealand Aquatic Environment and Biodiversity Report No. 291. 28 p.

Clark, M.R., Bowden, D.A., Stewart, R., Schnabel, K., Quinn, W., Lennard, B., Goode, S.L., Davis, A. (2021). Seamount Recovery: factual voyage report of a survey of seamounts on the Northwest and Southeast Chatham Rise (TAN2009). New Zealand Aquatic Environment and Biodiversity Report No. 262. 117 p.

Cordes, E., Mienis, F., Gasbarro, R., Davies, A., Baco, A.R., Bernardino, A.F., Clark, M., Freiwald, A., Hennige, S., Huvenne, V., Buhl-Mortensen, P., Orejas, C., Quattrini, A.M., Tracey, D., Wheeler, A.J., Wienberg, C. 2023. Ch. 1. A Global View of the Cold-Water Coral Reefs of the World. Invited Book Chapter In: Cold-Water Corals Reefs of the World. E. Cordes and F. Mienis editors. Springer. 19, https://doi.org/10.1007/978-3-031-40897-7_1.

Cui, Y., Wang, Q., Fang, X., Li, X., Liu, K., Liu, C., & Du, D. (2023). Ferromanganese precipitates from the Jiawang Seamount, Bransfield Strait, Antarctica. Ore Geology Reviews, 157, 105425. https://doi.org/10.1016/j.oregeorev.2023.105425

Delgado, James P., et al. "The hidden landscape: maritime cultural heritage of the Salas y Gómez and Nazca ridges with implications for conservation on the high seas." Marine Policy 136 (2022): 104877. https://doi.org/10.1016/j.marpol.2021.104877

Denda, A., Mohn, C., Wehrmann, H., & Christiansen, B. (2017). Microzooplankton and meroplanktonic larvae at two seamounts in the subtropical and tropical NE Atlantic. Journal of the Marine Biological Association of the United Kingdom, 97(1), 1-27. DOI: https://doi.org/10.1017/S0025315415002192

Diaz, C., Foster, N.L., Attrill, M.J. et al. Mesophotic coral bleaching associated with changes in thermocline depth. Nat Commun 14, 6528 (2023). https://doi.org/10.1038/s41467-023-42279-2.

Diaz, C. (2023) Investigating the diversity and distribution of Mesophotic Coral Ecosystems in the Chagos Archipelago. Thesis. University of Plymouth. Available at: https://doi.org/10.24382/5123

Domokos, R. (2022). Seamount effects on micronekton at a subtropical central Pacific seamount. Deep Sea Research Part I: Oceanographic Research Papers, 186, 103829. https://doi.org/10.1016/j.dsr.2022.103829

Du Preez, C., D. Amon, A.R. Baco, M. Best, G. Clyde, A. Colaço, H. Gartner, R.M. Lauer, B.N. Orcutt, A. Metaxas, V. Tunnicliffe. 2023. Identification of Ecologically or Biologically Significant Marine Areas (EBSAs) in Areas Beyond National Jurisdiction (ABNJ): the Northwest Pacific Seamounts. Canadian Technical Report of Fisheries and Aquatic Sciences 3571: vi + 21 p

Eager, D. S. (2024) Identifying and quantifying pelagic organisms around seamounts, atolls, and islands in the Chagos Archipelago in relation to local oceanographic processes. Thesis. University of Plymouth. Available at: https://doi.org/10.24382/5186

Emerson, D., & Moyer, C. L. (2002). Neutrophilic Fe-oxidizing bacteria are abundant at the Loihi Seamount hydrothermal vents and play a major role in Fe oxide deposition. Applied and environmental microbiology, 68(6), 3085-3093.

Food and Agriculture Organization of the United Nations, 2025. Background- About VMEs. https://www.fao.org/in-action/vulnerable-marine-ecosystems/background/en/ [Accessed 19 March 2025].

Gaymer C.F., D. Wagner, R. Alvarez-Varas, B. Boteler, L. Bravo, C.M. Brooks, V. Chavez-Molina, D. Currie, J. Delgado, B. Dewitte, E.E. Easton, A.M. Friedlander, M.A. Gallardo, M. Gianni, K. Gjerde, M. Gorny, S. Hormazabal, R. Hucke-Gaete, G. Luna-Jorquera, A. Mecho, N. Morales-Serrano, L. Morgan, P. Nuñez, M. Ramos, J. Rapu, C. Rodrigo, J. Sellanes, E. Soto, M. Thiel, L. Van der Meer, D. Veliz (2025). Research advances and conservation needs for an effective protection of the Salas y Gómez and Nazca ridges: a natural and cultural heritage hotspot in the southeastern Pacific Ocean. Marine Policy, 171. https://doi.org/10.1016/j.marpol.2024.106453

Geissler, W. H., Estrada, S., Riefstahl, F., O'Connor, J. M., Spiegel, C., Van den Boogard, P., & Klügel, A. (2019). Middle Miocene magmatic activity in the Sophia Basin, Arctic Ocean—evidence from dredged basalt at the flanks of Mosby Seamount. arktos, 5, 31-48. https://link.springer.com/article/10.1007/s41063-019-00066-8

Gevorgian, J., Sandwell, D. T., Yu, Y., Kim, S. S., & Wessel, P. (2023). Global distribution and morphology of small seamounts. Earth and Space Science, 10(4), e2022EA002331. https://doi.org/10.1029/2022EA002331

Guduff, S., Rochette, J., Simard, F., Spadone, A., Wright, G., 2018. Laying the foundations for management of a seamount beyond national jurisdiction. IUCN Report. pp 1-40. Available at: https://www.iddri.org/sites/default/files/PDF/Publications/Hors%20catalogue%20Iddri/201806-rapport%20walters%20shoalEN.pdf

Harris, S. A., Noyon, M., Marsac, F., Vianello, P., & Roberts, M. J. (2020). Ichthyoplankton assemblages at three shallow seamounts in the South West Indian Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 176, 104809. https://doi.org/10.1016/j.dsr2.2020.104809

Heyworth, S. M., Bell, J. B., Wade, C. M., Cavalcante, G., Robinson, N., Young, E., Glass, J., Feary, D. A., 2021. Genetic connectivity of seamount populations of bluenose warehou (Hyperoglyphe antarctica). Frontiers in Marine Science, 8, 640504.

Hosegood, P. J., Nimmo, S. WAM., Proud, R., Adams, K., & Brierley, A. S. (2019). Internal lee waves and baroclinic bores over a tropical seamount shark 'hot-spot'. Progress in Oceanography, 0(0). Advance online publication. https://doi.org/10.1016/j.pocean.2019.01.010

Idárraga-García, J., & León, H. (2019). Unraveling the underwater morphological features of Roncador bank, archipelago of San Andrés, Providencia and Santa Catalina (Colombian Caribbean). Frontiers in Marine Science, 6, 77. https://doi.org/10.3389/fmars.2019.00077

Laptikhovsky, V., Boersch-Supan, P., Bolstad, K., Kemp, K., Letessier, T., & Rogers, A. D. (2017). Cephalopods of the Southwest Indian OceanRidge: a hotspot of biological diversity and absence of endemism. Deep Sea Research Part II: Topical Studies in Oceanography, 136, 98-107. https://doi.org/10.1016/j.dsr2.2015.07.002

Leitner, A. B., Friedrich, T., Kelley, C. D., Travis, S., Partridge, D., Powell, B., & Drazen, J. C. (2021a). Biogeophysical influence of large-scale bathymetric habitat types on mesophotic and upper bathyal demersal fish assemblages: a Hawaiian case study. Marine Ecology Progress Series, 659, 219-236. https://doi.org/10.3354/meps13581

Leitner, A. B., Durden, J. M., Smith, C. R., Klingberg, E. D., & Drazen, J. C. (2021b). Synaphobranchid eel swarms on abyssal seamounts: Largest aggregation of fishes ever observed at abyssal depths. Deep Sea Research Part I: Oceanographic Research Papers, 167, 103423. https://doi.org/10.1016/j.dsr.2020.103423

Leitner, A. B., Drazen, J. C., & Smith, C. R. (2021c). Testing the seamount refuge hypothesis for predators and scavengers in the Western clarion-clipperton zone. Frontiers in Marine Science, 8, 636305. https://doi.org/10.3389/fmars.2021.636305

Letessier, T. B., Mouillot, D., Bouchet, P. J., Vigliola, L., Fernandes, M. C., Thompson, C., .& Meeuwig, J. J. (2019). Remote reefs and seamounts are the last refuges for marine predators across the Indo-Pacific. PLoS Biology, 17(8), e3000366. https://doi.org/10.1371/journal.pbio.3000366

Letessier, T. B., De Grave, S., Boersch-Supan, P. H., Kemp, K. M., Brierley, A. S., & Rogers, A. D. (2017). Seamount influences on mid-water shrimps (Decapoda) and gnathophausiids (Lophogastridea) of the South-West Indian Ridge. Deep Sea Research Part II: Topical Studies in Oceanography, 136, 85-97. https://doi.org/10.1016/j.dsr2.2015.05.009

Lima, F. D., Leite, T. S., & Lima, S. M. (2022). Seamounts and oceanic currents drive the population structure of Octopus insularis in the Southwest Tropical Atlantic. Aquatic Ecology, 56(4), 1143-1155. DOI: 10.1007/s10452-022-09955-9

Marsac, F., Annasawmy, P., Noyon, M., Demarcq, H., Soria, M., Rabearisoa, N., Bach, P., Cherel, Y., Grelet, J., Romanov, E., 2020. Seamount effect on circulation and distribution of ocean taxa in the vicinity of La Pérouse, a shallow seamount in the southwestern Indian Ocean. Deep-Sea Res. II. https://doi.org/10.1016/j.dsr2.2020.104806

Mejia-Mercado, B. and A.R. Baco. 2023. Patterns of distribution of deep-sea fish assemblages on three seamounts located in Papahānaumokuākea Marine National Monument. Deep-Sea Research I. 195 (2023) 104003. https://doi.org/10.1016/j.dsr.2023.104003

Mejia-Mercado, B. and A.R. Baco. 2022. Characterization and spatial variation of the deep-sea fish assemblages on Pioneer Bank, Northwestern Hawaiian Islands. Marine Ecology Progress Series 692:99-118. https://doi.org/10.3354/meps14071

Meyer, H. K., Davies, A. J., Roberts, E. M., Xavier, J. R., Ribeiro, P. A., Glenner, H., & Rapp, H. T. (2023). Beyond the tip of the seamount: Distinct megabenthic communities found beyond the charismatic summit sponge ground on an arctic seamount (Schulz Bank, Arctic Mid-Ocean Ridge). Deep Sea Research Part I: Oceanographic Research Papers, 191, 103920. https://doi.org/10.1016/j.dsr.2022.103920

Mohn, C., M. White, A. Denda, S. Erofeeva, B. Springer, R. Turnewitsch, and B. Christiansen (2021). Dynamics of currents and biological scattering layers around Senghor Seamount, a shallow seamount inside a tropical Northeast Atlantic eddy corridor, Deep Sea Research Part I: Oceanographic Research Papers, 171, 103497, doi:10.1016/j.dsr.2021.103497.

Morato, T., González-Irusta, J. M., Dominguez-Carrió, C., Wei, C. L., Davies, A., Sweetman, A. K., et al., (2020). Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. Global Change Biology, 26(4), 2181-2202.

Morganti, T. M., Slaby, B. M., de Kluijver, A., Busch, K., Hentschel, U., Middelburg, J. J., & Boetius, A. (2022). Giant sponge grounds of Central Arctic seamounts are associated with extinct seep life. Nature communications, 13(1), 638. DOI: 10.1038/s41467-022-28129-7

Mosquera Giménez, Á., et al. (2019), Ocean circulation over North Atlantic underwater features in the path of the Mediterranean Outflow Water: The Ormonde and Formigas Seamounts, and the Gazul Mud Volcano, Frontiers in Marine Science, 6(702), doi:10.3389/fmars.2019.00702.

North Pacific Fisheries Commission (NFPC), The Deep Sea Conservation Coalition and the Pew Charitable Trusts, 2024. Ecosystem-Based Management of Seamounts in the NPFC Convention Area: Recommendations from the Seamount Science Summit – Ecological Insights Workshop. October 23-25, 2024. University of Hawai‘i Mānoa (Honolulu, Hawai’i). https://www.npfc.int/ecosystem-based-management-seamounts-npfc-convention-area-recommendations-seamount-science-summit. [Accessed 21 March 2025].

Noyon, M., Rasoloarijao, Z., Huggett, J., Ternon, J. F., & Roberts, M. (2020). Comparison of mesozooplankton communities at three shallow seamounts in the South West Indian Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 176, 104759. https://doi.org/10.1016/j.dsr2.2020.104759

O'Hara, T. D. (2024). Geomorphology and oceanography of central-eastern Indian Ocean seamounts. Deep Sea Research Part II: Topical Studies in Oceanography, 218, 105415. https://doi.org/10.1016/j.dsr2.2024.105415

Perez, J.A.A., Vizuete, R.S., Rami, S., Castillo, S. (2022) Fish, cephalopods and associated habitats of the Discovery rise seamounts, Southeast Atlantic. Deep–Sea Research I 188, 103849. https://doi.org/10.1016/j.dsr.2022.103849

Quattrini, A. M., Demopoulos, A. W., Singer, R., Roa-Varon, A., & Chaytor, J. D. (2017). Demersal fish assemblages on seamounts and other rugged features in the northeastern Caribbean. Deep Sea Research Part I: Oceanographic Research Papers, 123, 90-104. https://doi.org/10.1016/j.dsr.2017.03.009

Read, J., & Pollard, R. (2017). An introduction to the physical oceanography of six seamounts in the southwest Indian Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 136, 44-58. https://doi.org/10.1016/j.dsr2.2015.06.022

Roberts, M., Ternon, J-F., 2020. The MADRidge project — Biophysical coupling around three shallow seamounts in the South-western Indian Ocean, with regional comparisons based on modelling, remote sensing and observational studies. Deep Sea Research Part II special issue: Topical Studies in Oceanography. 176(No. 3):104817. https://doi.org/10.1016/j.dsr2.2020.104817

Robinson, E., Hosegood, P., & Bolton, A. (2024). Modulation of the internal wave regime over a tropical seamount ecosystem by basin-scale oceanographic processes. Progress in Oceanography, 228, 103323. https://doi.org/10.1016/j.pocean.2024.103323

Rocke, E., Noyon, M., & Roberts, M. (2020). Picoplankton and nanoplankton composition on and around a seamount, affected by an eddy dipole south of Madagascar. Deep Sea Research Part II: Topical Studies in Oceanography, 176, 104744. https://doi.org/10.1016/j.dsr2.2020.104744

Rodrigo, C., Blamey, J. M., Huhn, O., & Provost, C. (2018). Is there an active hydrothermal flux from the Orca seamount in the Bransfield Strait, Antarctica? Andean geology, 45(3), 344. doi: 10.5027/andgeoV45n3-3086

Rogers, A. D. (2019). Threats to seamount ecosystems and their management. In World seas: an environmental evaluation (pp. 427-451). Academic Press.

Rogers, A. D. (2018). The biology of seamounts: 25 years on. Advances in marine biology, 79, 137-224. https://doi.org/10.1016/bs.amb.2018.06.001

Seabrook, S.; Mackay, K.; Watson, S.; Clare, M.; Hunt, J.; Yeo, I.; Lane, E.; Clark, M.; Wysoczanski, R.; Rowden, A.; Hoffmann, L.; Armstrong, E.; Williams, M. (2023). Pyroclastic density currents explain far-reaching and diverse seafloor impacts of the 2022 Hunga Tonga Hunga Ha'apai eruption. Nature Communications. https://doi.org/10.1038/s41467-023-43607-2

Sergi, S., Baudena, A., Cotté, C., Ardyna, M., Blain, S., & d'Ovidio, F. (2020). Interaction of the antarctic circumpolar current with seamounts fuels moderate blooms but vast foraging grounds

for multiple marine predators. Frontiers in Marine Science, 7, 416. https://doi.org/10.3389/fmars.2020.00416

Shu, Y., J. Wang, H. Xue, R.-X. Huang, J. Chen, D. Wang, Q. Wang, Q. Xie, W. Wang. (2022) Deep-current intraseasonal variability interpreted as topographic Rossby waves and deep eddies in the Xisha Islands of the South China Sea. J. Phys. Oceanogr. 52, 1415-1430. doi: 10.1175/JPO-D-21-0147.1

Stashchuk, N., and V. Vlasenko (2021), Internal wave dynamics over isolated seamount and its influence on coral larvae dispersion, Frontiers in Marine Science, 8(1289), doi:10.3389/fmars.2021.735358.

Stratmann, T., Simon-Lledó, E., Morganti, T. M., de Kluijver, A., Vedenin, A., & Purser, A. (2022). Habitat types and megabenthos composition from three sponge-dominated high-Arctic seamounts. Scientific Reports, 12(1), 20610. DOI: 10.1038/s41598-022-25240-z

Swanborn, D.J.B., Huvenne, V.A.I., Pittman, S.J., et al. (2023) Mapping, quantifying and comparing seascape heterogeneity of Southwest Indian Ridge seamounts. Landscape Ecology, 38(1), 185–203. https://doi.org/10.1007/s10980-022-01541-6

Tao, Z., Xian, H., Luan, Z., Nan, F., Wang, Y., & Sun, S. (2022). The diel vertical distribution and carbon biomass of the zooplankton community in the Caroline Seamount area of the western tropical Pacific Ocean. Scientific Reports, 12(1), 18908. doi: 10.1038/s41598-022-23522-0

Tong, R., Davies, A. J., Yesson, C., Yu, J., Luo, Y., Zhang, L., & Burgos, J. M. (2023). Environmental drivers and the distribution of cold-water corals in the global ocean. Frontiers in Marine Science, 10, 1217851.

Tosetto, E. G., Lett, C., Neumann-Leitão, S., Koch-Larrouy, A., Barrier, N., da Silva, A. C., & Bertrand, A. (2024). Diel vertical migration and seamount stepping stones promote species connectivity from coastal to offshore insular systems in the Tropical Southwestern Atlantic. Limnology and Oceanography, 69(9), 2071-2084. https://doi.org/10.1002/lno.12648

Vinha, B., Murillo, F. J., Schumacher, M., Hansteen, T. H., Schwarzkopf, F. U., Biastoch, A., & Huvenne, V. A. (2024). Ensemble modelling to predict the distribution of vulnerable marine ecosystems indicator taxa on data-limited seamounts of Cabo Verde (NW Africa). Diversity and Distributions, 30(8), e13896. https://doi.org/10.1111/ddi.13896

von Jackowski, A., Walter, M., Spiegel, T., Buttigieg, P. L., & Molari, M. (2023). Drivers of pelagic and benthic microbial communities on Central Arctic seamounts. Frontiers in Marine Science, 10, 1216442. https://doi.org/10.3389/fmars.2023.1216442

Wagner, Daniel, et al. "The Salas y Gómez and Nazca ridges: a review of the importance, opportunities and challenges for protecting a global diversity hotspot on the high seas." Marine Policy 126 (2021): 104377. https://doi.org/10.1016/j.marpol.2020.104377

Wang, X., Li, H., Zhang, J., Chen, J., Xie, X., Xie, W., & Kao, S. J. (2024). Seamounts generate efficient active transport loops to nourish the twilight ecosystem. Science Advances, 10(26), eadk6833. doi: 10.1126/sciadv.adk6833

Washburn, T. W., Turner, P. J., Durden, J. M., Jones, D. O., Weaver, P., & Van Dover, C. L. (2019). Ecological risk assessment for deep-sea mining. Ocean & coastal management, 176, 24-39.

Washburn, T. W., Simon-Lledó, E., Soong, G. Y., & Suzuki, A. (2023). Seamount mining test provides evidence of ecological impacts beyond deposition. Current Biology, 33(14), 3065-3071.

Watling, L., & Auster, P. J. (2021). Vulnerable marine ecosystems, communities, and indicator species: confusing concepts for conservation of seamounts. Frontiers in Marine Science, 8, 622586.

Watling, L., Auster, P.J. (2020) Seamounts, VMEs and Spatial management. 8th Meet of the Scientific Committee, New Zealand. Accessible at: https://www.researchgate.net/publication/344290011_Seamounts_VMEs_and_Spatial_management

Williams, A.; Althaus, F.; Maguire, K.; Green, M.; Untiedt, C.; Alderslade, P.; Clark, M.R.; Bax, N.; Schlacher, T.A. (2020). The Fate of Deep-Sea Coral Reefs on Seamounts in a Fishery-Seascape: What Are the Impacts, What Remains, and What Is Protected? Frontiers in Marine Science 7(798). http://dx.doi.org/10.3389/fmars.2020.567002

Woodall, L.C., Robinson, L.F., Rogers, A.D., Narayanaswamy, B.E., Paterson, G.L.J., 2015. Deep-sea litter: a comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. Front. Mar. Sci. 2(3). https://doi.org/10.3389/fmars.2015.00003

Yesson, C., Letessier, T.B., Nimmo-Smith, A., et al. (2021) Improved bathymetry leads to >4000 new seamount predictions in the global ocean – but beware of phantom seamounts! UCL Open Environment, 4. https://doi.org/10.14324/111.444/ucloe.000030

Yesson, C., Bedford, F., Rogers, A. D., & Taylor, M. L. (2017). The global distribution of deep-water Antipatharia habitat. Deep Sea Research Part II: Topical Studies in Oceanography, 145, 79-86. https://doi.org/10.1016/j.dsr2.2015.12.004

Yutsis, V., Levchenko, O., Ivanenko, A., Veklich, I., Turko, N., & Marinova, Y. (2023). New Insights into the Seamount Structure of the Northern Part of the Ninetyeast Ridge (Indian Ocean) through the Integrated Analysis of Geophysical Data. Journal of Marine Science and Engineering, 11(5), 924. https://doi.org/10.3390/jmse11050924

Section 4

Sub-chapter 5m: Abyssal plains

Writing team:

Name	Role	Nation	Affiliation	Gender	Relevant Experience	Status
Moriaki Yasuhara	Lead	Japan	The University of Hong Kong	M	*Deep-sea biology*	
Paul V. R. Snelgrove	Co-author	Canada	Memorial University of Newfoundland	M	*Deep-sea biology*	
Daniel O. B. Jones	Co-author	UK	National Oceanography Centre	M	*Deep-sea biology*	
Malcolm R. Clark	Co-author	New Zealand	National Institute of Water and Atmospheric Research	M	*Deep-sea biology*	
Jeroen Ingels	Co-author	United States	National Institute of Water and Atmospheric Research	M	*Deep-sea biology*	
Roberto Danovaro	Co-author	Italy	Polytechnic University of Marche	M	*Deep-sea ecology*	
Craig R. McClain	Co-author	United States	University of Louisiana at Lafayette	M	*Deep-sea biology*	
Jingwen Zhang	Co-author	China	The University of Hong Kong	F	*Deep-sea paleobiology*	

Moriaki Yasuhara, Paul V. R. Snelgrove, Daniel O. B. Jones, Malcolm R. Clark, Jeroen Ingels, Roberto Danovaro, Craig R. McClain, Jingwen Zhang

Keynote Points

- Despite improvements in understanding abyssal biodiversity, knowledge gaps in abyssal evolution and biogeography, connectivity, and biotic responses to natural temporal and anthropogenic change remain. The incomplete knowledge of abyssal systems reflects major challenges in sampling this vast and remote area.

- Abyssal environments support processes underlying deep-sea and global ecosystem functioning and link closely to surface production and pelagic processes.

- Marine Carbon Dioxide Removal (mCDR) and Ocean Based Carbon Interventions (OBCI) may affect abyssal systems directly if deployed on the seafloor or affect pelagic processes that could indirectly result in changes in abyssal ecosystem function.

- Despite knowledge improvements on abyssal biodiversity linked to deep-sea mineral exploration, full assessment of impacts of exploitation on abyssal ecosystems requires further scientific research.

2 Introduction

Abyssal plains refer to the deep-ocean floor between 3000 and 6000 m. Potentially lower alpha biodiversity characterizes abyssal relative to bathyal depths (Rex and Etter, 2010). Yet, given their vastness, abyssal plains likely host similar or more species globally compared to other deep seafloor habitats. Because most abyssal plains occur beyond national jurisdiction (ABNJ), the diversity and genetic resources they contain fall under the recently adopted Agreement under the United Nations Convention on the Law of the Sea (UNCLOS) on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement), which aims at ensuring the conservation and sustainable use ~~strengthening the protection~~ of marine biological diversity ~~in~~ of ABNJ. In addition, mineral resource presence and the abyss' potential to help mitigate climate change increases interest in abyssal habitats.

While WOA I briefly described abyssal environments, WOA II offered a detailed account of abyssal biodiversity. Building on these efforts, this review examines current regional abyssal biodiversity knowledge and how abyssal biodiversity may respond to future changes.

3 Environmental change since WOAII

3.1 Changes in the overall status

Ongoing climate change and ocean surface warming will likely carry through to the water column and abyssal depths (Levin and Le Bris, 2015). Models suggest that many abyssal ocean regions will exceed their historic range of variability over the next decade (Levin and others, 2020). Sutton and others (2024) documented warming at full ocean depth east of New Zealand, driven by ocean heat gradient changes between mid and high latitudes that reduce local flows of deeper and colder sub-Antarctic water masses. These patterns continue at the global level (Johnson and Purkey, 2024). Additionally, growing recognition of shifting—and often declining—ocean productivity (Bryndum-Buchholz and others, 2019) may link to abyssal ecosystems that depend on surface production; these changes, combined with rising temperatures, could affect abyssal biodiversity and ecosystem function (McClain and others, 2012, Smith and others, 2018).

Documenting long-term changes in abyssal communities remains challenging, but some long-term abyssal observations show that climate cycles likely alter communities. At Porcupine Abyssal Plain (PAP; 48°50′N 16°30′W, 4850 m depth), scavenging amphipod species composition varies with the Atlantic Multi-decadal Oscillation index (Horton and others, 2020) and at Station M ~~off the California coast~~ (34°50′N, 123° 00′W, 4100 m depth) off the California coast, megafaunal variation may link to heat anomalies (Kuhnz and others, 2020). Climate-driven changes in organic matter supply explain some changes in seafloor oxygen consumption (Smith and others, 2018), feeding activity (Durden and others, 2020), and benthic community structure and standing stocks (Horton and others, 2020; Kuhnz and others, 2020). Increased data resolution ~~data~~ shows episodic carbon fluxes vary more temporally than thought (Huffard and others, 2020), while ~~at longer time scales,~~ deep-sea fossil records over longer time scales indicate reorganization of deep-sea benthic communities with climatic changes such as reduced deep-water formation and changes in temperature and POC flux (e.g., Cronin and others, 1996; Yasuhara and others, 2014; Yasuhara and others, 2025).

Historically, most direct human-induced pressures (e.g., trawling, hydrocarbon drilling) focused on shelf and bathyal depths (Glover and Smith, 2003), but anthropogenic alterations are deepening (Ramirez-Llodra and others, 2011). Recent studies document organic pollution and microplastics at abyssal depths and deeper (Jamieson and others, 2017; Abel and others, 2021; Nakajima and others, 2021). Some argue that the greening of global society will require advancing blue economy initiatives such as exploitation of abyssal mineral resources and Marine Carbon Dioxide Removal (mCDR) ~~or~~ and Ocean Based Carbon Interventions (OBCI) (see Section 3.2 below).

Understanding potential impacts from deep-sea mineral exploitation activities on abyssal habitats and their biodiversity has improved following extensive baseline surveys and experimental studies in the abyssal Pacific Clarion-Clipperton Zone (CCZ) (Muñoz-Royo and others, 2021; Muñoz-

Royo and others, 2022; Jones and others, 2025). Trials of polymetallic nodule collectors in the CCZ spurred scientific monitoring (e.g. Gazis and others, 2025) that identified limited impacts on densities and diversity inside test tracks against a background of substantial spatial and potential temporal variation (Lefaible and others, 2024). Gravity flow may dominate benthic sediment plumes, limiting their extent compared to previous predictions (Muñoz-Royo and others, 2022). Despite– limited information on ecological and biological effects of suspended sediment concentrations in abyssal environments (Hauton and others, 2017), multiple stress responses may occur (Stenvers and others, 2023). ~~There are e~~Effects on community structure (Simon-Lledó and others, 2019a), functioning (de Jonge and others, 2020; Vonnahme and others, 2020) and ecosystem services (Orcutt and others, 2020) ~~that~~ may persist for decades (Jones and others, 2025). The timescales of recovery and species-specific responses remain an important knowledge gap~~,~~ and require realistic mining tests and comprehensive monitoring (e.g. Lefaible and others, 2024). Anticipated impacts of chemical toxicity, noise, and light related to deep-sea mineral exploitation are equally poorly documented (Williams and others, 2022). Developing restoration capacity in deep-sea and abyssal ecosystems, an area of active research (Danovaro and others, 2021), will draw on proposed novel technologies (Aguzzi and others, 2024).

3.2 Effects of change and interaction with other components of the abyssal marine system

mCDR and OBCI incorporate diverse potential approaches, including artificial iron fertilization, which will likely change the quantity and quality of carbon flux to the abyss (Keller and others, 2018). A fossil study shows that not only warming but also changes in dust flux and resulting iron fertilization alter deep-sea ecosystems (Yasuhara and others, 2025). Some deep-ocean carbon technologies may directly alter abyssal communities, indicated in small-scale experiments (Barry and others, 2013) and natural analog studies of organic falls (Amon and others, 2017; Harbour and others, 2021). Precautionary management of mCDR and OBCI should also consider potential second-order effects on abyssal seafloor systems and often-overlooked interaction and feedbacks between carbon reservoirs (Keller and others, 2018). Importantly, even if these climate mitigations stabilize global temperatures, climate trends and changes in global ocean circulation and shallow-water and deep-sea marine systems may continue (e.g., Sigmond and others, 2020).

4. Region-specific changes in benthic biodiversity knowledge

4.1 The Arctic Ocean

A recent synthesis revealed high diversity of deep Arctic geomorphological features and a paucity of biodiversity data in deep basins (Ramirez-Llodra and others, 2024). Abyssal Arctic fauna is

highly sensitive to sea ice melt and resulting enhanced algal bloom and flux (Boetius and others, 2013). Ongoing projects are investigating the Arctic seafloor response to changing ice conditions (e.g. www.arctic.ac.uk) to identify changes at species and community levels but also in functional characteristics across the abyssal Arctic Oecean. Biogeographic distribution information over large spatial scales merits further investigation.

4.2 The European Baltic Sea, Northeast Atlantic Ocean, Mediterranean Sea

The European Baltic Sea does not reach abyssal depths, and the Mediterranean Sea's abyss (Calypso Deep, Ionian Sea) remains poorly investigated. Hence we focus on comparatively well-described and studied Northeast Atlantic Ocean abyssal systems, including newly discovered rocky habitats and biodiversity (Riehl and others, 2020). Integrated taxonomic study demonstrates the importance of knowledge on habitat heterogeneity for inferring large-scale biodiversity patterns (e.g. Schmidt and others, 2024). Understanding of deep-water mass properties and how they influence biodiversity and biogeography of Northeast Atlantic abyssal ecosystems has improved, including the role climatic changes play in these processes (Puerta and others, 2020). Improved understanding of deep-sea change critically requires abyssal temporal observations. Despite few deep-sea long-term monitoring stations, those that exist have provided crucial information. These stations include PAP in the Northeast Atlantic, operational since the mid-1980s (Horton and others, 2020). Recent insights from PAP highlight regional oxygen differences over decadal time scales (Ruhl and others, 2024). Although funding cuts threaten these time series, assessing long-term abyssal ecosystem changes requires extended temporal observations. Paleoecological data from deep-sea sediment cores such as IODP (International Ocean Discovery Program) provide historical biodiversity time-series spanning much longer durations (e.g. tens of thousands to millions of years, Yasuhara and others, 2008; Thomas and Gooday, 1996), and causally link deep-sea diversity to deep-sea temperature (Doi and others, 2021) as an important driver of abyssal biodiversity. Better understanding of abyssal biodiversity dynamics and its drivers will require more scientific effort.

4.3 The South Atlantic Ocean and the Wider Caribbean

Bridges and others (2023) recently emphasized the paucity of recent abyssal biodiversity studies in the Central and South Atlantic region. Shallow coastal studies dominate Caribbean Sea biodiversity research. The scarce available information shows some regional megafauna variation in the Caribbean abyss (Briggs and others, 1996) and reduced biodiversity in the continental rise-abyssal zone relative to slope depths (Hernández-Ávila and others, 2018).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf, Strait of Malacca and the South China Sea

Noting that the Gulf of Aden, the Persian Gulf, and Strait of Malacca do not reach abyssal depths and the limited Red Sea abyssal areas, we omit these seas here and focus on the Indian Ocean (including the Bay of Bengal) and the South China Sea.

Despite some abyssal Indian Ocean biodiversity records in OBIS (Thomas and others, 2024), data remains very limited (Saraswat and others, 2022). Presence of deep-sea minerals motivated Indian-led abyssal research since the 1980s but efforts have slowed, reinforcing a need for wider Indian Ocean biodiversity research.

In the deep South China Sea biodiverse communities on large plastic debris dumps demonstrate plastics as habitats for deep-sea epibenthos (Song and others, 2021). South China Sea biodiversity knowledge generally remains limited for abyssal depths (Ng and Tan, 2000; Liu, 2013). ~~Increasingly, d~~Deep-sea biological investigations in the South China Sea in the last decade have emphasized bathyal cold seep habitats (e.g., Wang and others, 2022).

4.5 The North Pacific Ocean

Since WOAII, considerable new abyssal knowledge has accrued for the North Pacific, particularly the CCZ with its abyssal polymetallic nodule fields. Higher species richness may characterize some CCZ fauna compared to other abyssal habitats (Stewart and others, 2023). Regional CCZ animal species richness is estimated at 6,000 to >8,000, 88–92% of which are undescribed (Rabone and others, 2023). Although e~~E~~xperts describe new abyssal species each year (Rabone and others, 2023) and target new geographic locations (Bribiesca-Contreras and others, 2022), ~~but~~ limited taxonomic expertise constrains descriptions of new species. Regional-scale syntheses have enabled better understanding of biodiversity and identified knowledge gaps and standardization issues (e.g., Wear and others, 2021; Hauquier and others, 2019; Smith and others, 2021; Stewart and others, 2023; Simon-Lledó and others, 2023a). Findings include linking basin-scale productivity gradients and a major biogeographic discontinuity related to the carbonate compensation depth (Simon-Lledó and others, 2023a). ~~There is hi~~High environmental heterogeneity characterizes~~of~~ abyssal environments (Washburn and others, 2021), noting the role of topography (Simon-Lledó and others, 2019a), substratum (Francesca and others, 2021; Simon-Lledó and others, 2019b), episodic food supply (Simon-Lledó and others, 2023b) and ecosystem engineers (Danovaro and others, 2024; Quintanilla and others, 2022).

Despite increasing studies of abyssal connectivity, understanding remains limited and inconsistent among faunal groups (Taylor and Roterman, 2017), an important gap in the context of potential deep-sea mineral exploitation. Most abyssal studies note the high proportion of rarely sampled species (McClain, 2021), but population genetic studies at multiple locations suggest well-connected populations over broad regions (Stewart and others, 2023; Taboada and others, 2018). At the global scale biogeophysical environments broadly define deep-sea biogeographic provinces (Watling and others, 2013; Maureaud and others, 2023), although Watling and Lapointe (2022) found weaker~~only partial~~ support using lower bathyal data for anthozoans. Brandt and others (2019) noted the hadal Kuril Kamchatka trench potentially limited connectivity and created faunal discontinuities in some abyssal faunal groups in the NW Pacific.

4.6 The South Pacific Ocean

Outside areas of mineral resource interest, few studies have addressed South Pacific abyssal environments. However, in 2024 the Ocean Census Programme sampled the Bounty Trough east of New Zealand to 5000 m depth, focusing on biodiversity discovery (Mills and others, 2024), and documented numerous new species and extended many distributional records.

The Hunga Tonga - Hunga Ha'apai eruption off Tonga in 2022, among the largest in recent history (Proud and others, 2022; Seabrook and others, 2023), catalysed several scientific voyages to map changes in topography and faunal communities. Few epifauna and macro-infauna survived the ash that blanketed hydrothermal vent fields >80 km from the volcano (Beinart and others, 2024) and adjacent abyssal plains, except where topographic highs such as knolls and hills provided shelter from direct ~~path of~~ sediment flows (Mackay and others, 2022, Seabrook and others, 2023). Surveys in 2024-2025 are investigating the recovery of benthic communities from this eruption. In addition, efforts to map and prioritize hydrothermal vent ecosystem protection at a global scale continue (Menini and others, 2023).

4.7 The Southern Ocean

Noting limited advances in knowledge regarding biodiversity and biogeography on Southern Ocean abyssal plains, researchers nonetheless report new species and habitats. Sampling of a Ross Sea seamount at 3380 m depth revealed seven new species (Lörz and others, 2023). Numerous hydrothermal vents reported from the South Sandwich Arc in the Southern Ocean (Linse and others, 2022) lack characteristic vent or seep megafauna although taxa in the vicinity varied greatly.

5. Implications for achieving the targets of the Sustainable Development Goals of the 2030 Agenda for Sustainable Development.

Society must determine the appropriate balance between economic and socio-climatic gains, and the environmental consequences of human activities, including deep-sea mineral exploitation and mCDR.

Long-term research ~~investigations~~ of abyssal ecosystems demonstrate community responses to temporal changes in organic carbon flux, underscoring their critical role in global ocean processes. The increase in environmental baseline studies — particularly ~~for~~ in the context of mineral explorations~~s~~ in the CCZ ~~and~~ , the Central Indian Basin, and the Northwest Pacific Ocean — has accelerated abyssal taxonomic and ecological research, as reflected in a stock taking report on the contribution of the International Seabed Authority (ISA) to the scientific objectives of the UN Ocean Decade. However, the ~~urgent~~ need for biological research, environmental monitoring, and evidence-based decision-making ~~regulation~~ to guide sustainable management and conservation of these ecosystems remains, reflecting requirements ~~needs~~ described under UNCLOS and the regulatory mandate of the ~~International Seabed Authority (~~ISA~~)~~.

6. Remaining key knowledge and capacity changes and any new gaps

Despite increased biological sampling in areas of interest for mineral resources, considerable knowledge gaps remain (Amon and others, 2022). These gaps include understanding of trophic relationships, life histories, population and ecosystem connectivity, and natural temporal variability of communities. Roest and others (2024) prioritized ecosystem-level functioning as a key management focus, recognizing the impracticality of obtaining detailed species-level data.

Key knowledge gaps include:

1. A global paucity of abyssal biodiversity knowledge remains, particularly for hard-bottom habitats.
2. Knowledge of species geographic ranges, connectivity patterns, and resilience of assemblages to climate stressors and human activities in the abyss.
3. Emerging geoengineering technologies present new opportunities to combat global change, yet may also pose risks of impact to abyssal ecosystems. Sustained monitoring, ~~and~~ fundamental ecological research, and rational governance is needed.

7 Acknowledgements

No artificial intelligence was used for the writing of the chapter.

8 References

Abel, Serena M., and others. Systematic identification of microplastics in abyssal and hadal sediments of the Kuril Kamchatka trench. Environmental Pollution, vol. 269, art. 116095, 2021.

Aguzzi, Jacopo, and others. New Technologies for Monitoring and Upscaling Marine Ecosystem Restoration in Deep-Sea Environments. Engineering, vol. 34, pp. 195–211, 2024.

Amon, Diva J., and others. Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. Marine Policy, vol. 138, art. 105006, 2022.

Barry, James P., and others. The response of abyssal organisms to low pH conditions during a series of CO2-release experiments simulating deep-sea carbon sequestration. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 92, pp. 249–260, 2013.

Beinart, Roxanne A., and others. Deep seafloor hydrothermal vent communities buried by volcanic ash from the 2022 Hunga eruption. Communications Earth & Environment, vol. 5, No. 1, art. 254, 2024.

Boetius, Antje, and others. Export of Algal Biomass from the Melting Arctic Sea Ice. Science, vol. 339, No. 6126, pp. 1430–1432, 2013.

Brandt, Angelika, and others. Biodiversity and biogeography of the abyssal and hadal Kuril-Kamchatka Trench and adjacent NW Pacific deep-sea regions. Progress in Oceanography, vol. 181, art. 102232, 2019.

Bribiesca-Contreras, Guadalupe, and others. Benthic megafauna of the western Clarion-Clipperton Zone, Pacific Ocean. Zookeys, vol. 1113, pp. 1–110, 2022.

Bridges, Amelia, and others. Review of the Central and South Atlantic Shelf and Deep-Sea Benthos: Science, Policy, and Management. Oceanography and Marine Biology: An Annual Review, vol. 61, pp. 127–218, 2023.

Briggs, Kevin B., and others. The classification and structure of megafaunal assemblages in the Venezuela Basin, Caribbean Sea. Journal of Marine Research, vol. 54, pp. 705–730, 1996.

Bryndum-Buchholz, Andrea, and others. Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. Global Change Biology, vol. 25, No. 2, pp. 459–472, 2019.

Cronin, Tom, and others. Pliocene (3.2-2.4 Ma) ostracode faunal cycles and deep ocean circulation, North Atlantic Ocean. Geology, vol. 24, No. 8, pp. 695–698, 1996.

Danovaro, Roberto, and others. Marine ecosystem restoration in a changing ocean. Restoration Ecology, vol. 29, No. S2, art. e13432, 2021.

Danovaro, Roberto, and others. Microbes as marine habitat formers and ecosystem engineers. Nature Ecology & Evolution, vol. 8, No. 8, pp. 1407–1419, 2024.

de Jonge, Daniëlle S. W., and others. Abyssal food-web model indicates faunal carbon flow recovery and impaired microbial loop 26 years after a sediment disturbance experiment. Progress in Oceanography, vol. 189, art. 102446, 2020.

Doi, Hideyuki, and others. Causal analysis of the temperature impact on deep-sea biodiversity. Biology Letters, vol. 17, No. 7, art. 20200666, 2021.

Durden, Jennifer M., and others. Response of deep-sea deposit-feeders to detrital inputs: A comparison of two abyssal time-series sites. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 173, art. 104677, 2020.

Francesca, Pasotti, and others. A local scale analysis of manganese nodules influence on the Clarion-Clipperton Fracture Zone macrobenthos. Deep Sea Research Part I: Oceanographic Research Papers, vol. 168, art. 103449, 2021.

Gazis, Iason-Zois, and others. Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining. Nature Communications, vol. 16, No. 1, art. 1229, 2025.

Glover, Adrian G., and Smith, Craig R. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environmental Conservation, vol. 30, No. 3, pp. 219–241, 2003.

Harbour, Rob P., and others. Biodiversity, community structure and ecosystem function on kelp and wood falls in the Norwegian deep sea. Marine Ecology Progress Series, vol. 657, pp. 73–91, 2021.

Hauquier, Frejia, and others. Distribution of free-living marine nematodes in the Clarion–Clipperton Zone: implications for future deep-sea mining scenarios. Biogeosciences, vol. 16, No. 18, pp. 3475–3489, 2019.

Hauton, Chris, and others. Identifying Toxic Impacts of Metals Potentially Released during Deep-Sea Mining—A Synthesis of the Challenges to Quantifying Risk. Frontiers in Marine Science, vol. 4, 2017.

Hernández-Ávila, Iván, and others. Variation in species diversity of deep-water megafauna assemblages in the Caribbean across depth and ecoregions. PLoS One, vol. 13, No. 8, art. e0201269, 2018.

Horton, Tammy, and others. Are abyssal scavenging amphipod assemblages linked to climate cycles? Progress in Oceanography, vol. 184, art. 102318, 2020.

Huffard, Christine L., and others. Temporally-resolved mechanisms of deep-ocean particle flux and impact on the seafloor carbon cycle in the northeast Pacific. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 173, art. 104763, 2020.

Jamieson, Alan J., and others. Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nature Ecology & Evolution, vol. 1, No. 3, art. 0051, 2017.

Johnson, Gregory C., and Purkey, Sarah G. Refined Estimates of Global Ocean Deep and Abyssal Decadal Warming Trends. Geophysical Research Letters, vol. 51, No. 18, art. e2024GL111229, 2024.

Jones, Daniel O. B., and others. Long-term impact and biological recovery in a deep-sea mining track. Nature, vol. 642, No. 8066, pp. 112–118, 2025.

Keller, David P., and others. The Effects of Carbon Dioxide Removal on the Carbon Cycle. Current Climate Change Reports, vol. 4, No. 3, pp. 250–265, 2018.

Kuhnz, Linda, and others. Benthic megafauna assemblage change over three decades in the abyss: Variations from species to functional groups. Deep Sea Research Part II Topical Studies in Oceanography, vol. 173, art. 104761, 2020.

Lefaible, Nene, and others. Industrial mining trial for polymetallic nodules in the Clarion-Clipperton Zone indicates complex and variable disturbances of meiofaunal communities. Frontiers in Marine Science, vol. 11, 2024.

Levin, Lisa A., Amon, Diva J. and Lily, Hannah. Challenges to the sustainability of deep-seabed mining. Nature Sustainability, vol. 3, No. 10, pp. 784–794, 2020.

Levin, Lisa A., and Le Bris, Nadine. The deep ocean under climate change. Science, vol. 350, No. 6262, pp. 766–768, 2015.

Linse, Katrin, and others. Megabenthos habitats influenced by nearby hydrothermal activity on the Sandwich Plate, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 198, art. 105075, 2022.

Liu, J. Y. Status of marine biodiversity of the China seas. PLoS One, vol. 8, No. 1, art. e50719, 2013.

Lörz, Anne-Nina, and others. Multi-ocean distribution of a brooding predator in the abyssal benthos. Scientific Reports, vol. 13, No. 1, art. 15867, 2023.

Mackay, Kevin, and others. Environmental impacts of the 2022 eruption of Hunga Tonga-Hunga Ha'apai: voyage report of part 1 of the TesMAP survey of the region in April-May 2022 (TAN2206). Wellington: National Institute of Water and Atmospheric Research Ltd., 2023.

Maureaud, Aurore A., and others. A global biogeographic regionalization of the benthic ocean. OSF Preprints, 2023.

McClain, Craig R. The commonness of rarity in a deep-sea taxon. Oikos, vol. 130, No. 6, pp. 863–878, 2021.

McClain, Craig R., and others. Energetics of life on the deep seafloor. Proceedings of the National Academy of Sciences, vol. 109, No. 38, pp. 15366–15371, 2012.

Menini, Elisabetta, and others. Towards a global strategy for the conservation of deep-sea active hydrothermal vents. npj Ocean Sustainability, vol. 2, No. 1, art. 22, 2023.

Mills, Sadie, and others. Ocean Census Bounty Trough: voyage report of the TAN2402 survey in February 2024. NIWA Client Report No. 2024098WN. 2024.

Muñoz-Royo, Carlos, and others. An in situ study of abyssal turbidity-current sediment plumes generated by a deep seabed polymetallic nodule mining preprototype collector vehicle. Science Advances, vol. 8, No. 38, art. eabn1219, 2022.

Muñoz-Royo, Carlos, and others. Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. Communications Earth & Environment, vol. 2, No. 1, pp. 148, 2021.

Nakajima, Ryota, and others. Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the North West Pacific. Marine Pollution Bulletin, vol. 166, art. 112188, 2021.

Ng, Peter K. L., and Tan, K. S. The state of marine biodiversity in the South China Sea. The Raffles Bulletin of Zoology, vol. 48, No. 8, pp. 3–7, 2000.

Orcutt, Beth N., and others. Impacts of deep-sea mining on microbial ecosystem services. Limnology and Oceanography, vol. 65, No. 7, pp. 1489–1510, 2020.

Proud, Simon R., and others. The January 2022 eruption of Hunga Tonga-Hunga Ha'apai volcano reached the mesosphere. Science, vol. 378, No. 6619, pp. 554–557, 2022.

Puerta, Patricia, and others. Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. Frontiers in Marine Science, vol. 7, art. 239, 2020.

Quintanilla, Elena, and others. Microbial Associations of Abyssal Gorgonians and Anemones (>4,000 m Depth) at the Clarion-Clipperton Fracture Zone. Frontiers in Microbiology, vol. 13, 2022.

Rabone, Muriel, and others. How many metazoan species live in the world's largest mineral exploration region? Current Biology, vol. 33, No. 12, pp. 2383–2396.e5, 2023.

Ramirez-Llodra, Eva, and others. Man and the last great wilderness: human impact on the deep sea. PLoS One, vol. 6, No. 8, art. e22588, 2011.

Rex, Michael A, and Etter, Ron K. Deep-Sea Biodiversity: Pattern and Scale. Cambridge: Harvard University Press, 2010.

Riehl, Torben, and others. Discovery of widely available abyssal rock patches reveals overlooked habitat type and prompts rethinking deep-sea biodiversity. Proceedings of the National Academy of Sciences, vol. 117, No. 27, pp. 15450–15459, 2020.

Roest, Walter R, and others. “The scientific challenges of deep-sea mining”, in Routledge Handbook of Seabed Mining and the Law of the Sea, Campanella, Virginie T., eds. (New York, Routledge, 2024).

Saraswat, Rajeev, and others. Editorial: Benthic Biodiversity of the Indian Ocean. Frontiers in Marine Science, vol. 9, 2022.

Schmidt, Lydia A., and others. Unveiling ophiuroid biodiversity across North Atlantic habitats via an integrative perspective. Scientific Reports, vol. 14, No. 1, art. 20405, 2024.

Seabrook, Sarah, and others. Volcaniclastic density currents explain widespread and diverse seafloor impacts of the 2022 Hunga Volcano eruption. Nature Communications, vol. 14, No. 1, art. 7881, 2023.

Sigmond, Michael, and others. Ongoing AMOC and related sea-level and temperature changes after achieving the Paris targets. Nature Climate Change, vol. 10, No. 7, pp. 672–677, 2020.

Simon-Lledó, Erik, and others. Carbonate compensation depth drives abyssal biogeography in the northeast Pacific. Nature Ecology & Evolution, vol. 7, No. 9, pp. 1388–1397, 2023a.

Simon-Lledó, Erik, and others. Mass falls of crustacean carcasses link surface waters and the deep seafloor. Ecology, vol. 104, No. 2, pp. e3898, 2023b.

Simon-Lledó, Erik, and others. Megafaunal variation in the abyssal landscape of the Clarion Clipperton Zone. Progress in Oceanography, vol. 170, pp. 119–133, 2019a.

Simon-Lledó, Erik, and others. Ecology of a polymetallic nodule occurrence gradient: Implications for deep-sea mining. Limnology and Oceanography, vol. 64, No. 5, pp. 1883–1894, 2019b.

Smith, Craig, and others. Editorial: Biodiversity, Connectivity and Ecosystem Function Across the Clarion-Clipperton Zone: A Regional Synthesis for an Area Targeted for Nodule Mining. Frontiers in Marine Science, vol. 8, art. 797516, 2021.

Smith, Kenneth L., and others. Episodic organic carbon fluxes from surface ocean to abyssal depths during long-term monitoring in NE Pacific. Proceedings of the National Academy of Sciences, vol. 115, No. 48, pp. 12235–12240, 2018.

Song, Xikun, and others. Large Plastic Debris Dumps: New Biodiversity Hot Spots Emerging on the Deep-Sea Floor. Environmental Science & Technology Letters, vol. 8, No. 2, pp. 148–154, 2021.

Stenvers, Vanessa I., and others. Experimental mining plumes and ocean warming trigger stress in a deep pelagic jellyfish. Nature Communications, vol. 14, No. 1, art. 7352, 2023.

Stewart, Eva C. D., and others. Biodiversity, biogeography, and connectivity of polychaetes in the world's largest marine minerals exploration frontier. Diversity and Distributions, vol. 29, No. 6, pp. 727–747, 2023.

Sutton, Philip J. H., and others. Southwest Pacific Ocean Warming Driven by Circulation Changes. Geophysical Research Letters, vol. 51, No. 13, art. e2024GL109174, 2024.

Taboada, Sergi, and others. Implications of population connectivity studies for the design of marine protected areas in the deep sea: An example of a demosponge from the Clarion-Clipperton Zone. Molecular Ecology, vol. 27, No. 23, pp. 4657–4679, 2018.

Taylor, Michelle L. and Roterman, C N. Invertebrate population genetics across Earth's largest habitat: The deep-sea floor. Molecular Ecology, vol. 26, No. 19, pp. 4872–4896, 2017.

Thomas, Ellen and Gooday, Andrew J. Cenozoic deep-sea benthic foraminifers: Tracers for changes in oceanic productivity? Geology, vol. 24, No. 4, pp. 355–358, 1996.

Vonnahme, Tobias R., and others. Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. Science Advances, vol. 6, No. 18, art. eaaz5922, 2020.

Wang, Xudong, and others. Macro-ecology of cold seeps in the South China Sea. Geosystems and Geoenvironment, vol. 1, No. 3, art. 100081, 2022.

Washburn, Travis W., and others. Environmental Heterogeneity Throughout the Clarion-Clipperton Zone and the Potential Representativity of the APEI Network. Frontiers in Marine Science, vol. 8, No. 319, art. 661685, 2021.

Watling, Les, and others. A proposed biogeography of the deep ocean floor. Progress in Oceanography, vol. 111, pp. 91–112, 2013.

Watling, Les, and Lapointe, Abby. Global biogeography of the lower bathyal (700–3000 m) as determined from the distributions of cnidarian anthozoans. Deep Sea Research Part I: Oceanographic Research Papers, vol. 181, art. 103703, 2022.

Wear, Emma, and others. Bacterial and Archaeal Communities in Polymetallic Nodules, Sediments, and Bottom Waters of the Abyssal Clarion-Clipperton Zone: Emerging Patterns and Future Monitoring Considerations. Frontiers in Marine Science, vol. 8, art. 480, 2021.

Williams, Rob, and others. Noise from deep-sea mining may span vast ocean areas. Science, vol. 377, No. 6602, pp. 157–158, 2022.

Yasuhara, Moriaki, and others. Abrupt climate change and collapse of deep-sea ecosystems. Proceedings of the National Academy of Sciences, vol. 105, No. 5, pp. 1556–1560, 2008.

Yasuhara, Moriaki, and others. Climatic forcing of the Southern Ocean deep-sea ecosystem. Current Biology, vol. 35, No. 2, pp. 347–353.e1, 2025.

Yasuhara, Moriaki, and others. Response of deep-sea biodiversity to abrupt deglacial and Holocene climate changes in the North Atlantic Ocean. Global Ecology and Biogeography, vol. 23, No. 9, pp. 957–967, 2014.

Section 4

Sub-chapter 5n: Pelagic Domain

Marta Coll, Camila Indira Artana, José María Bellido, Peter Croot, Antonio Di Natale, Flavia Lucena Frédou, Susana Garrido, Ryan Henegan, Brian Hunt, Francisco Ramírez, James J. Ruzicka, Lynne J. Shannon, Lloyd Spencer Davis, Akinori Takasuka.

Lead and co-lead authors

Rafael González-Quirós - rafael.gonzalez-quiros@ieo.csic.es

Tymon Zielinski - tymon@iopan.pl

Coordinating author

Marta Coll (ESP) – mcoll@icm.csic.es

Writing team

Camila Indira Artana (FR) - camila.artana@locean-ipsl.upmc.fr

Francisco Ramírez (ESP) - ramirez@icm.csic.es

José María Bellido (ESP) - josem.bellido@ieo.csic.es

Peter Croot (IR) - peter.croot@universityofgalway.ie

Antonio Di Natale (IT) - adinatale@costaedutainment.com

Flavia Lucena Frédou (Brazil) - flavia.fredou@ufrpe.br

Susana Garrido (PT) - susana.garrido@ipma.pt

Ryan Henegan (AU) - r.heneghan@qut.edu.au

Brian Hunt (CAN) - b.hunt@oceans.ubc.ca

James J. Ruzicka (USA) - james.ruzicka@noaa.gov

Lynne Shannon (SA) - Lynne.Shannon@uct.ac.za

Lloyd Spencer Davis (NZ) - lloyd.davis@otago.ac.nz

Akinori Takasuka (JP) - atakasuka@g.ecc.u-tokyo.ac.jp

Keynotes

The pelagic domain encompasses the entire water column and is the largest oceanic region. Due to its vastness and limited accessibility, it remains less studied and understood than the benthic and intertidal counterparts. The existing knowledge underscores its biological richness and essential contribution to ecosystem functioning. It also offers significant potential for humans, providing valuable ecosystem services such as living resources, energy, and climate regulation.

Introduction

Key components and structure

From the Latin *pelagus*, the pelagic domain refers to the open ocean environment, consisting of all the organisms that live within the water column, rather than on the ocean floor or near the coast. A key characteristic is the high mobility and dynamism of its organisms, which are not anchored to substrate and move through the water column. Their movements link habitats and drive processes like benthopelagic coupling (**Figure 1**). An exception to that mobility is some mesopelagic species that are non-migratory, particularly the Cyclothone genus that are largely responsible for what are known as the deep scattering layers, ubiquitous features of the mesopelagic (Sarmiento-Lezcano et al., 2023) and bathypelagic depths (Peña et al., 2021).

The pelagic domain is influenced by physical and biogeochemical factors that create distinct and dynamic habitats for marine life at different depths (**Figure 1**). It is subdivided into zones based on light penetration: epipelagic (0-200m), mesopelagic (200-1,000m), bathypelagic (1,000-4,000m), abyssopelagic (4,000-6,000m), and hadalpelagic (>6,000m) zones. This classification aids its description although oversimplification may misrepresent ecosystem processes (Eduardo et al., 2024).

Past drivers and pressures

Since the 1800s, the key factors controlling the pelagic domain underwent significant shifts, driven by human-induced climate change. These changes are altering species distributions and productivity, biodiversity, and the overall health of the oceans (Williamson and Guinder, 2021), with significant socio-ecological and economic consequences. Human activities like intense fishing, energy production, and global trade are also increasingly affecting the pelagic zone (**Figure 1**), with rising impacts now reaching even remote and once-pristine areas (Paolo et al., 2024).

Scientific advances from WOA I & II to WOA III

New discoveries and technological advances

Advancements in observational technologies have enhanced our ability to monitor Earth and wildlife, utilizing high-resolution data from sensors in various environments (Joo et

al., 2022; McCauley et al., 2024). Research vessels now serve as motherships for robots, enabling extensive data collection and multidisciplinary studies (Miller and Virmani, 2023). The Biogeochemical Argo program has expanded global insights into ocean productivity and dissolved oxygen (Izett et al., 2024; Jemai et al., 2021; Stoer et al., 2023).

Environmental DNA (eDNA) techniques have enhanced biodiversity understanding across ecosystems (Deeg et al., 2023; Zhang et al., 2020). They provide new insights into the diets of pelagic species, particularly informing the contribution of gelatinous zooplankton (Dischereit et al., 2024). On the other hand, advancements in the study of trophic ecology and ecosystem functioning include compound-specific stable isotope analyses (CSIA-AA) (Gimenez et al., 2023; Stahl et al., 2023).

New assessments and modelling efforts

The latest Coupled Model Intercomparison Project (CMIP6) Earth System Models have projected greater warming, acidification, deoxygenation, and nitrate reductions in the ocean, with smaller declines in primary production compared to CMIP5 (Kwiatkowski et al., 2020). CMIP6 also better captures extreme events like Marine Heatwaves (MHWs) (Qiu et al., 2021). Species Distribution Models and Marine Ecosystem Models now integrate complex datasets and environmental dynamics, simulating marine biomass on a global scale (Lotze et al., 2019; Tittensor et al., 2018). These models have revealed uncertainties and help project ecosystem responses to climate changes (Blanchard and Novaglio, 2024; Heneghan et al., 2021; Tittensor et al., 2021). Recent advancements in functional trait standardization have aided eDNA and their applications in ecosystem modelling, connecting ecosystem components based on functional roles and properties (Green et al., 2022; Heneghan et al., 2020; Pata and Hunt, 2023).

Emergent drivers and effects

Recent analyses have shown how changes in energy transfer efficiency due to ocean warming may lead to ~~greater~~ reduced biomass ~~losses in~~of ~~-~~fish and marine mammals, a phenomenon known as trophic amplification (Atkinson et al., 2024; Lotze et al., 2019).

Extreme ocean events have received increased attention due to their abrupt nature and severe impacts. Studies show spatial overlap and temporal synchronicity of compound extreme events, which exacerbate their effects (Amaya et al., 2023; Li et al., 2024). Recent advancements in ocean reanalysis models enable ~~analyzing~~ the analysis of vertical structures of these events (Wong et al., 2024; Zhang et al., 2023).

Emergent pollutants, transported through oceanic and atmospheric means, also pose an increasing risk to pelagic systems. Global levels may be exceeding planetary boundaries (Richardson et al., 2023).

Description of the current state and recent trends

a) Changes in physical and chemical state

Global ocean temperatures are rising, especially at high latitudes (**Figure 2**) (Garcia-Soto et al., 2021; Storto and Yang, 2024) (S4.C3, section 3.11). In addition, natural variability, such as the Pacific Decadal Oscillation and El Niño Southern Oscillation, affects regional trends (Johnson and Lyman, 2020). The 2023 El Niño led to record sea surface temperatures (SST), with the global average 0.23°C higher than in 2022, while Antarctic sea ice extent reached unprecedented lows (Copernicus, 2023[21]).

Warming trends also increase the frequency and intensity of marine heatwaves (MHWs) (Collins et al., 2022; Oliver et al., 2021) (**Figure 3**). MHWs impact marine ecosystems by altering species distributions and food web efficiency (Smith et al., 2023). They can trigger low-oxygen events, worsening ocean deoxygenation (Li et al., 2024), leading to habitat compression (Jorda et al., 2020).

The ocean absorbs anthropogenic CO_2, leading to increased acidity (decreased pH) and decrease aragonite saturation state (Bednaršek et al., 2023; Garcia-Soto et al., 2021; Ma et al., 2023) (see S4.C3; sections 3.2.1 and 3.2.2). Ocean salinity and circulation are also changing (S4.C3; section 3.1.2) impacting the pelagic domain (**Figure 2**) (Bograd et al., 2023; Ditlevsen and Ditlevsen, 2023; Douville and Cheng, 2024; Fox et al., 2023; Gutierrez-Guerra et al., 2024; Rahmstorf, 2024).

b) Changes in marine productivity/chlorophyll-a concentration

Marine productivity has declined across ocean basins, primarily due to ocean warming, increased stratification, and reduced oxygen and nutrient fluxes (Boyce et al., 2010) (S4.C3, section 3.2.4). Recent satellite data indicate ongoing declines in chlorophyll-a concentrations, impacting marine predators' reproductive performance, particularly in the Northern Hemisphere (Sydeman et al., 2021). While strong natural variability masks climate-change effects on phytoplankton, trends in ocean color reflectance are more detectable, revealing that low-latitude oceans have become greener (Cael et al., 2023). Negative extreme events decrease at high latitudes, while positive extremes intensify, especially along the circumpolar current (**Figure 4**).

c) Human activities

Plastic debris is increasingly found in marine organisms (Liu et al., 2023; Marmara et al., 2023; Wieczorek et al., 2018). Plastics affect marine ecosystems by influencing carbon sinking rates and oxygen levels (Kvale et al., 2023). Humans are exposed to plastics through contaminated seafood (Akhbarizadeh et al., 2020; Leslie et al., 2022; Marmara et al., 2023).

While small-scale trials for mesopelagic fish exist, they are not a significant target for commercial fishing, with total reported catches at 2.7 million tons since the 1950s (Pauly

[21] https://marine.copernicus.eu/news/2023-northern-hemisphere-summer-record-breaking-oceanic-events

et al., 2021). Economic viability is limited by distance to fishing areas, high fuel costs, rapid fish deterioration, and low fish density (Kourantidou and Jin, 2022; Paoletti et al., 2021; Vastenhoud et al., 2023). Rising demand for fishmeal and improved storage methods may make mesopelagic fisheries profitable in the future (Paoletti et al., 2021).

d) Key zones

The mesopelagic zone (200 – 1,000 m) covers 60% of surface of the Earth and 20% of the ocean's volume. This community is vital to the Biological Carbon Pump (BCP) and the global carbon cycle, transporting carbon to depth through Diel Vertical Migration (DVM) (Anderson et al., 2019; Kiko et al., 2020) and mediating the flux of sinking carbon-containing particles (Baumas et al., 2021) (S5B.C1). Mesopelagic fish and zooplankton contribute 16% each to the global BCP, corresponding to the sinking particulate organic carbon (POC) flux from surface waters (Archibald et al., 2019; Saba et al., 2021). Climate-driven changes are altering mesopelagic communities, impacting the BCP (Kiko et al., 2020).

Primary production in Eastern Boundary Upwelling Systems (EBUS) is disrupted by climate change, as SST rises and upwelling winds intensify. Shifts in pelagic species are observed in upwelling systems, such as the California Current and Southern Benguela (Blamey et al., 2015; Fiechter et al., 2021).

The Arctic and Antarctic Oceans are highly vulnerable to climate change, particularly in their oceans and cryosphere. Changes in sea ice conditions are leading to profound shifts in the magnitude and phenology of pelagic marine productivity pulses typical of highly seasonal polar systems, with far-reaching implications for polar ecosystems and their roles in global biogeochemical cycles (S4.C3; section 3.1.4 and S4.C5k) (Willis et al., 2023).

e) Key species groups

Climate-driven declines in phytoplankton size and biomass have led to greater losses in higher trophic organisms like fish and marine mammals across the open ocean (Henson et al., 2022; Lotze et al., 2019). Ocean warming has also shifted zooplankton distribution, favored smaller species, and altered seasonal patterns of productivity (Benedetti et al., 2021; Ratnarajah et al., 2023). These shifts have large impacts on fish~~eries~~ recruitment (Beaugrand et al., 2003; Jaspers et al., 2023; Johnston et al., 2022; Pinchuk et al., 2021; Steinberg and Landry, 2017) (S4.C4a).

Small pelagic fish (SPF) contribute over 15% of energy flowing to top predators, supporting 22% of seabirds and 15% of marine mammals in assessed ecosystems (Ruzicka et al., 2024). SPF represent 43% of total fish production and 18% of global catches, (Ruzicka et al., 2024). Their worldwide status is complex and regionally variable (FAO, 2024). Historically, fluctuations in SPF populations have been linked to environmental variability, while high fishing pressure and competition among pelagic organisms play crucial roles (Alheit and Peck, 2019; Coll et al., 2024; Hilborn et al., 2022). These fluctuations significantly affect fisheries and predatory species of conservation concern. In 2023, El Niño conditions reduced the habitats of cold-water species like Peruvian anchoveta (*Engraulis ringens*), the world's largest monospecific

fishery, leading to a 50% reduction in industrial landings compared to 2022. Such losses impacted local economies and global aquaculture due to the fishery's role in producing fishmeal and fish oil (S4.C4).

Deep-pelagic fish are crucial for oceanic carbon sequestration (Eduardo et al., 2024; Klevjer et al., 2016; Saba et al., 2021) but they face threats from pollutants (Ferreira et al., 2023; Justino et al., 2022), potential exploitation from fisheries (Hidalgo and Browman, 2019; Pauly et al., 2021), the offshore oil and gas industry (Hawkins et al., 2023), and from the emerging deep-sea mining (Kung et al., 2021).

The open ocean catch was estimated at 11 million t/y in 2022, primarily consisting of species with open ocean distributions (FAO, 2024). Global tuna catches reached 8.3 million t/y in 2022, with 87% of world tuna stocks considered sustainably fished (FAO, 2024). Skipjack tuna (*Katsuwonus pelamis*) is the third-largest catch among harvested species, while some previously overfished stocks, like bluefin tuna (*Thunnus thynnus*), have recovered, demonstrating the benefits of effective management ~~benefits~~ (Juan-Jordá et al., 2022). However, not all species and stocks are assessed, particularly the small tunas (Lucena-Frédou et al., 2021).

Chondrichthyans are highly vulnerable to overfishing and bycatch due to slow growth and low reproductive rates (Dulvy et al., 2021). Recent trends do not indicate major recoveries (Juan-Jordá et al., 2022), and many shark species are threatened with extinction, with three-quarters of studied species being at risk (Dulvy et al., 2021).

Despite recent recoveries (Duarte et al., 2020), marine mammals in pelagic ecosystems face significant conservation challenges from human activities and climate change (S4.4e). Key threats include bycatch, vessel collisions, plastic and noise pollution, and habitat degradation that affects food availability and migratory patterns (Avila et al., 2018; Fortuna et al., 2024). Many seabird species are also in decline (BirdLife International, 2018), with invasive species, overfishing, and climate change as the primary threats (Dias et al., 2019; Gimeno et al., 2024; Sydeman et al., 2021) (C4.C4g). The pelagic phase of marine turtles is largely under-studied (Robinson et al., 2023), and while many populations are declining, a few are increasing (Hays et al., 2024) (S4.C4f).

f) Effects of changes for humans

Wild-capture fisheries have remained around 90 million tons per year since the 1980s (FAO, 2024), while commercial fisheries now cover nearly all pelagic ocean areas (Rousseau et al., 2024) (C5A.C1a and S5A.C1b). This expansion may obscure warming-induced shifts in species richness from equatorial waters since the 1970s (Chust et al., 2024). With global demand for marine protein expected to double by 2050, pressure on pelagic ecosystems will likely increase and move northwards (Cruz et al., 2024).

The blue economy is projected to grow to US$3 trillion annually by 2030 (Jolly, 2016) facing challenges due to insufficient ocean knowledge (Narwal et al., 2024). It heavily relies on fisheries, with small pelagic fish and tuna comprising a significant portion of catches (FAO, 2024). Intensive fisheries management has generally improved abundance of several stocks ~~abundance~~ (Hilborn et al., 2020). However, increased

interest in exploiting deeper waters could jeopardize essential species, leading to declines in biomass and diversity (Ariza et al., 2022; Eduardo et al., 2024; Lin et al., 2023).

Pelagic ecosystems suffer from accumulated pollutants, particularly persistent ones like Polychlorinated biphenyls (PCBs) and Per- and polyfluorinated alkyl substances (PFASs), which do not decompose naturally and cause carcinogenesis, teratogenesis, and endocrine disruption (Worm et al., 2017). Nanoplastics and microplastics are of concern, contaminating marine organisms and posing health risks to humans as they bioaccumulate in the food web (Fauvelle et al., 2021; Sala et al., 2022). Risks to the open ocean include light and noise pollution and sediment discharges from mining operations, which contain harmful particulates and chemical additives (Christiansen and Bräger, 2023; Duarte et al., 2021). Mining plumes may impact fisheries (Van Der Grient and Drazen, 2021) and human health through bioaccumulation of toxins.

g) Evolution of management and conservation

Managing the high seas is challenging due to their vast and dynamic nature, and the complex impact of climate change. Regional Fishery Management Organizations (RFMOs) play crucial roles in managing pelagic species and addressing bycatch, and they are expanding to incorporate ecosystem and climate change considerations (S5A.C1a) (SCRS-ICCAT, 2024). Proposing Marine Protected Areas (MPAs) in the pelagic zone faces obstacles due to species' migratory behavior, impacts of climate change, technological gaps and enforcement difficulties. Recent t~~T~~echnological advances have improved monitoring capabilities, although the observation of biological variables and processes still presents important challenges (S4.C2).

The International Seabed Authority (ISA) regulates ~~deep-sea~~ exploration for deep-sea minerals in Areas ~~mining b~~Beyond ~~national~~ National ~~boundaries~~ Jurisdiction but has yet to adopt a regulatory code for exploitation activities. In 2023, the ISA Assembly adopted a roadmap with a view to the adoption during the thirtieth session. ~~and environment protection policy~~ (ISA, 2024). ~~One company and subsidiary within a sponsoring state have announced intentions to submit an application in June 2025 to commence mining operations for polymetallic nodules within international waters (TMC, 2025).~~ The regulatory framework and time-frame for ISA approval are uncertain (Pickens et al., 2024). The unprecedented geographic scale of deep-sea mining, along with new technologies and poorly understood ecosystems, complicates environmental impact assessments.

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) aims to protect marine biodiversity in international waters by area-based management tools, including MPAs, and mandate environmental impact assessments. It establishes a framework for sustainable use of ocean resources, enhancing global cooperation to manage the unique challenges of pelagic ecosystems. The BBNJ Agreement was adopted on 19 June 2023 by the Intergovernmental Conference on Marine Biodiversity of Areas Beyond National Jurisdiction convened under the auspices of the United Nations, but is yet to be ratified

by sufficient countries. The BBNJ Agreement becomes the third implementing agreement to the United Nations Convention on the Law of the Sea, which marked a significant step in ocean conservation and governance.

Region-specific issues relating to current state

a) The Arctic Ocean

The Arctic is experiencing rapid climate transformations, known as Arctic Amplification (Carmack et al., 2015), fueled by sea ice loss and radiative feedbacks (Jenkins and Dai, 2021). Sea ice extent has significantly declined (Ivanov, 2023), and the Barents Sea has become a "hot spot" for climate change, marked by intensified inflow of warmer, saltier Atlantic waters, known as "Atlantification," which further accelerates sea ice loss (Skagseth et al., 2020) (S4.C5k). These changes affect biodiversity and abundance of marine communities (Gordó-Vilaseca et al., 2024; Gordó-Vilaseca et al., 2023). The region seems to be a sink for contaminants and litter from global sources, transported from lower latitudes (ICES, 2022).

b) The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

The North Atlantic faced strong to severe marine heatwaves in the summer of 2023, causing a significant decrease in chlorophyll-a concentration (up to 50-60%) in the Eastern North Atlantic, which had a notable impact on ocean productivity. A persistent cold anomaly in the Subpolar Gyre and low salinity along the Greenland coast, likely due to increased precipitation and ice sheet melting, have altered the distribution of several species (mackerels, bluefin tuna, humpback whales, common eiders, great cormorants) (Josey et al., 2018). In the North Sea, warming surface waters are affecting plankton, fish, and fisheries distribution, with the 0-200m depth zone heavily trawled. While most commercial fish stocks are stable, seabird populations are declining, and seal numbers are increasing. In the Baltic Sea, climate-driven changes are reshaping ~~the ecosystems~~ecosystem. ~~, with~~While most pelagic fish stocks are increasing, with the exception of the Baltic herring, ~~and~~ non-indigenous species are spreading. The Baltic population of the harbour porpoise is critically endangered and presently confined to the western basin, with a dramatic population decline caused by bycatch in fishing gear, underwater noise, chemical pollution, and prey depletion[22].

Mediterranean SST have shown positive anomalies (Salat et al., 2019), with February 2023 reaching a record high of 1.2°C. Rising temperatures and declining primary productivity have affected small pelagic fish, altering their distribution and reducing catches (Coll et al., 2024), and the spread of non-native pelagic species is changing the biodiversity (Zenetos et al., 2022). In the Black Sea, the situation remains poorly assessed, but some large pelagic species, like bluefin tuna and swordfish, were slowly returning before recent extreme events.

[22] https://www.ascobans.org/en/species/phocoena-phocoena

c) The South Atlantic Ocean and the Wider Caribbean

The Southwestern Atlantic Ocean is highly vulnerable to MHWs (Artana et al., 2024). These MHWs contributed to massive fish mortality and toxic algal blooms in the summer of 2017 (Manta et al., 2018). Moreover, ~~in~~ on particular occasions, MHWs coincided with a severe drought in Southeast Brazil such as in January 2014 (Rodrigues et al., 2019). In South Africa, management trade-offs between the conservation needs of the endangered African penguin and small pelagic purse seine fisheries have sparked intense debate and legal battles (Cochrane et al., 2024; McInnes et al., 2024).

The increase in *Sargassum* seaweed blooms (D4.C4i) is now stretching across the Great Atlantic Sargassum Belt from the Gulf of Mexico to the western Atlantic. These blooms are exacerbated by warmer sea temperatures and nutrients runoff from coastal areas, and create hypoxic zones affecting marine species, local tourism and fisheries (Marsh et al., 2023; Robledo et al., 2021).

d) The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

Warming ocean temperatures and oxygen depletion in the Indian Ocean impact pelagic species, leading to shifts in the distribution of tuna, sardines and mackerel, with species moving towards cooler southern waters (Waller et al., 2024). For example, in the Arabian Sea, low-oxygen zones are expanding, reducing habitat for pelagic organisms such as Indian mackerel and scads (Lachkar et al., 2023). The Bay of Bengal faces increased hypoxia, threatening key pelagic fish species due to changing monsoon patterns (Vidhya et al., 2022). In the Persian Gulf, the effects of climate change impacts pelagic fish populations (Khalfeh Nilsaz et al., 2024).

e) The North Pacific Ocean

This region is increasingly contaminated by microplastics (Van Sebille et al., 2015; Yu and Singh, 2023). In the western North Pacific, plankton and small pelagic fish biomass fluctuations respond to the Pacific Decadal Oscillation (PDO) at a multidecadal scale. However, the SST regime has been unconventional in the last decade (Kuroda et al., 2020). Despite a negative PDO phase around 2010, lower SSTs were recorded in some seasons, and small pelagic fish population dynamics have not followed past trends.

f) The South Pacific Ocean

Global warming and rising SST impacts marine life, leading to major changes in currents and upwelling zones (Bograd et al., 2023; Sutton et al., 2024; Wang et al., 2023). These changes affect the distribution, reproduction, and behavior of many marine animals (Avila et al., 2020; Montalva et al., 2022; Peters et al., 2022). Concerns about anthropogenic stressors persist, including fisheries (Ortiz and Hermosillo-Núñez, 2024). The ubiquity of microplastics (Bakir et al., 2020; Bleszynski and Clark, 2023) and the spread of avian influenza A(H5N1) are affecting seabirds and marine mammals (Gamarra-Toledo et al., 2023; Leguia et al., 2023; Stokstad, 2023).

g) The Southern Ocean

Circumpolar deep-water warms and CO_2 concentrations have been rising (Morley et al., 2020). Atmospheric warming and declining sea-ice extent is most pronounced around the Antarctic Peninsula (Gimeno et al., 2024) (S4.C5k). This impacts the recruitment success of Antarctic krill, a keystone species (Johnston et al., 2022). While current and future physical and biogeochemical changes may increase primary production (Pinkerton et al., 2021), the food web responses will depend on zooplankton reactions to warming and acidification, affecting higher trophic levels (Johnston et al., 2022; Swadling et al., 2023).

The long history of resource exploitation, primarily driven by Antarctic krill and toothfish fisheries, remains low compared to global averages (Paolo et al., 2024). However, advancements in technology and favorable environmental conditions could increase the accessibility and pressure on these resources (Rogers et al., 2020). Climate change exacerbates these challenges (Gimeno et al., 2024), alongside rising tourism, pollution, pathogens, and disturbances from invasive species (Becker et al., 2024). The growing vulnerability of marine life in the Antarctic has sparked a recent initiative aiming to strengthen humankind's duty in supporting Southern Ocean ecosystems[23].

Key knowledge and capacity gaps

a) Gaps on key processes

Although there has been progress (Eduardo et al., 2024; Egorova et al., 2024), the mesopelagic zone remains data poor. Increased interest in deep-water ecosystems highlights their ecological significance, alongside significant knowledge gaps and rising threats. Much of the biodiversity below 1,000 meters also remains undiscovered, with gaps in taxonomy (smaller organisms being less studied) and species interactions.

Little is known about species movements and ecological interactions among organisms across trophic levels and regions, hindering the understanding of species distribution, ecosystem changes and effective management and conservation effects. Understanding these interactions is crucial for advancing our comprehension of ocean ecosystems and the impact of management actions (Schaber et al., 2022). Technological advancements like in situ imaging and eDNA are starting to address some of these important gaps.

The cumulative impact of extreme climate events is becoming a critical research focus, particularly regarding compound events and their influence on ocean dynamics, biodiversity and human livelihoods. Moreover, these events are exacerbated by other anthropogenic impacts on ocean ecosystems, such as pollution and fishing. As the~~ir~~ frequency and intensity of extreme events rise, it is essential to understand their effects at various spatiotemporal scales. For instance, the interplay of global warming

[23] https://antarcticrights.org/

(centennial scale), Atlantic Multidecadal Oscillation (AMO) (multidecadal scale), Pacific Decadal Oscillation (PDO), and El Niño/La Niña events, along with marine heatwaves (annual scale), could intricately affect organism and community dynamics in ocean ecosystems.

The start of deep-sea mining operations may soon pose a new threat to the deep pelagic communities of the open ocean that play a crucial role as prey for higher trophic levels and in the global BCP. Assessing the severity of this threat is challenging. Moreover, the interactive effects of multiple stressors on pelagic organisms, populations, and communities (and dependencies with benthic counterparts) present a key knowledge gap that requires further research (Pinsky et al., 2020; Van de Waal and Litchman, 2020). Fisheries impacts and value chains, and food nutrition with a pelagic origin, are important knowledge gaps, going beyond the impacts of climate change on fish production (Heneghan et al., 2023; Van de Waal and Litchman, 2020).

b) Technological gaps

The pelagic domain remains among the least explored areas on Earth. There is still a critical need for enhanced observational data. Biogeochemical parameters are poorly sampled compared to physical variables. Most monitoring efforts focus on surface-level measurements, limiting our understanding of the deep ocean's role in heat and carbon storage, especially below 2,000 meters. Recent studies using deep Argo floats reveal that decadal heat content trends are significant in these underexplored regions (Johnson and Purkey, 2024). Gaps remain in measuring vertical ocean velocities, particularly in sub-mesoscale processes. The launch of the Surface Water and Ocean Topography (SWOT) satellite in December 2022 is a significant advancement (Fu et al., 2024).

Challenges remain in obtaining quantitative estimates of fish and plankton biomass. An estimated 81% of zooplankton monitoring data are either unavailable or only partially accessible (Ratnarajah et al., 2023). There is a pressing need to implement FAIR (Findable, Accessible, Interoperable, and Reusable) data standards in pelagic data (Wilkinson et al., 2016) for biodiversity assessments (Becker et al., 2024; Ramírez et al., 2022). Further efforts on eDNA techniques are needed to build reference libraries (Ratnarajah et al., 2023).

c) Capacity building needs

Another challenge is about digitizing and mobilizing existing data and knowledge (Meyer et al., 2015; Rogers et al., 2022). Enhancing the collaboration in international data-sharing programs through partnerships and capacity-building can improve marine biodiversity monitoring. Taxonomic training, especially for less-known non-vertebrate groups, should remain a priority, as the value of digitized collections depends on accurate species identifications and taxonomic completeness.

Quantitative socio-ecological assessments are essential for analyzing pelagic systems and understanding human impacts. ~~These~~ Socio-ecological models~~models~~ must be scientifically robust yet accessible to managers and decision-makers (Heymans et al.,

2020). Despite progress in quantifying marine modeling uncertainty (Rynne et al., 2025; Steenbeek et al., 2024), further development is still needed.

Figures

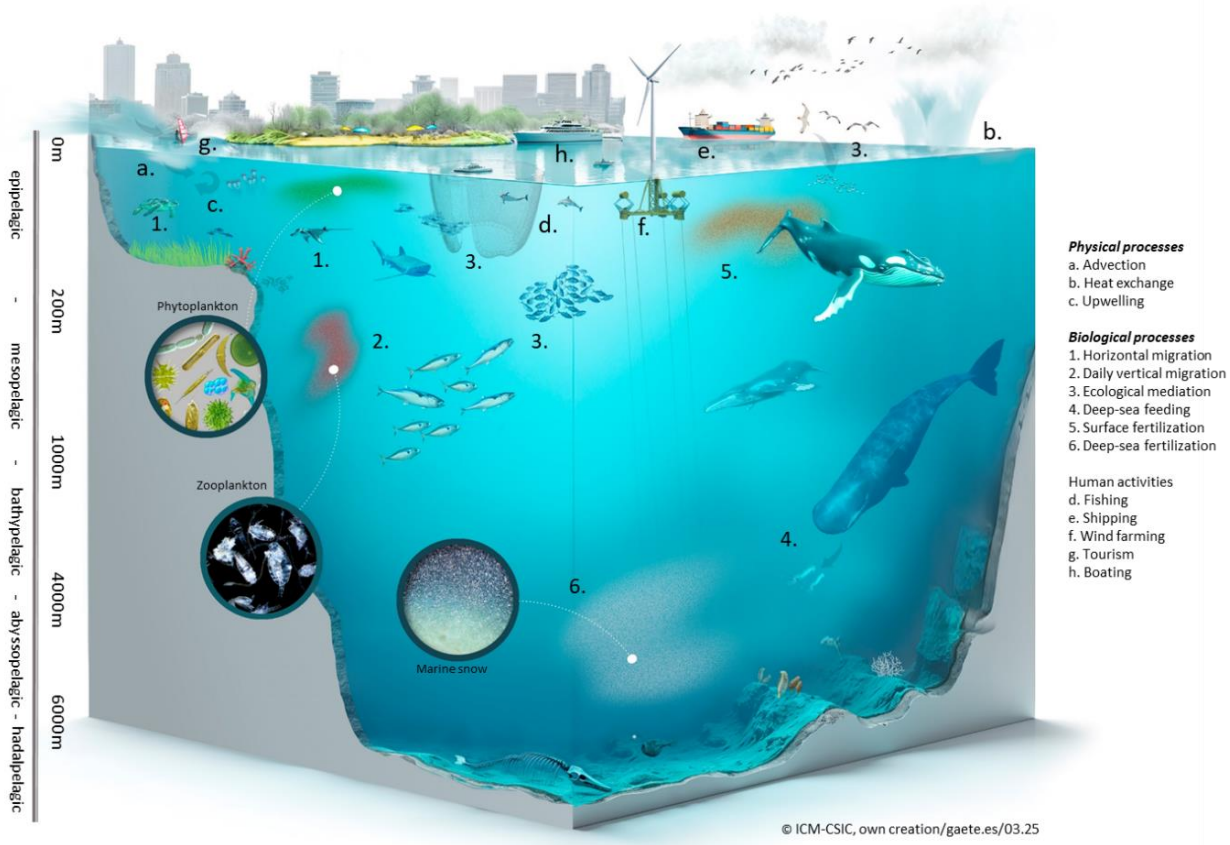


Figure 1: Schematic representation of the pelagic domain where main regions and species type are represented, along with some key ecological processes and human activities that accumulate in the pelagic domain (Image: ICM-CSIC, own creation/gaete.es/03.25).

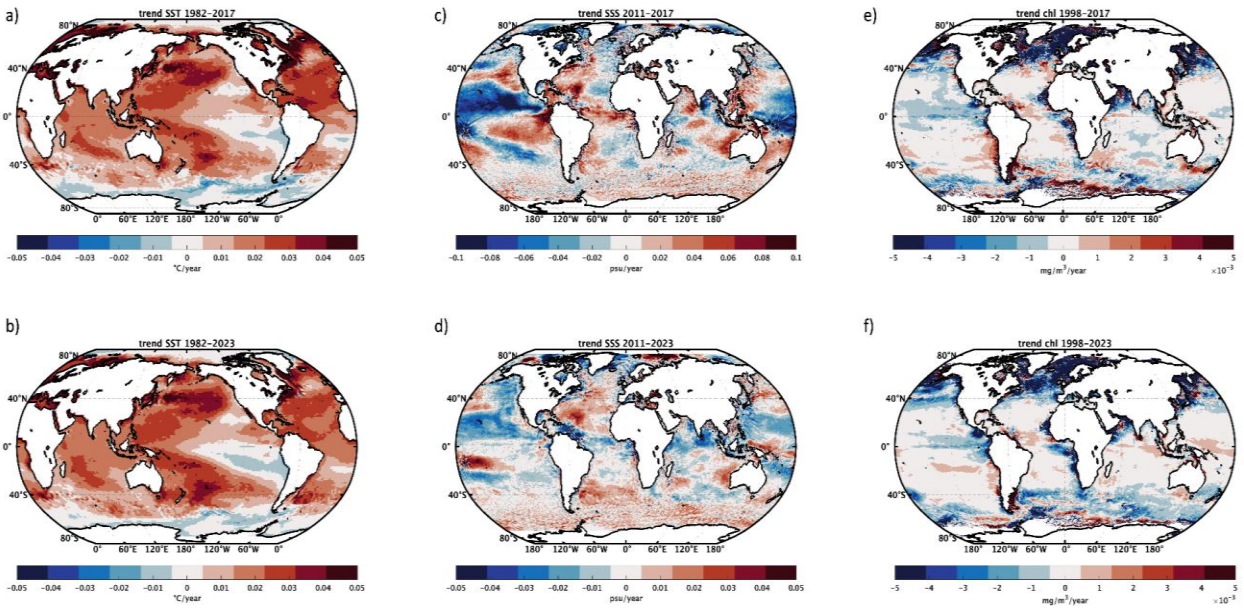


Figure 2: Temperature trend for the period (a)1982-2017 and (b) 1982-2023. Salinity trend for the period (c) 2011-2017 and (d) 2011-2023. Chlorophyll-a trend for the period (e) 1998-2017 and (f) 1998-2023 (Salinity data from https://doi.org/10.1175/JTECH-D-20-0093.1, chlorophyll-a data from https://doi.org/10.48670/moi-00281 downloaded from the Copernicus marine service website: https://data.marine.copernicus.eu/products; temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL, Boulder, Colorado, USA, https://psl.noaa.gov/).

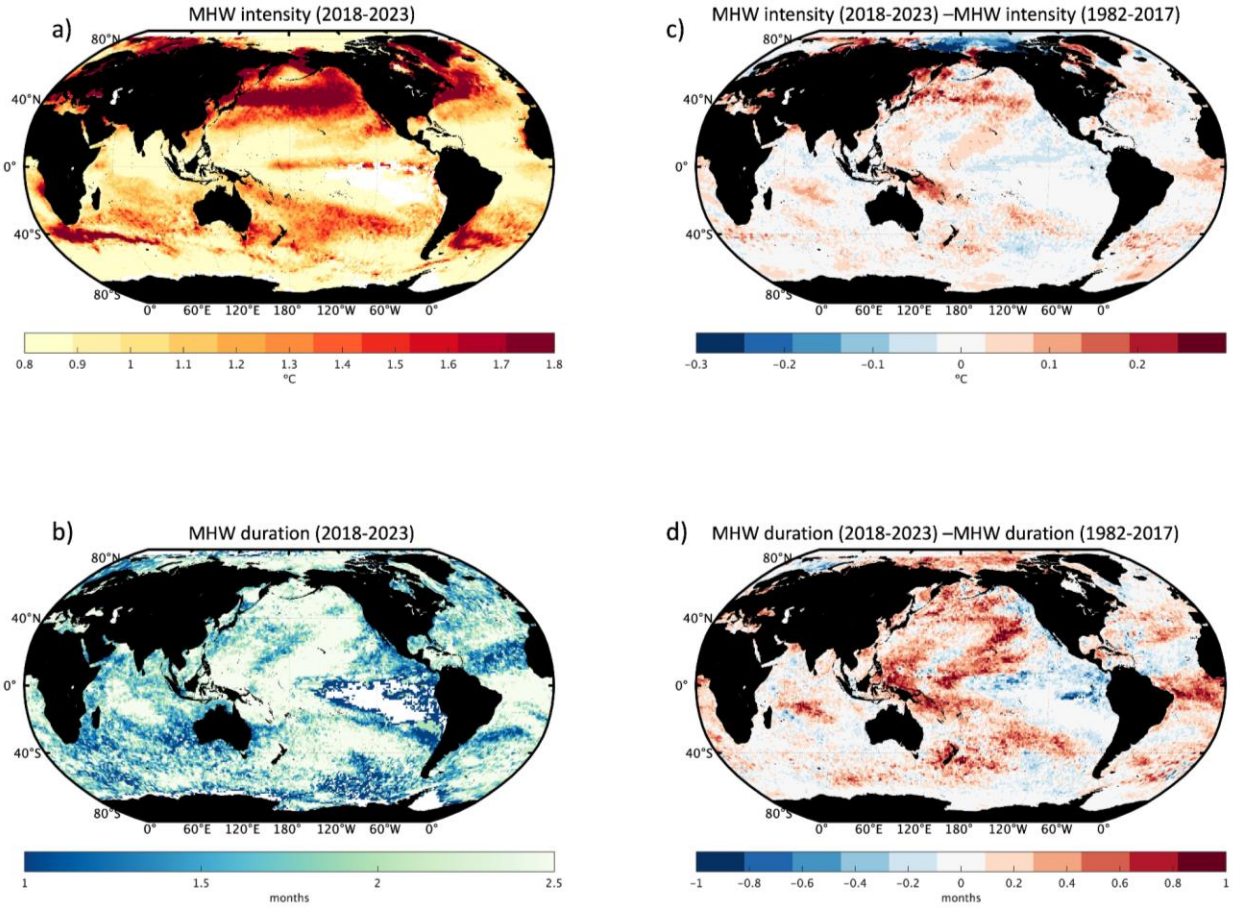


Figure 3: (a) Mean MHWs intensity for the period 2018-2023. (b) Same as a) but for MHW duration. (c) Difference between mean MHW intensity computed over the period 2018-2023 and mean MHW intensity computed over the period 1982-2017. (d) Same as c) but for MHW duration (Temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL, Boulder, Colorado, USA, https://psl.noaa.gov/).

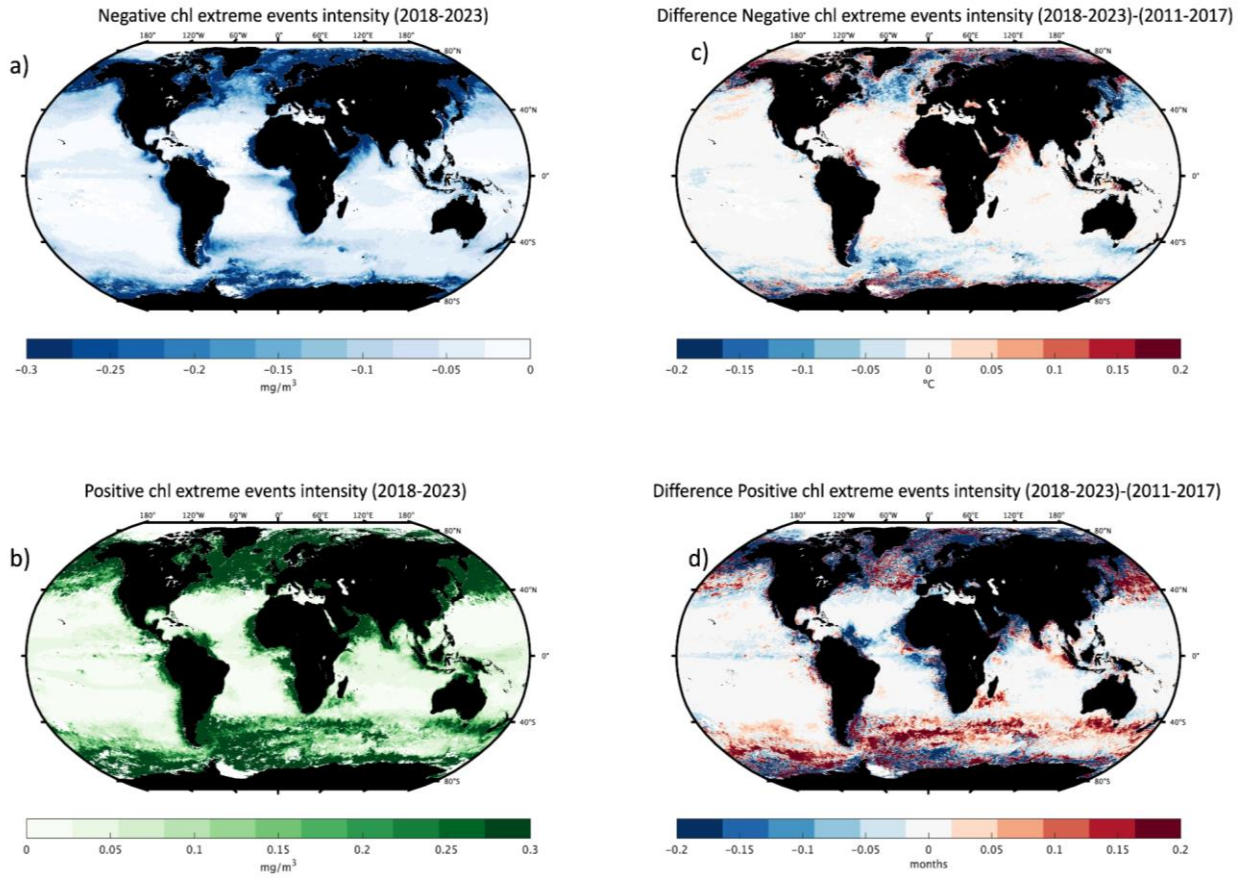


Figure 4: (a) Negative and (b) positive extreme events of Chlorophyll-a intensity for the period 2018-2023. (c) Differences between negative extreme events of chl computed over the period 2018-2023 and 2011-2017. Blue colors indicate that negative extreme events were more intense during 2011-2017. (d) Same as c) but for positive extreme events of chl (Chlorophyll-a data from https://doi.org/10.48670/moi-00281 downloaded from the Copernicus marine service website: https://data.marine.copernicus.eu/products).

1

2

References

Akhbarizadeh R, Dobaradaran S, Nabipour I, Tajbakhsh S, Darabi AH, Spitz J. Abundance, composition, and potential intake of microplastics in canned fish. Marine Pollution Bulletin 2020; 160: 111633.

Alheit J, Peck MA. Drivers of dynamics of small pelagic fish resources: biology, management and human factors. Marine Ecology Progress Series 2019; 617: 1-6.

Amaya DJ, Jacox MG, Alexander MA, Scott JD, Deser C, Capotondi A, et al. Bottom marine heatwaves along the continental shelves of North America. Nature Communications 2023; 14: 1038.

Anderson TR, Martin AP, Lampitt RS, Trueman CN, Henson SA, Mayor DJ. Quantifying carbon fluxes from primary production to mesopelagic fish using a simple food web model. ICES Journal of Marine Science 2019; 76: 690-701.

Archibald KM, Siegel DA, Doney SC. Modeling the impact of zooplankton diel vertical migration on the carbon export flux of the biological pump. Global Biogeochemical Cycles 2019; 33: 181-199.

Ariza A, Lengaigne M, Menkes C, Lebourges-Dhaussy A, Receveur A, Gorgues T, et al. Global decline of pelagic fauna in a warmer ocean. Nature Climate Change 2022; 12: 928-934.

Artana C, Rodrigues RR, Fevrier J, Coll M. Characteristics and drivers of marine heatwaves in the western South Atlantic. Communications Earth & Environment 2024; 5.

Atkinson A, Rossberg AG, Gaedke U, Sprules G, Heneghan RF, Batziakas S, et al. Steeper size spectra with decreasing phytoplankton biomass indicate strong trophic amplification and future fish declines. Nature Communications 2024; 15: 381.

Avila IC, Dormann CF, García C, Payán LF, Zorrilla MX. Humpback whales extend their stay in a breeding ground in the Tropical Eastern Pacific. ICES Journal of Marine Science 2020; 77: 109-118.

Avila IC, Kaschner K, Dormann CF. Current global risks to marine mammals: taking stock of the threats. Biological Conservation 2018; 221: 44-58.

Bakir A, Desender M, Wilkinson T, Van Hoytema N, Amos R, Airahui S, et al. Occurrence and abundance of meso and microplastics in sediment, surface waters, and marine biota from the South Pacific region. Marine Pollution Bulletin 2020; 160: 111572.

Baumas CM, Le Moigne FA, Garel M, Bhairy N, Guasco S, Riou V, et al. Mesopelagic microbial carbon production correlates with diversity across different marine particle fractions. The ISME Journal 2021; 15: 1695-1708.

Beaugrand G, Brander KM, Alistair Lindley J, Souissi S, Reid PC. Plankton effect on cod recruitment in the North Sea. Nature 2003; 426: 661-664.

Becker SL, Boyd C, Handley JM, Raymond B, Reisinger R, Ropert-Coudert Y, et al. Scaling up ocean conservation through recognition of key biodiversity areas in the Southern Ocean from multispecies tracking data. Conservation Biology 2024: e14345.

Bednaršek N, Feely RA, Pelletier G, Desmet F. Global synthesis of the status and trends of ocean acidification impacts on shelled pteropods. Oceanography 2023; 36: 130-137.

Benedetti F, Vogt M, Elizondo UH, Righetti D, Zimmermann NE, Gruber N. Major restructuring of marine plankton assemblages under global warming. Nature communications 2021; 12: 5226.

BirdLife International. State of the world's birds: taking the pulse of the planet. BirdLife International 2018.
Blamey LK, Shannon LJ, Bolton JJ, Crawford RJ, Dufois F, Evers-King H, et al. Ecosystem change in the southern Benguela and the underlying processes. Journal of Marine Systems 2015; 144: 9-29.
Blanchard JL, Novaglio C. Climate change risks to marine ecosystems and fisheries – Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project. . In: Blanchard JL, Novaglio C, editors. FAO Fisheries and Aquaculture Technical Paper. 707. FAO, Rome, 2024.
Bleszynski M, Clark E. Preliminary Assessment into the Prevalence and Distribution of Microplastics in North and South Pacific Island Beaches. Microplastics 2023; 2: 219-229.
Bograd SJ, Jacox MG, Hazen EL, Lovecchio E, Montes I, Pozo Buil M, et al. Climate change impacts on eastern boundary upwelling systems. Annual Review of Marine Science 2023; 15: 303-328.
Boyce DG, Lewis MR, Worm B. Global phytoplankton decline over the past century. Nature 2010; 466: 591-596.
Cael B, Bisson K, Boss E, Dutkiewicz S, Henson S. Global climate-change trends detected in indicators of ocean ecology. Nature 2023; 619: 551-554.
Carmack E, Polyakov I, Padman L, Fer I, Hunke E, Hutchings J, et al. Toward quantifying the increasing role of oceanic heat in sea ice loss in the new Arctic. Bulletin of the American Meteorological Society 2015; 96: 2079-2105.
Christiansen S, Bräger S. Developing best environmental practice for polymetallic nodule mining-a review of scientific recommendations. Frontiers in Marine Science 2023; 10: 1243252.
Chust G, González Taboada F, Fernandes-Salvador JA, Cheung W, Coll M. Climate change impacts on marine fish ecology and fisheries. In: Cabral H, editor. Ecology of Marine Fishes. Elsevier, 2024, pp. 29.
Cochrane K, Butterworth D, Hilborn R, Parma A, Plagányi É, Sissenwine M. Errors and bias in marine conservation and fisheries literature: Their impact on policies and perceptions. Marine Policy 2024; 168: 106329.
Coll M, Bellido JM, Pennino MG, Albo-Puigserver M, Báez JC, Christensen V, et al. Retrospective analysis of the pelagic ecosystem of the Western Mediterranean Sea: drivers, changes and effects. Science of The Total Environment 2024; 167790.
Collins M, Sutherland M, Bouwer L, Cheong S, Frölicher T, Jacot Des Combes H, et al. Extremes, abrupt changes and managing risks. IPCC special report on the ocean and cryosphere in a changing climate. Cambridge University Press, 2022, pp. 589-655.
Cruz L, Pennino M, Lopes P. Fisheries track the future redistribution of marine species. Nature Climate Change 2024: 1-8.
Deeg CM, Li S, Esenkulova S, Hunt BP, Schulze AD, Miller KM. Environmental DNA survey of the Winter Salmonosphere in the Gulf of Alaska. Environmental DNA 2023; 5: 519-539.
Dias MP, Martin R, Pearmain EJ, Burfield IJ, Small C, Phillips RA, et al. Threats to seabirds: a global assessment. Biological Conservation 2019; 237: 525-537.

Dischereit A, Throm JK, Werner KM, Neuhaus S, Havermans C. A belly full of jelly? DNA metabarcoding shows evidence for gelatinous zooplankton predation by several fish species in Greenland waters. Royal Society Open Science 2024; 11: 240797.
Ditlevsen P, Ditlevsen S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation, Nat. Commun., 14, 4254, 2023.
Douville H, Cheng L. Asymmetric sea surface salinity response to global warming:“Fresh gets fresher but salty hesitates”. Geophysical Research Letters 2024; 51: e2023GL107944.
Duarte CM, Agusti S, Barbier E, Britten GL, Castilla JC, Gattuso J-P, et al. Rebuilding marine life. Nature 2020; 580: 39-51.
Duarte CM, Chapuis L, Collin SP, Costa DP, Devassy RP, Eguiluz VM, et al. The soundscape of the Anthropocene ocean. Science 2021; 371: eaba4658.
Dulvy NK, Pacoureau N, Rigby CL, Pollom RA, Jabado RW, Ebert DA, et al. Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Current Biology 2021; 31: 4773-4787. e8.
Eduardo LN, Mincarone MM, Sutton T, Bertrand A. Deep-Pelagic Fishes Are Anything But Similar: A Global Synthesis. Ecology Letters 2024; 27: e14510.
Egorova Y, Reygondeau G, Cheung WW, Pakhomov EA. Species Distribution Models for Mesopelagic Mesozooplankton Community. Journal of Biogeography 2024.
FAO. The State of World Fisheries and Aquaculture - Blue Transformation in action. Rome, 2024.
Fauvelle V, Garel M, Tamburini C, Nerini D, Castro-Jiménez J, Schmidt N, et al. Organic additive release from plastic to seawater is lower under deep-sea conditions. Nature Communications 2021; 12: 4426.
Ferreira GV, Justino AK, Eduardo LN, Schmidt N, Martins JR, Ménard F, et al. Influencing factors for microplastic intake in abundant deep-sea lanternfishes (Myctophidae). Science of The Total Environment 2023; 867: 161478.
Fiechter J, Pozo Buil M, Jacox MG, Alexander MA, Rose KA. Projected shifts in 21st century sardine distribution and catch in the California Current. Frontiers in Marine Science 2021; 8: 685241.
Fortuna C, Fortibuoni T, Bueno-Pardo J, Coll M, Franco A, Giménez G, et al. Top predator status and trends: ecological implications, monitoring and mitigation strategies to promote ecosystem-based management. Frontiers in Marine Science - Marine Ecosystem Ecology 2024.
Fox MD, Guillaume-Castel R, Edwards CB, Glanz J, Gove JM, Green JM, et al. Ocean currents magnify upwelling and deliver nutritional subsidies to reef-building corals during El Niño heatwaves. Science Advances 2023; 9: eadd5032.
Fu LL, Pavelsky T, Cretaux JF, Morrow R, Farrar JT, Vaze P, et al. The surface water and ocean topography mission: A breakthrough in radar remote sensing of the ocean and land surface water. Geophysical Research Letters 2024; 51: e2023GL107652.
Gamarra-Toledo V, Plaza PI, Gutiérrez R, Inga-Diaz G, Saravia-Guevara P, Pereyra-Meza O, et al. Mass mortality of sea lions caused by highly pathogenic avian influenza A (H5N1) virus. Emerging Infectious Diseases 2023; 29: 2553.
Garcia-Soto C, Cheng L, Caesar L, Schmidtko S, Jewett EB, Cheripka A, et al. An overview of ocean climate change indicators: Sea surface temperature, ocean heat content, ocean pH, dissolved oxygen concentration, arctic sea ice extent, thickness and volume, sea

level and strength of the AMOC (Atlantic Meridional Overturning Circulation). Frontiers in Marine Science 2021; 8: 642372.
Gimenez J, Albo-Puigserver M, Laiz-Carrión R, Lloret-Lloret E, Bellido JM, Coll M. Trophic position variability of European sardine by compound-specific stable isotope analyses. Canadian Journal of Fisheries and Aquatic Sciences 2023; 80: https://doi.org/10.1139/cjfas-2022-019.
Gimeno M, Giménez J, Chiaradia A, Lloyd D, Seddon P, Ropert-Coudert Y, et al. Climate and human stressors on global penguin hotspots: current assessments for future conservation. Global Change Biology 2024; 30: e17143.
Gordó-Vilaseca C, Costello MJ, Coll M, Jüterbock A, Reiss H, Stephenson F. Future trends of marine fish biomass distributions from the North Sea to the Barents Sea. Nature Communications 2024; 15: 5637.
Gordó-Vilaseca C, Stephenson F, Coll M, Lavin C, Costello MJ. Three decades of increasing fish biodiversity across the north-east Atlantic and the Arctic Ocean. Proceedings of the National Academy of Science of the United States of America 2023; 120: e2120869120.
Green SJ, Brookson CB, Hardy NA, Crowder LB. Trait-based approaches to global change ecology: moving from description to prediction. Proceedings of the Royal Society B 2022; 289: 20220071.
Gutierrez-Guerra MÁ, Pérez-Hernández MD, Vélez-Belchí P. Intensified upwelling: normalized sea surface temperature trends expose climate change in coastal areas. Ocean Science 2024; 20: 1291-1308.
Hawkins S, Todd P, Russell B, Lemasson A, Allcock A, Byrne M, et al. Review of the central and south atlantic shelf and deep-sea benthos: science, policy, and management. Oceanography and Marine Biology: An annual review. Volume 61 2023; 61: 127-218.
Hays GC, Schofield G, Papazekou M, Chatzimentor A, Katsanevakis S, Mazaris AD. A pulse check for trends in sea turtle numbers across the globe. Iscience 2024; 27.
Heneghan RF, Everett JD, Blanchard JL, Sykes P, Richardson AJ. Climate-driven zooplankton shifts cause large-scale declines in food quality for fish. Nature Climate Change 2023; 13: 470-477.
Heneghan RF, Everett JD, Sykes P, Batten SD, Edwards M, Takahashi K, et al. A functional size-spectrum model of the global marine ecosystem that resolves zooplankton composition. Ecological Modelling 2020; 435: 109265.
Heneghan RF, Galbraith ED, Blanchard JL, Harrison C, Barrier N, Bulman C, et al. Disentangling diverse responses to climate change among global marine ecosystem models. Progress in Oceanography 2021; 198.
Henson SA, Laufkötter C, Leung S, Giering SL, Palevsky HI, Cavan EL. Uncertain response of ocean biological carbon export in a changing world. Nature Geoscience 2022; 15: 248-254.
Heymans JJ, Bundy A, Christensen V, Coll M, De Mutsert K, Fulton E, et al. The Ocean Decade: A true ecosystem modelling challenge. Frontiers in Marine Science – Marine Fisheries, Aquaculture and Living Resources 2020; 10.3389/fmars.2020.554573
Hidalgo M, Browman HI. Developing the knowledge base needed to sustainably manage mesopelagic resources. 76. Oxford University Press, 2019, pp. 609-615.

Hilborn R, Amoroso RO, Anderson CM, Baum JK, Branch TA, Costello C, et al. Effective fisheries management instrumental in improving fish stock status. Proceedings of the National Academy of Sciences 2020.
Hilborn R, Buratti CC, Díaz Acuña E, Hively D, Kolding J, Kurota H, et al. Recent trends in abundance and fishing pressure of agency-assessed small pelagic fish stocks. Fish and Fisheries 2022; 23: 1313-1331.
ICES. Central Arctic Ocean ecoregion – Ecosystem Overview. . Report of the ICES Advisory Committee, 2022. ICES Advice 2022, Section 2.1. https://doi.org/10.17895/ices.advice.21731240 2022.
ISA. ISA Assembly concludes its twenty-ninth session. International Seabed Authority Press Release, June 28, 2024. www.isa.org.jm/news/, 2024.
Ivanov V. Arctic sea ice loss enhances the oceanic contribution to climate change. Atmosphere 2023; 14: 409.
Izett RW, Fennel K, Stoer AC, Nicholson DP. Reviews and syntheses: expanding the global coverage of gross primary production and net community production measurements using Biogeochemical-Argo floats. Biogeosciences 2024; 21: 13-47.
Jaspers C, Hopcroft RR, Kiørboe T, Lombard F, López-Urrutia Á, Everett JD, et al. Gelatinous larvacean zooplankton can enhance trophic transfer and carbon sequestration. Trends in ecology & evolution 2023; 38: 980-993.
Jemai A, Wollschläger J, Voß D, Zielinski O. Radiometry on Argo floats: From the multispectral state-of-the-art on the step to hyperspectral technology. Frontiers in Marine Science 2021; 8: 676537.
Jenkins M, Dai A. The impact of Sea-Ice loss on Arctic climate feedbacks and their role for Arctic Amplification. Geophysical Research Letters 2021; 48: e2021GL094599.
Johnson GC, Lyman JM. Warming trends increasingly dominate global ocean. Nature Climate Change 2020; 10: 757-761.
Johnson GC, Purkey SG. Refined estimates of global ocean deep and abyssal decadal warming trends. Geophysical Research Letters 2024; 51: e2024GL111229.
Johnston NM, Murphy EJ, Atkinson A, Constable AJ, Cotté C, Cox M, et al. Status, change, and futures of zooplankton in the Southern Ocean. Frontiers in Ecology and Evolution 2022; 9: 624692.
Jolly C. The ocean economy in 2030. Proceedings of the Workshop on Maritime Cluster and Global Challenges 50th Anniversary of the WP6, Paris, France. 1, 2016.
Joo R, Picardi S, Boone ME, Clay TA, Patrick SC, Romero-Romero VS, et al. Recent trends in movement ecology of animals and human mobility. Movement ecology 2022; 10: 26.
Jorda G, Marbà N, Bennett S, Santana-Garcon J, Agusti S, Duarte CM. Ocean warming compresses the three-dimensional habitat of marine life. Nature Ecology & Evolution 2020; 4: 109-114.
Juan-Jordá MJ, Murua H, Arrizabalaga H, Merino G, Pacoureau N, Dulvy NK. Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health. Science 2022; 378: eabj0211.
Justino AK, Ferreira GV, Schmidt N, Eduardo LN, Fauvelle V, Lenoble V, et al. The role of mesopelagic fishes as microplastics vectors across the deep-sea layers from the Southwestern Tropical Atlantic. Environmental Pollution 2022; 300: 118988.

Khalfeh Nilsaz M, Aliabadi S, Savari A, Dehghan Mediseh S. Predict the effects of climate change on primary production and vulnerability of fisheries species in coastal waters of the northern Persian Gulf. Iranian Journal of Fisheries Sciences 2024; 23: 893-909.
Kiko R, Bianchi D, Grenz C, Hauss H, Iversen M, Kumar S, et al. Zooplankton and nekton: Gatekeepers of the biological pump. 7. Frontiers Media SA, 2020, pp. 545.
Klevjer TA, Irigoien X, Røstad A, Fraile-Nuez E, Benítez-Barrios VM, Kaartvedt S. Large scale patterns in vertical distribution and behaviour of mesopelagic scattering layers. Scientific reports 2016; 6: 19873.
Kourantidou M, Jin D. Mesopelagic–epipelagic fish nexus in viability and feasibility of commercial-scale mesopelagic fisheries. Natural Resource Modeling 2022; 35: e12350.
Kung A, Svobodova K, Lèbre E, Valenta R, Kemp D, Owen JR. Governing deep sea mining in the face of uncertainty. Journal of Environmental Management 2021; 279: 111593.
Kuroda H, Saito T, Kaga T, Takasuka A, Kamimura Y, Furuichi S, et al. Unconventional sea surface temperature regime around Japan in the 2000s–2010s: potential influences on major fisheries resources. Frontiers in Marine Science 2020; 7: 574904.
Kvale K, Hunt C, James A, Koeve W. Regionally disparate ecological responses to microplastic slowing of faecal pellets yields coherent carbon cycle response. Frontiers in Marine Science 2023; 10: 1111838.
Kwiatkowski L, Torres O, Bopp L, Aumont O, Chamberlain M, Christian JR, et al. Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. Biogeosciences 2020; 17: 3439-3470.
Lachkar Z, Levy M, Hailegeorgis D, Vallivattathillam P. Differences in recent and future trends in the Arabian Sea oxygen minimum zone: processes and uncertainties. Frontiers in Marine Science 2023; 10: 1122043.
Leguia M, Garcia-Glaessner A, Muñoz-Saavedra B, Juarez D, Barrera P, Calvo-Mac C, et al. Highly pathogenic avian influenza A (H5N1) in marine mammals and seabirds in Peru. Nature Communications 2023; 14: 5489.
Leslie HA, Van Velzen MJ, Brandsma SH, Vethaak AD, Garcia-Vallejo JJ, Lamoree MH. Discovery and quantification of plastic particle pollution in human blood. Environment international 2022; 163: 107199.
Li C, Huang J, Liu X, Ding L, He Y, Xie Y. The ocean losing its breath under the heatwaves. Nature Communications 2024; 15: 6840.
Lin C-H, Wei C-L, Ho SL, Lo L. Ocean temperature drove changes in the mesopelagic fish community at the edge of the Pacific Warm Pool over the past 460,000 years. Science Advances 2023; 9: eadf0656.
Liu Y, Ayaka M, Toshikazu K, Helena F, Takashi M. Analysis of microplastics in the intestines of stranded cetaceans. AACL Bioflux 2023; 16: 2746-2756.
Lotze HK, Tittensor DP, Bryndum-Buchholz A, Eddy TD, Cheung WL, Galbraith ED, et al. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proceedings of the National Academy of Science of the United States of America 2019; 116: 12907-12912.

Lucena-Frédou F, Mourato B, Frédou T, Lino PG, Muñoz-Lechuga R, Palma C, et al. Review of the life history, fisheries, and stock assessment for small tunas in the Atlantic Ocean. Reviews in Fish Biology and Fisheries 2021; 31: 709-736.
Ma D, Gregor L, Gruber N. Four decades of trends and drivers of global surface ocean acidification. Global Biogeochemical Cycles 2023; 37: e2023GB007765.
Manta G, de Mello S, Trinchin R, Badagian J, Barreiro M. The 2017 record marine heatwave in the southwestern Atlantic shelf. Geophysical Research Letters 2018; 45: 12,449-12,456.
Marmara D, Katsanevakis S, Brundo M-V, Tiralongo F, Ignoto S, Krasakopoulou E. Microplastics ingestion by marine fauna with a particular focus on commercial species: a systematic review. Frontiers in Marine Science 2023; 10: 1240969.
Marsh R, Skliris N, Tompkins EL, Dash J, Dominguez Almela V, Tonon T, et al. Climate-sargassum interactions across scales in the tropical Atlantic. PLOS Climate 2023; 2: e0000253.
McCauley DJ, Andrzejaczek S, Block BA, Cavanaugh KC, Cubaynes HC, Hazen EL, et al. Improving Ocean Management Using Insights from Space. Annual Review of Marine Science 2024; 17.
McInnes AM, Weideman EA, Carpenter-Kling T, Barham P, Christian M, Day K, et al. Commercial fishery no-take zones for African penguins minimize fisheries losses at the expense of conservation gains. ICES Journal of Marine Science 2024; 81: 1632-1646.
Meyer C, Kreft H, Guralnick R, Jetz W, Boitani L. Global priorities for an effective information basis of biodiversity distributions. Nat Commun 6: 8221, 2015.
Miller A, Virmani JI. Advanced marine technologies for ocean research. Deep Sea Research Part II: Topical Studies in Oceanography 2023: 105340.
Montalva F, Pavés H, Pérez-Venegas D, Barrientos E KG, Valencia C, Miranda-Urbina D, et al. Lower marine productivity increases agonistic interactions between sea lions and fur seals in Northern Pacific Patagonia. Current Zoology 2022; 68: 657-666.
Morley SA, Abele D, Barnes DK, Cárdenas CA, Cotté C, Gutt J, et al. Global drivers on southern ocean ecosystems: changing physical environments and anthropogenic pressures in an earth system. Frontiers in Marine Science 2020; 7: 547188.
Narwal S, Kaur M, Yadav DS, Bast F. Sustainable blue economy: Opportunities and challenges. Journal of Biosciences 2024; 49: 18.
Oliver EC, Benthuysen JA, Darmaraki S, Donat MG, Hobday AJ, Holbrook NJ, et al. Marine heatwaves. Annual review of marine science 2021; 13: 313-342.
Ortiz M, Hermosillo-Núñez B. Quantifying stability and resilience of eco-social keystone species complexes for coastal marine ecosystems of the Caribbean Sea and eastern Pacific: applications in conservation and monitoring programmes. Philosophical Transactions B 2024; 379: 20230176.
Paoletti S, Nielsen JR, Sparrevohn CR, Bastardie F, Vastenhoud BM. Potential for mesopelagic fishery compared to economy and fisheries dynamics in current large scale Danish pelagic fishery. Frontiers in Marine Science 2021; 8: 720897.
Paolo FS, Kroodsma D, Raynor J, Hochberg T, Davis P, Cleary J, et al. Satellite mapping reveals extensive industrial activity at sea. Nature 2024; 625: 85-91.
Pata PR, Hunt BP. Harmonizing marine zooplankton trait data toward a mechanistic understanding of ecosystem functioning. Limnology and Oceanography 2023.

Pauly D, Piroddi C, Hood L, Bailly N, Chu E, Lam V, et al. The biology of mesopelagic fishes and their catches (1950–2018) by commercial and experimental fisheries. Journal of Marine Science and Engineering 2021; 9: 1057.
Peña M, Munuera–Fernández I, Nogueira E, González-Quirós R. First recording of a bathypelagic deep scattering layer in the Bay of Biscay. Progress in oceanography 2021; 198: 102669.
Peters KJ, Stockin KA, Saltré F. On the rise: Climate change in New Zealand will cause sperm and blue whales to seek higher latitudes. Ecological Indicators 2022; 142: 109235.
Pickens C, Lily H, Harrould-Kolieb E, Blanchard C, Chakraborty A. From what-if to what-now: Status of the deep-sea mining regulations and underlying drivers for outstanding issues. . Marine Policy 2024; 169: 105967.
Pinchuk AI, Batten SD, Strasburger WW. Doliolid (Tunicata, Thaliacea) blooms in the southeastern Gulf of Alaska as a result of the recent marine heat wave of 2014–2016. Frontiers in Marine Science 2021; 8: 625486.
Pinkerton MH, Boyd PW, Deppeler S, Hayward A, Höfer J, Moreau S. Evidence for the impact of climate change on primary producers in the Southern Ocean. Frontiers in Ecology and Evolution 2021; 9: 592027.
Pinsky ML, Selden RL, Kitchel ZJ. Climate-driven shifts in marine species ranges: scaling from organisms to communities. Annual review of marine science 2020; 12: 153-179.
Qiu Z, Qiao F, Jang CJ, Zhang L, Song Z. Evaluation and projection of global marine heatwaves based on CMIP6 models. Deep Sea Research Part II: Topical Studies in Oceanography 2021; 194: 104998.
Rahmstorf S. Is the Atlantic Overturning Circulation approaching a tipping point? Oceanography 2024; 37: 16-29.
Ramírez F, Sbragaglia V, Soacha K, Coll M, Piera J. Challenges for Marine Ecological Assessments: Completeness of Findable, Accessible, Interoperable, and Reusable Biodiversity Data in European Seas. Frontiers in Marine Science, section Ocean Observation 2022.
Ratnarajah L, Abu-Alhaija R, Atkinson A, Batten S, Bax NJ, Bernard KS, et al. Monitoring and modelling marine zooplankton in a changing climate. Nature Communications 2023; 14: 564.
Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, et al. Earth beyond six of nine planetary boundaries. Science advances 2023; 9: eadh2458.
Robinson NJ, Aguzzi J, Arias S, Gatto C, Mills SK, Monte A, et al. Global trends in sea turtle research and conservation: Using symposium abstracts to assess past biases and future opportunities. Global Ecology and Conservation 2023; 47: e02587.
Robledo D, Vázquez-Delfín E, Freile-Pelegrín Y, Vásquez-Elizondo RM, Qui-Minet ZN, Salazar-Garibay A. Challenges and opportunities in relation to Sargassum events along the Caribbean Sea. Frontiers in Marine Science 2021; 8: 699664.
Rodrigues RR, Taschetto AS, Sen Gupta A, Foltz GR. Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. Nature Geoscience 2019; 12: 620-626.
Rogers AD, Appeltans W, Assis J, Ballance LT, Cury P, Duarte C, et al. Discovering marine biodiversity in the 21st century. Advances in Marine Biology 2022; 93: 23-115.

Rogers AD, Frinault BA, Barnes D, Bindoff NL, Downie R, Ducklow HW, et al. Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. Annual Review of Marine Science 2020; 12: 87-120.
Rousseau Y, Blanchard JL, Novaglio C, Pinnell KA, Tittensor DP, Watson RA, et al. A database of mapped global fishing activity 1950–2017. Scientific Data 2024; 11: 48.
Ruzicka J, Chiaverano L, Coll M, Garrido S, Tam J, Murase H, et al. The role of small pelagic fish in diverse ecosystems: knowledge gleaned from food-web models. Marine Ecology Progress Series 2024; SPF2av9.
Rynne N, Novaglio C, Blanchard JL, Bianchi D, Christensen V, Coll M, et al. A Skill Assessment Framework for the Fisheries and Marine Ecosystem Model Intercomparison Project. Earth's Future 2025; 13.
Saba GK, Burd AB, Dunne JP, Hernández-León S, Martin AH, Rose KA, et al. Toward a better understanding of fish-based contribution to ocean carbon flux. Limnology and Oceanography 2021; 66: 1639-1664.
Sala B, Gimenez J, Fernandez-Arribas J, Bravo C, Lloret Lloret E, Esteban A, et al. Organophosphate ester plasticizers in edible fish from the Mediterranean Sea: Marine pollution and human exposure. Environmental Pollution 2022; 292.
Salat J, Pascual J, Flexas M, Chin TM, Vazquez-Cuervo J. Forty-five years of oceanographic and meteorological observations at a coastal station in the NW Mediterranean: a ground truth for satellite observations. Ocean Dynamics 2019; 69: 1067-1084.
Sarmiento-Lezcano AN, Olivar MP, Caballero MJ, Couret M, Hernandez-Leon S, Castellón A, et al. Swimbladder properties of Cyclothone spp. in the northeast Atlantic Ocean and the Western Mediterranean Sea. Frontiers in Marine Science 2023; 10: 1093982.
Schaber M, Gastauer S, Cisewski B, Hielscher N, Janke M, Peña M, et al. Extensive oceanic mesopelagic habitat use of a migratory continental shark species. Scientific Reports 2022; 12: 2047.
SCRS-ICCAT. Report of the standing committee on research and statistics (SCRS). ICCAT 2024; https://www.iccat.int/Documents/Meetings/Docs/2024/Reports/2024_SCRS_ENG.pdf.
Skagseth Ø, Eldevik T, Årthun M, Asbjørnsen H, Lien VS, Smedsrud LH. Reduced efficiency of the Barents Sea cooling machine. Nature Climate Change 2020; 10: 661-666.
Smith KE, Burrows MT, Hobday AJ, King NG, Moore PJ, Sen Gupta A, et al. Biological impacts of marine heatwaves. Annual Review of Marine Science 2023; 15: 119-145.
Stahl AR, Rynearson TA, McMahon KW. Amino acid carbon isotope fingerprints are unique among eukaryotic microalgal taxonomic groups. Limnology and Oceanography 2023; 68: 1331-1345.
Steenbeek J, Ortega P, Bernardello R, Christensen V, Coll M, Exarchou E, et al. Making ecosystem modelling operational - a novel distributed execution framework to systematically explore ecological responses to divergent climate trajectories. Earth's Future 2024; 12: e2023EF004295.
Steinberg DK, Landry MR. Zooplankton and the ocean carbon cycle. Annual review of marine science 2017; 9: 413-444.
Stoer AC, Takeshita Y, Maurer TL, Begouen Demeaux C, Bittig HC, Boss E, et al. A census of quality-controlled Biogeochemical-Argo float measurements. Frontiers in Marine Science 2023; 10: 1233289.

Stokstad E. Deadly avian flu hits Galapagos Concerns rise for boobies, finches, and other endemic species. Science 2023; 381: 1382.
Storto A, Yang C. Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. Nature Communications 2024; 15: 545.
Sutton P, Rickard G, Roemmich D. Southwest Pacific Ocean warming driven by circulation changes. Geophysical Research Letters 2024; 51: e2024GL109174.
Swadling KM, Constable AJ, Fraser AD, Massom RA, Borup MD, Ghigliotti L, et al. Biological responses to change in Antarctic sea ice habitats. Frontiers in Ecology and Evolution 2023; 10: 1073823.
Sydeman WJ, Schoeman DS, Thompson SA, Hoover BA, García-Reyes M, Daunt F, et al. Hemispheric asymmetry in ocean change and the productivity of ecosystem sentinels. Science 2021; 372: 980-983.
Tittensor DP, Eddy TD, Lotze HK, Galbraith ED, Cheung W, Barange M, et al. A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0 Geoscientific Model Development 2018; 11: 1421–1442.
Tittensor DP, Novaglio C, Harrison CS, Heneghan RF, Barrier N, Bianchi D, et al. Next-generation Earth System Models reveal higher climate risks for marine ecosystems. Nature Climate Change 2021; 11: 973–981.
TMC. TMC Announces June 27, 2025 Submission Date for Subsidiary NORI's ISA Application, and Expanded Company Strategy. Nov 12, 2024, Globe Newswire, New York. https://investors.metals.co/news-releases/news-release-details/tmc-announces-june-27-2025-submission-date-subsidiary-noris-isa, 2025.
Van de Waal DB, Litchman E. Multiple global change stressor effects on phytoplankton nutrient acquisition in a future ocean. Philosophical Transactions of the Royal Society B 2020; 375: 20190706.
Van Der Grient J, Drazen J. Potential spatial intersection between high-seas fisheries and deep-sea mining in international waters. Marine Policy 2021; 129: 104564.
Van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, Van Franeker JA, et al. A global inventory of small floating plastic debris. Environmental Research Letters 2015; 10: 124006.
Vastenhoud BM, Bastardie F, Andersen KH, Speirs DC, Nielsen JR. Economic viability of a large vessel mesopelagic fishery under ecological uncertainty. Frontiers in Marine Science 2023; 10: 1285793.
Vidhya V, Jyothibabu R, Jagadeesan L, Rashid C, Alok K, Arunpandi N, et al. Oxygen minimum zone copepods in the Arabian Sea and the Bay of Bengal: Their adaptations and status. Progress in Oceanography 2022; 206: 102839.
Waller MJ, Humphries NE, Womersley FC, Loveridge A, Jeffries AL, Watanabe Y, et al. The vulnerability of sharks, skates, and rays to ocean deoxygenation: Physiological mechanisms, behavioral responses, and ecological impacts. Journal of Fish Biology 2024.
Wang S, Jing Z, Wu L, Sun S, Peng Q, Wang H, et al. Southern hemisphere eastern boundary upwelling systems emerging as future marine heatwave hotspots under greenhouse warming. Nature Communications 2023; 14: 28.

Wieczorek AM, Morrison L, Croot PL, Allcock AL, MacLoughlin E, Savard O, et al. Frequency of microplastics in mesopelagic fishes from the Northwest Atlantic. Frontiers in Marine Science 2018; 5: 339138.
Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Scientific data 2016; 3: 1-9.
Williamson P, Guinder VA. Effect of climate change on marine ecosystems. The impacts of climate change 2021: 115-176.
Willis MD, Lannuzel D, Else B, Angot H, Campbell K, Crabeck O, et al. Polar oceans and sea ice in a changing climate. Elementa 2023; 11.
Wong J, Münnich M, Gruber N. Column-compound extremes in the global ocean. AGU Advances 2024; 5: e2023AV001059.
Worm B, Lotze HK, Jubinville I, Wilcox C, Jambeck J. Plastic as a persistent marine pollutant. Annual Review of Environment and Resources 2017; 42.
Yu R-S, Singh S. Microplastic pollution: threats and impacts on global marine ecosystems. Sustainability 2023; 15: 13252.
Zenetos A, Tsiamis K, Galanidi M, Carvalho N, Bartilotti C, Canning-Clode J, et al. Status and trends in the rate of introduction of marine non-indigenous species in European seas. Diversity 2022; 14: 1077.
Zhang Y, Du Y, Feng M, Hobday AJ. Vertical structures of marine heatwaves. Nature Communications 2023; 14: 6483.
Zhang Y, Pavlovska M, Stoica E, Prekrasna I, Yang J, Slobodnik J, et al. Holistic pelagic biodiversity monitoring of the Black Sea via eDNA metabarcoding approach: From bacteria to marine mammals. Environment International 2020; 135: 105307.

Section 4
Sub-chapter 5o: Ridges, Plateaus and Trenches*

Ana Colaço; **Malcolm R. Clark; Jose Angel Alvarez Perez; Imants George Priede; Angelika Brandt; Ana Hilário; Hiromi Kayama Watanabe; Anna Metaxas**

I. Key points:

- Greatest advances have been in studies of Hadal trench systems facilitated by newly available technologies.
- Progress on exploration of ridge systems has slowed and immense gaps remain despite new discoveries in the Indian Ocean.
- Most plateaus are important fishery areas and are studied in that context.
- Changes owing to human pressures have been observed, leading to protection measures for bottom habitats (applied or are under discussion).

II. Introduction and context.

Ridges, plateaus and hadal trenches are distinctive offshore habitats, identified by WOA I (2017) as potentially threatened by human disturbances such as fisheries, pollution and mining. WOA II (2021) reported that despite this vulnerability and added climate change pressures they remained poorly known. This chapter assesses the extensive slopes of mid-ocean spreading ridges that divide ocean basins (Figure 1); (Ridge-associated hydrothermal vents (Beaulieu et al., 2013) and seamounts are considered in chapters S4C5p and S4C5l); Hadal trenches at depths greater than 6000 m (Figure 1); Plateaus, either continent-derived fragments or other origins (Figure 1).

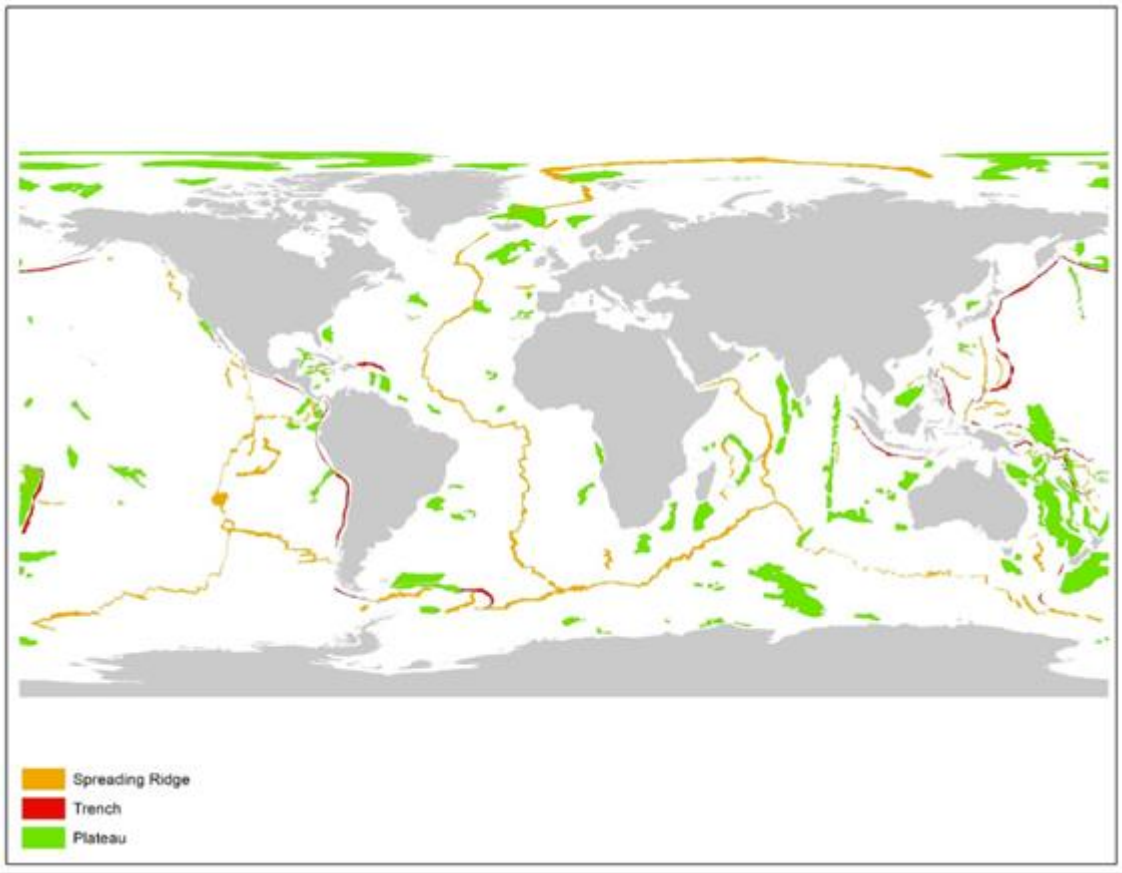


Figure. 1 World map, hadal trenches in red; mid ocean spreading ridges in orange, and plateaus in green. (Adapted from Harris et al, 2014)

III. Description of environmental changes between 2020 and 2024

New Knowledge acquired since 2020 and how it can be used to evaluate changes

Ridges

The bathyal (200-3000 m depth) slopes of the mid-ocean ridge system, dominated by soft sediments interspersed with rocky outcrops at summits and fracture zones remain poorly surveyed. The Mid Atlantic Ridge (MAR) provides about half the living space for bathyal species in the North Atlantic. North of the Azores, surface productivity is high, supporting diverse demersal fish (Priede et al. 2022) and benthic invertebrates (Alt et al. 2019) with overlying waters exploited by migratory seabirds (Davies et al. 2021). Predicted seafloor biomass is lower between the Azores and the Equator, and the benthic fauna is almost unknown even in proposed deep-sea mining contract areas (26-32°N), (Radziejewska et al. 2022).

The Arctic Mid-Ocean Ridge (AMOR) hosts many geological features and habitat types. Although some research was done on impacts of fishing (e.g. Morrison et al. 2020), biodiversity (e.g. Ramirez-Llodra et al. 2020), mineral resources (e.g. Juliani and Ellefmo 2018), and bioprospecting (e.g. Royseth et al. 2023), more studies are needed on the “typical” soft sedimentary slopes (Ramirez-Llodra et al. 2024). On the Central Indian Ridge and the Southwest

Indian Ridge (SWIR), new species or range extensions for polychaetes, corals sponges and crustaceans were discovered (Periasamy and Ingole 2022, Periasamy et al., 2022, 2023a, 2023b, 2023c 2023d). The Southeast Indian Ridge remains one of the least studied regions on the Indian Ocean.

No new information was published on Pacific Oceanic Ridges.

The mid-ocean ridge system extends over 65,000 km around the globe but only in small areas around islands, sea-mount summits and sites of special interest such as hydrothermal vents is anything known about species, abundance, biomass and ecosystems. The Mid -Atlantic Ridge between Iceland and the Azores has been explored (Priede et al. 2022), but this represents only 5% of the global ridge system; the South Atlantic and other ocean ridges remain largely unknown.

Hadal Trenches

Globally, all major hadal trenches have been surveyed with new technologies revealing a rich diversity of habitats (Weston & Jamieson, 2022, Jamieson et al. 2022). Abyssal taxa have extended into hadal depths (Jamieson & Vecchione, 2022) and new trench-endemic species and ecological relationships revealed (Lörz et al. 2018, Kniesz et al. 2018, Riehl et al. 2018, Peoples et al. 2024) with a rich hadal microbial flora including viruses (Zhou et al. 2022), bacteria (Rastelli et al. 2019) and fungi (Peng et al. 2021) that contribute to biochemical processes.

In the Indian Ocean, various habitats were observed, including soft and hard substrates in Sunda Trench (Jamieson et al. 2022). In the South Pacific, the Kermadec Trench was revisited in 2022 (Peng et al. 2022) revealing, habitats driven by flow and substrate characteristics. Across the Pacific Trenches, seafloor biological oxygen consumption varies greatly but is always greater than on adjacent abyssal plains, reflecting increased fertilization from the rain of particles funnelled into the trenches (Glud et al. 2021).

Human impacts include accumulation of pollutants such as plastics (Abel et al. 2021), mercury (Sanei et al. 2021), halogenated organics (Cui et al. 2020) and black carbon (Zhang et al. 2022). Trench habitats are vulnerable to disturbances with estimated recovery times of over 100 years (Jamieson et al. 2022). Renewed proposals for permanent sequestration of captured liquid CO_2 into hadal trenches, that would eliminate all resident biota are a matter for concern (Goldthorpe, 2017, Luo et al. 2023).

Plateaus

The two largest plateaus in the North Atlantic (Harris et al. 2014) are the Hatton-Rockall and Azores plateaus, both highly biodiverse and important fishery areas. The Azores plateau has interconnected assemblages of cold-water corals (CWCs) that differ according to the temperature and properties of surrounding waters and regional productivity (Taranto et al 2023). It is a hotspot for large migratory marine mammals, turtles, sharks and tunas (Afonso et al. 2020), but knowledge gaps remain (Vecchione and Bergstad 2022).

In the Southeast Atlantic, mapping of Vulnerable Marine Ecosystems of the Walvis Ridge/plateau (Bridges et al., 2023, Bergstad et al., 2019ab) shows patchy cold-water coral communities among relict coral rubble on flat-topped seamounts. In the Southwest Atlantic, exploration of the summit of the Rio Grande Rise (Kitazato et al. 2017) indicated distinctive communities of corals and sponges associated with ferromanganese cobalt crusts, depth and slope (Corrêa et al., 2022; Perez et al., 2018), along with hexactinellid 'sponge gardens' of *Sarostegia oculata*, (Hajdu et al., 2017).

The São Paulo Plateau extends SE from the Brazilian Continental Margin (2000 - 4500 m depths) encompassing over 80% of Brazil's oil and gas production (Perez et al., 2020a). In the Noretg, asphalt seeps harbor mainly hexactinellid sponges and typical deep-sea isidid octocorals, brisingid starfishes and galatheid crabs (Fujikura et al., 2017). Along the escarpment to the south, Perez et al. (2020b) described benthic habitats and communities at 4219–2644 m depths associated with topography and deep-water mass distribution.

High productivity over ~~the Malvinas-Falklands Platea~~ the plateau surrounding

the Falkland Islands (Malvinas) ~~u~~[1] is driven by an influx of sub-Antarctic waters ~~supporting important fisheries administered by CCAMLR~~.. Deep benthic biomass is dominated by Stylasteridae (lace corals), sponges, Pennatulacea (sea pens) and cup corals (Pearman et al. 2022).

In the southern Indian Ocean, the Kerguelen Plateau (45-65°S) traverses the Polar Front (e.g., Bestley et al. 2020), resulting in major differences in phytoplankton, zooplankton and mesopelagic fish productivity (Matsuno et al. 2020, Hunt and Swadling 2021, Cotte et al. 2022) with different trophic dynamics between the western and eastern parts of the Plateau (Hunt et al. 2021, Constable & Swadling 2020)

In the western Indian Ocean, the Mascarene Plateau supports the largest seagrass beds in the world that, along with rhodolith beds provide key shallow-water biogenic habitats for various taxa, including new species. Dominant mega-epifauna taxa were cnidarians, fish, echinoids and shrimps/prawns (Bhagooli (ed) 2021).

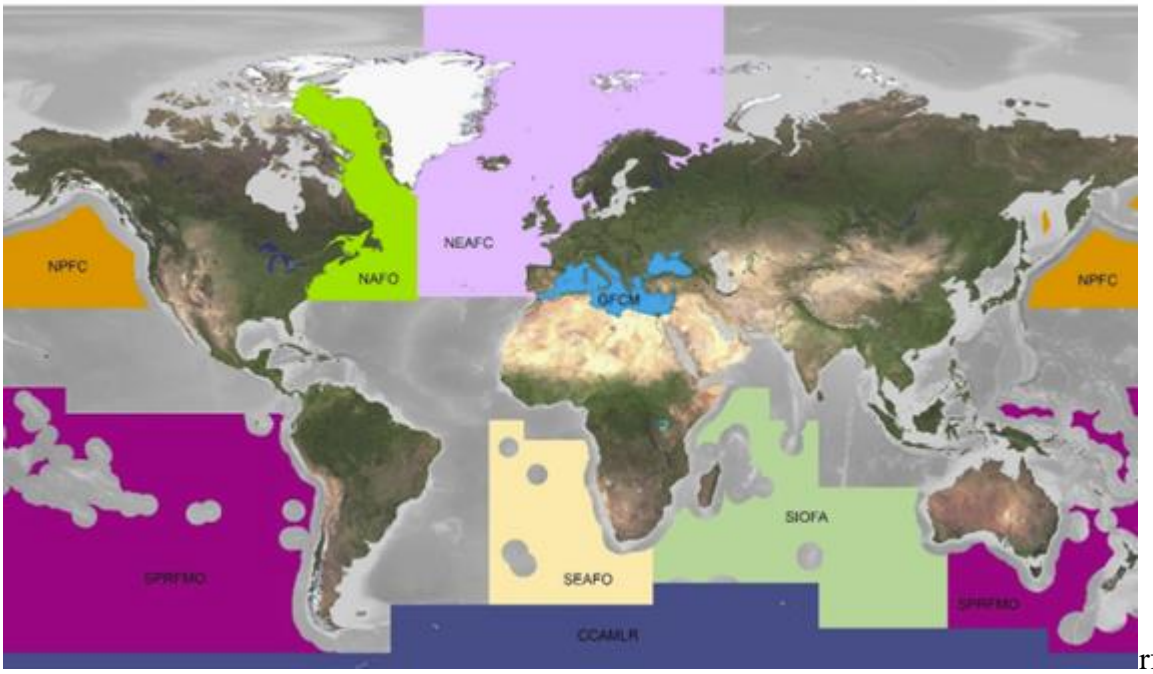
Around New Zealand, benthic species distributions of the Chatham Rise and Campbell plateau have been studied in support of habitat suitability modelling to enhance effectiveness in data-poor areas (Stephenson et al. 2021),

Unique faunal assemblages have been found on Arctic Ocean plateaus that are vulnerable to both fisheries and global warming (Jørgensen et al. 2022). In the Pacific-Arctic region, epifaunal communities of the Chukchi plateau are proposed as long-term observatories of responses to climate changes (Zhulay et al. 2019)

III. Description of economic and social changes between 2020 and 2024 and the relevant governance

Fisheries (S5.C1a)

Deep-sea fisheries extend across slopes, seamounts, ridges and plateaus in all the world's oceans. UN Resolutions require States to safeguard these environments either through national measures or through Regional Fisheries Management Organisations (RFMOs) (Kaikkonen et al. 2024) (Figure 2). Fisheries stocks and Vulnerable marine ecosystems (VMEs), are increasingly being protected by multiple regulations and spatial protection measures, including closed areas ~~(Figure 3)~~.



rfv

Figure 2. Map of Regional Fisheries Management Organizations (RFMOs) and CCAMLR~~,~~. NEAFC- North-East Atlantic Fisheries Commission; NAFO- Northwest Atlantic Fisheries Organization; NPFC- North Pacific Fisheries Commission; GFCM- General Fisheries Commission for the Mediterranean; SPRFMO -South Pacific Regional Fisheries Management Organization; SEAFO- South East Atlantic Fisheries Organization; SIOFA- Southern Indian Ocean Fisheries Agreement~~,~~ CCAMLR-Commission for the Conservation of Antarctic Marine Living Resources.

In the North Atlantic, Hatton-Rockall plateau extends across EEZs and ABNJ and presents spatial management challenges in the face of international bottom trawling fleets (Johnson et al. 2019) whereas the Azores plateau is mainly exploited by locally based vessels managed by national measures (Morato et al., 2020). In the SW Pacific, bottom trawl fisheries on the Challenger Plateau are managed by New Zealand within the EEZ, and by the South Pacific RFMO in the ABNJ further offshore. Fisheries for hoki, ling and blue whiting on the Campbell Plateau are within the EEZ (Fisheries New Zealand 2024).

Major trawl and bottom-set longline fisheries for Patagonian toothfish and mackerel icefish occur on some southern plateaus of the Indian Ocean, especially the Kerguelen Plateau. This has been the focus of extensive food web modelling (Subramaniam et al. 2020, 2021, Hindell et al. 2022, McCormack et al., 2021).

Globally, ridge and plateau habitats are impacted by marine litter largely originating from lost fishing gear (Canals et al, 2021; Duncan et al, 2023).

Mining (S5A.C7):

Deep-sea mining on ridges and plateaus remains in the exploration phase under contracts issued by the International Seabed Authority (ISA) that proposes Regional Environmental Management Plans (REMP) for mining areas. (Blanchard et al. 2023).

Climate change:

The deep ocean is warming more slowly than surface waters, but analysis of shifts in expected species' range (climate velocity), indicates that deep-ocean biodiversity is highly sensitive to projected climate changes (Brito Morales et al, 2020). Direct evidence has been recorded in the South Pacific Ocean off New Zealand where warming over the Chatham Rise is 5 times faster than the global rate with implications for local sustainability of fish stocks (Sutton et al. 2024).

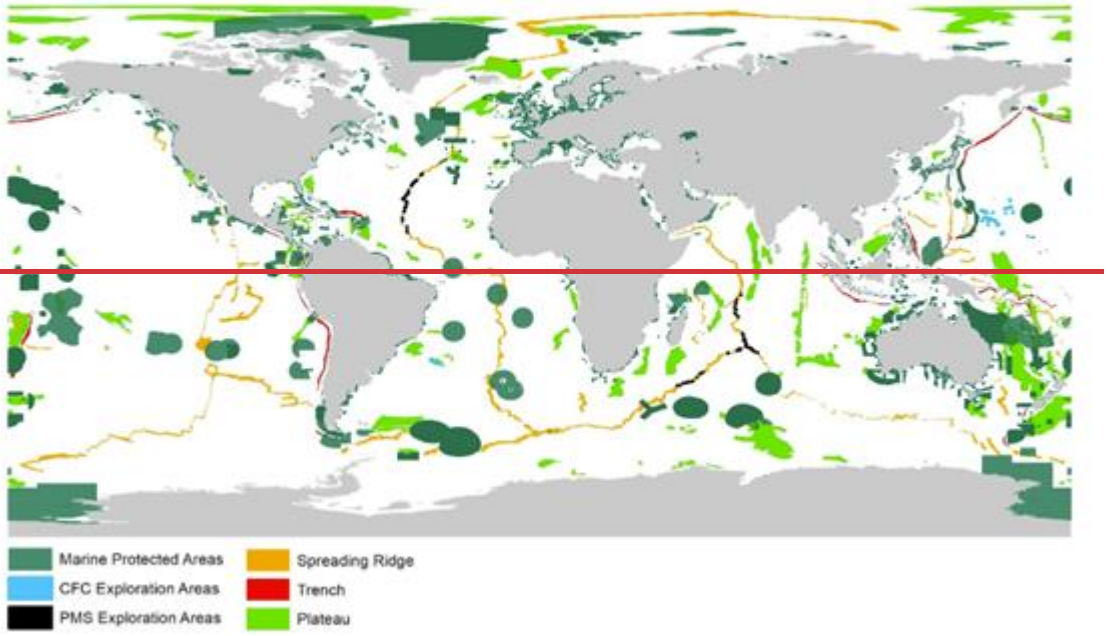
IV: Region-specific changes

Since 2020, several regions across the world's oceans have experienced significant environmental and human pressures, including fisheries, mineral resource exploration, climate change, and pollution. In the Arctic Ocean, for example, the Chukchi Borderland plateau has been impacted by both fisheries and climate change. Protection measures such as the Agreement to Prevent Unregulated High Seas Fisheries, effective since June 2021, and Norwegian regulations in the Yermak Plateau, have been put in place. Similarly, in the North Atlantic Ocean, areas like the Hatton-Rockall Bank and Azores Plateau have faced fisheries pressure, with the closure of multiple regions to bottom fishing gears and the development of draft Regional Environmental Management Plans (REMP) for the area. These protective actions aim to mitigate the impacts of human activity, while pollution remains a significant concern.

In the South Atlantic and Indian Oceans, fisheries, mineral exploration, and pollution continue to affect marine ecosystems. The South Atlantic, with regions like the Rio Grande Rise and Walvis Ridge, has seen significant protective measures, including fully protected MPAs such as Ascension Island and Tristan da Cunha, and various fishing closures across important areas like the Southern Mid-Atlantic Ridge. Brazil has also terminated cobalt crust exploration contracts in the Rio Grande Rise, claiming it as part of its extended EEZ. The Indian Ocean has seen similar pressures, with areas like the Sunda Trench and Amirante to Fortuna Banks being fully protected. Fishing closures have been enforced in regions like the Atlantis Bank and Walter's Shoal, while developments like the Central Indian Basin REMP are being implemented to safeguard these fragile ecosystems.

In the Pacific and Southern Oceans, the situation mirrors that of the other regions, with key areas facing both human-induced and natural challenges. The North Pacific, for instance, has seen the

development of a draft REMP for the Northwest Pacific, and the establishment of protected areas such as the Hawaiian Papahānaumokuākea National Monument. Meanwhile, in the South Pacific, countries like New Zealand and Australia have implemented strict protections, such as prohibiting bottom trawling along the Kermadec Ridge and creating networks of Marine Protected Areas (MPAs). In the Southern Ocean, the Ross Sea and South Orkney Islands are subject to comprehensive protection, with commercial fishing prohibited in specific areas. These ongoing efforts across diverse oceans emphasize the importance of international collaboration and proactive conservation strategies to address the growing pressures on marine ecosystems.



~~Figure 3. Map of oceanic ridges, hadal trenches, plateau, marine protected areas[2], and mineral exploration areas. After Harris et al.,(2014); ©ProtectedPlanet 2014-2024. All rights reserved Ricardo Medeiros ©*Imag*DOP~~

V. Key Advances in Knowledge and Understanding

New knowledge based on advances in technology: exploration, AI tools and the resulting implications

Knowledge of Hadal trenches is being revolutionised by the advent of human occupied vehicles (HOVs) capable of repeated dives to maximum ocean depth (11 km) e.g. the US DSV Limiting Factor and Chinese HOV Fendouzhe (Zhou & Peng, 2023). Together with autonomous landers these have enable global sampling programmes, the Five Deeps Expedition (Jamieson 2020) and Global Trench Exploration and Diving Program (Global TREnD) to all the major trenches with detailed mapping, discovery of new species and studies of biogeological processes.

Increasing use of sea-floor imagery enabled by advances in digital camera technology is providing non-destructive means of surveying the sea floor (Bell et al. 2022). Beyond the area surveyed by cameras, Habitat Suitability Modelling (HSM) can extrapolate the predicted distribution of faunal communities to data-poor areas. Off New Zealand, for example, habitat suitability maps for deep-sea corals have been developed based on seafloor imagery (Anderson et al. 2023) and modelled coral densities were used to identify areas for conservation efforts. The SPRFMO has used zonation decision-support software to help define management areas that can protect predicted VME habitat while permitting deep-sea commercial fishing. This analysis identified priority areas for conservation where the impact on fisheries is small (Australia-New Zealand 2023) within the Lord Howe Rise, South Tasman Rise, Challenger Plateau, and West Norfolk Ridge. Mapping at an unprecedented scale, coupled with rapidly evolving artificial intelligence is rapidly increasing HSM modeling capability. Deep learning, specifically, can both accelerate and standardize the interpretation of biological imagery data (Clark et al. 2024).

VI. Remaining key knowledge and capacity gaps and any new gaps

Despite progress since WOA I, gaps remain and research on ridges continues to be focussed on chemosynthetic environments, seamounts and deep-sea mining, neglecting the wider ridge environment so that most of the global ridge system remains poorly known, particularly in the Arctic which is inaccessible for most of the year. Plateaus in active fishing areas are well surveyed, but no new research has been done on plateaus in the Arctic. Deep-sea ecosystems include slow-growing, long-lived and late reproducing species, making them particularly vulnerable to anthropogenic impacts yet individual and cumulative effects remain poorly known.

Management of ridges, plateaus and trenches in areas beyond national jurisdiction exists for fisheries and mining under RFMO'S and ISA.The new Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ agreement) may provide additional biodiversity protection and potential solutions for conflicts.

Sampling the deep-sea requires access to large ships and advanced technologies available only in a few institutions in a few nations. This creates a lack of equitability in access and the problem of parachute, colonial or ~~po~~arasitic science whereby highly resourced agencies extract samples and data from poorer regions with no reference to local populations or their expertise (Stefanoudis et al. 2021) which needs to be addressed urgently. Collaborative networks developing low-cost deep-sea imaging systems that can be used from small local, traditional or I~~i~~ndigenous Peoples' fishing vessels may overcome some of these problems- (Bell et al. 2020)

Human pressures, on these high-seas ecosystems belonging to all humankind, continue. Calls for capacity development and knowledge transfer get louder (including in international agreements such as the Kunming-Montreal Global Biodiversity Framework (GBF) -and BBNJ) but we are still far from achieving their targets.

References

Abel,S.M., Primpke,S., Int-Veen,I., Brandt,A., and Gerdts, G. (2021) Systematic identification of microplastics in abyssal and hadal sediments of the Kuril Kamchatka trench. Environmental Pollution 269, 116095

Afonso, P., Fontes, J., Giacomello, E., Magalhães, M. C., Martins, H. R., Morato, T., ... & Vandeperre, F. (2020). The Azores: a mid-Atlantic hotspot for marine megafauna research and conservation. *Frontiers in Marine Science*, *6*, 826.

Alt, C.H.S., Kremenetskaia (Rogacheva), A., Gebruk, A.V., Gooday, A.J., Jones, D.O.B. (2019) Bathyal benthic megafauna from the Mid-Atlantic Ridge in the region of the Charlie-Gibbs fracture zone based on remotely operated vehicle observations. *Deep Sea Research Part I: Oceanographic Research Papers*. 145: 1-12. https://doi.org/10.1016/j.dsr.2018.12.006

Anderson OF, Schnabel KE, Bowden D, Davey N, Hart A. 2023. Identification of protected coral hotspots using species distribution modelling., NIWA, Wellington, New Zealand. [https://dxcprod.doc.govt.nz/our-work/conservation-services-programme/csp-reports/202223-csp-reports/identification-of-protected-coral-hotspots-using-species-distribution-modelling/]

Australia-New Zealand (2023). Cumulative bottom fishery impact assessment for Australian and New Zealand bottom fisheries, 2023. SPRFMO Scientific Committee document SC11-DW01_rev1. 222p.

Beaulieu, S.E., Baker, E.T., German, C.R. and Maffei, A., 2013. An authoritative global database for active submarine hydrothermal vent fields. *Geochemistry, Geophysics, Geosystems*, *14*(11), pp.4892-4905.

Bell KLC, Chow JS, Hope A, Quinzin MC, Cantner KA, Amon DJ, Cramp JE, Rotjan RD, Kamalu L, de Vos A, Talma S, Buglass S, Wade V, Filander Z, Noyes K, Lynch M, Knight A, Lourenço N, Girguis PR, de Sousa JB, Blake C, Kennedy BRC, Noyes TJ and McClain CR (2022) Low-Cost, Deep-Sea Imaging and Analysis Tools for Deep-Sea Exploration: A Collaborative Design Study. *Front. Mar. Sci*. 9:873700. https://doi.org/10.3389/fmars.2022.873700

Bergstad, O.A., Gil, M., Hoines, A.S., Serralde, R., Maletzky, E., Mostarda, E., Singh, L., Ant´onio, M.A., Ramil, F., Clerkin, P., Campanis, G., (2019a). Megabenthos and benthopelagic fishes on Southeast Atlantic seamounts. Afr. J. Mar. Sci. 41, 29–50. https://doi.org/10.2989/1814232X.2019.1571439.

Bergstad, O.A., Hoines, A.S., Serralde, R., Campanis, G., Gil, M., Ramil, F., Maletzky, E., Mostarda, E., Singh, L., Ant´onio, M.A. (2019b). Bathymetry, substrate and fishing areas of Southeast Atlantic high-seas seamounts. Afr. J. Mar. Sci. 41, 11–28. https://doi.org/10.2989/1814232X.2019.1569160.

Bestley S., van Wijk E., Rosenberg M., Eriksen R., Corney S., Tattersall K., et al. (2020). Ocean circulation and frontal structure near the southern Kerguelen Plateau: The physical context for the Kerguelen Axis ecosystem study. *Deep Sea Res. Part II: Topical Stud. Oceanography* 174. doi: 10.1016/j.dsr2.2018.07.013

Blanchard C, Harrould-Kolieb E, Jones E, Taylor ML. 2023. The current status of deep-sea mining governance at the International Seabed Authority. Marine Policy 147: 105396

Bridges, A.H.; Howell, K.L.; Amaro, T.; Atkinson, L.; Barnes, D.K. et al. (2023). Review of the Central and South Atlantic Shelf and Deep Sea Benthos: Science, Policy, and Management. *Oceanography and Marine Biology: An Annual Review*, 2023, 61, 127-218. DOI: 10.1201/9781003363873-5

CCAMLR, (2023) Schedule of Conservation Measures in Force 2023/24. Commission for the Conservation of Antarctic Marine Living Resources, Hobart, Tasmania, Australia. https://www.ccamlr.org/en/document/conservation-and-management/schedule-conservation-measures-force-2023/24, Accessed 18 October 2024

Canals, M., Pham, C.K., Bergmann, M., Gutow, L., Hanke, G., Van Sebille, E., Angiolillo, M., Buhl-Mortensen, L., Cau, A., Ioakeimidis, C. and Kammann, U., 2021. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environmental Research Letters, 16(2), p.023001

Clark H.P., Smith A.G., McKay F. D., Larsson A.I., Jaspars M. and De Clippele L.H. (2024) New interactive machine learning tool for marine image analysis *R. Soc. Open Sci.*11231678. http://doi.org/10.1098/rsos.231678

Constable, A. J., & Swadling, K. M. (2020). Ecosystem drivers of food webs on the Kerguelen Axis of the Southern Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, *174*, 104790.

Corrêa, P.V.F.; Jovane, L;; Murton, B.J; Sumida, P.Y.G. (2022). .Benthic megafauna habitats, community structure and environmental drivers at Rio Grande Rise (SW Atlantic). *Deep-Sea Research Part I* 186 (2022) 103811

Cotté, C., Ariza, A., Berne, A., Habasque, J., Lebourges-Dhaussy, A., Roudaut, G., ... & Cherel, Y. (2022). Macrozooplankton and micronekton diversity and associated carbon vertical patterns and fluxes under distinct productive conditions around the Kerguelen Islands. *Journal of Marine Systems*, *226*, 103650.

Cui,J., Yu,Z., Mi,M., He,L , Sha,Z., Yao,P., Fang,J., and Sun, W. (2020) Occurrence of Halogenated Organic Pollutants in Hadal Trenches of the Western Pacific Ocean. *Environmental Science & Technology* 54 (24), 15821-15828. DOI: 10.1021/acs.est.0c04995

Davies, T.E., Carneiro,A.P.B., Tarzia, M. et al. (2021) Multispecies tracking reveals a major seabird hotspot in the North Atlantic. *Conservation Letters*. 14:e12824. https://doi.org/10.1111/conl.12824

Duncan, E.M., Vieira, N., González-Irusta, J.M., Dominguez-Carrió, C., Morato, T., Carreiro-Silva, M., Jakobsen, J., Jakobsen, K., Porteiro, F., Schläpfer, N. and Herrera, L., 2023. Predicting the distribution and abundance of abandoned, lost or discarded fishing gear (ALDFG) in the deep sea of the Azores (North Atlantic). Science of the Total Environment, 900, p.166579.

Fujikura, K., Yamanaka, T., Sumida, P.Y., Bernardino, A.F., Pereira, O.S., Kanehara, T., Nagano, Y., Nakayama, C.R., Nobrega II, M., Pellizari, V.H. & Shigeno, S. (2017). Discovery of asphalt seeps in the deep Southwest Atlantic off Brazil. Deep Sea Research Part II: Topical Studies in Oceanography 146, doi:10.1016/j. dsr2.2017.04.002

Goldthorpe, S (2017) Potential for Very Deep Ocean Storage of CO2 Without Ocean Acidification: A Discussion Paper. *Energy Procedia,* 114: 5417-5429, https://doi.org/10.1016/j.egypro.2017.03.1686.

Hajdu, E., Castello-Branco, C., Lopes, D.A., Sumida, P.Y.G., Perez, J.A.A., (2017). Deep-sea dives reveal an unexpected hexactinellid sponge garden on the Rio Grande Rise (SW Atlantic). A mimicking habitat? Deep Sea Res. Part II Top. Stud. Oceanogr. 146, 93–100. ttps://doi.org/10.1016/j.dsr2.2017.11.009.Harris, P.T., Macmillan-Lawler, M., Rupp, J., and Baker, E.K. (2014) Geomorphology of the oceans. *Marine Geology*. 352:4-24. http://dx.doi.org/10.1016/j.margeo.2014.01.011

Harris, P.T., Macmillan-Lawler, M., Rupp, J., and Baker, E.K. (2014) Geomorphology of the oceans. *Marine Geology*. 352:4-24. http://dx.doi.org/10.1016/j.margeo.2014.01.011

Hunt, B. P. V., & Swadling, K. M. (2021). Macrozooplankton and micronekton community structure and diel vertical migration in the Heard Island Region, Central Kerguelen Plateau. *Journal of Marine Systems*, *221*, 103575.Hunt, B. P., Espinasse, B., Pakhomov, E. A., Cherel, Y., Cotté, C., Delegrange, A., & Henschke, N. (2021). Pelagic food web structure in high nutrient low chlorophyll (HNLC) and naturally iron fertilized waters in the Kerguelen Islands region, Southern Ocean. *Journal of Marine Systems*, *224*, 103625.

Jamieson, A. J. & Vecchione, M. (2022), Hadal cephalopods: first squid observation (Oegopsida, Magnapinnidae, *Magnapinna* sp.) and new records of finned octopods (Cirrata) at depths > 6000 m in the Philippine Trench. In: Marine Biology. 169, 1, 11.

Jamieson A.J. (2020) The Five Deeps Expedition and an Update of Full Ocean Depth Exploration and Explorers. *Marine Technology Society Journal* 54(1):6-12. https://doi.org/10.4031/MTSJ.54.1.1

Jamieson, A. J., Stewart, H. A., Weston, J. N. J., Lahey, P. & Vescovo, V. L. (2022) Hadal Biodiversity, Habitats and Potential Chemosynthesis in the Java Trench, Eastern Indian Ocean. Frontiers in Marine Science. 9, 856992.

Johnson DE, Barrio Froján C, Neat F, Van Oevelen D, Stirling D, Gubbins MJ and Roberts JM (2019) Rockall and Hatton: Resolving a Super Wicked Marine Governance Problem in the High Seas of the Northeast Atlantic Ocean. *Front. Mar. Sci.* 6:69. doi: 10.3389/fmars.2019.00069

Jørgensen, L.L., Pecuchet, L., Ingvaldsen, R.B. and Primicerio, R., 2022. Benthic transition zones in the Atlantic gateway to a changing Arctic ocean. *Progress in Oceanography*, *204*, p.102792.

Jørgensen, L.L., Bakke, G. and Hoel, A.H., 2020. Responding to global warming: New fisheries management measures in the Arctic. *Progress in Oceanography*, *188*, p.102423.

Juliani, C. and Ellefmo, S.L., 2018. Resource assessment of undiscovered seafloor massive sulfide deposits on an Arctic mid-ocean ridge: Application of grade and tonnage models. *Ore geology reviews*, *102*, pp.818-828.

Kaikkonen, L., Teresa Amaro, Peter J. Auster, David M. Bailey, James B. Bell, Angelika Brandt, Malcolm R. Clark, Jeffrey C. Drazen, Cherisse Du Preez, Elva Escobar-Briones, Eva Giacomello, Matthew Gianni, Andrew F. Johnson, Lisa A. Levin, Rosanna J. Milligan, Stephen Oduware, Tabitha R.R. Pearman, Christopher K. Pham, Sofia P. Ramalho, Ashley A. Rowden, Tracey T. Sutton, Michelle L. Taylor, Les Watling, Lissette Victorero, (2024) Improving impact assessments to reduce impacts of deep-sea fisheries on vulnerable marine ecosystems. Marine Policy,167, 106281, https://doi.org/10.1016/j.marpol.2024.106281

Kiko, R., Biastoch, A., Brandt, P., Cravatte, S., Hauss, H., Hummels, R., Kriest, I., Marin, F., McDonnell, A.M.P., Oschlies, A., Picheral,M., Schwarzkopf, F.U., Thurnherr,A.M., Stemmann, L. (2017) Biological and physical influences on marine snowfall at the equator. Nature Geosciences, 10. DOI: 10.1038/NGEO3042.

Kitazato, H., Fujikura, K., Pellizari, V., Perez, J. A. A., and Sumida, P. (2017). Editorial: Rich geo- and bio-diversities exist in the South West Atlantic deep-sea: the first human-occupied submersible Shinkai 6500 dive cruise (Iatá-piúna). *Deep Sea Res. II* 146, 1–3. doi: 10.1016/j.dsr2.2017.11.007

Kniesz, K., Brandt, A., and Riehl, T., (2018) Peritrich epibionts on the hadal isopod species *Macrostylis marionae* n. sp. from the Puerto Rico Trench used as indicator for sex-specific behaviour. *Deep Sea Research Part II: Topical Studies in Oceanography*, 148,105-129. https://doi.org/10.1016/j.dsr2.2017.10.007

Lörz A., Jażdżewska, A.M., and Brandt A. (2018) A new predator connecting the abyssal with the hadal in the Kuril-Kamchatka Trench, NW Pacific. PeerJ 6, e4887 https://doi.org/10.7717/peerj.4887

Luo, J., Xie,Y., Hou, M.Z., Xiong, Y, Wu,X., Lüddeke, C.T. & Huang, L. (2023) Advances in subsea carbon dioxide utilization and storage. Energy Reviews, 2:100016, https://doi.org/10.1016/j.enrev.2023.100016.

Matsuno, K., Wallis, J. R., Kawaguchi, S., Bestley, S., & Swadling, K. M. (2020). Zooplankton community structure and dominant copepod population structure on the southern Kerguelen Plateau during summer 2016. *Deep Sea Research Part II: Topical Studies in Oceanography*, *174*, 104788.

Montserrat, F., Guilhon, M., Corrˆea, P.V.F., Bergo, N.M., Signori, C.N., Tura, P.M., Santos Maly, M. de los, Moura, D., Jovane, L., Pellizari, V., Sumida, P.Y.G., Brandini, F.P., Turra, A., (2019). Deep-sea mining on the Rio Grande Rise (Southwestern Atlantic): a review on environmental baseline, ecosystem services and potential impacts. *Deep-Sea Res. Part A Oceanogr. Res. Pap*. 145, 31–58. https://doi.org/10.1016/j.dsr.2018.12.007.

Morato T, Afonso P, Menezes GM, Santos RS and Silva MA (2020) Editorial: The Azores Marine Ecosystem: An Open Window into North Atlantic Open Ocean and Deep-Sea Environments. *Front. Mar. Sci.* 7:601798. doi: 10.3389/fmars.2020.601798.

Morrison, K.M., Meyer, H.K., Roberts, E.M., Rapp, H.T., Colaço, A. and Pham, C.K., 2020. The first cut is the deepest: trawl effects on a deep-sea sponge ground are pronounced four years on. *Frontiers in Marine Science*, *7*, p.605281.

NEAFC, (2024) VMEs and Closures Maps and Coordinates. North-East Atlantic Fisheries Commission. London, United Kingdom, https://www.neafc.org/managing_fisheries/vmec Accessed 18 October 2024

Pearman, T.R.R.; Brewin, P.E.; Baylis, A.M.M.; Brickle, P. (2022) Deep-Sea Epibenthic Megafaunal Assemblages of the Falkland Islands, Southwest Atlantic. *Diversity: 14*, 637. https://doi.org/10.3390/d14080637

Peng, D., & Liu, L. (2022). Quantifying slab sinking rates using global geodynamic models with data-assimilation. *Earth-Science Reviews*, *230*, 104039.

Peng, Q., Li, Y., Deng, L. et al. High hydrostatic pressure shapes the development and production of secondary metabolites of Mariana Trench sediment fungi. *Sci Rep* 11, 11436 (2021). https://doi.org/10.1038/s41598-021-90920-1

Peoples Logan M., Gerringer Mackenzie E., Weston Johanna N. J., León-Zayas Rosa, Sekarore Abisage, Sheehan Grace, Church Matthew J., Michel Anna P. M., Soule S. Adam and Shank Timothy M. 2024A deep-sea isopod that consumes Sargassum sinking from the ocean's surfaceProc. R. Soc. B.29120240823 http://doi.org/10.1098/rspb.2024.0823

Perez, J.A.A., Abreu, J.G.N., Lima, A.O.S., Silva, M.A.C., Souza, L.H.P. & Bernardino, A.F. (2020a). Living and non-living resources in Brazilian deep-waters. In Brazilian Deep-Sea Biodiversity 2020, P.Y.G. Sumida et al. (eds.). Switzerland: Springer, 217–254.

Perez, J.A.A., Gavazzoni, L., De Souza, L.H.P., Sumida, P.Y.G. & Kitazato, H. (2020b). Deep-sea habitats and megafauna on the slopes of the São Paulo Ridge, SW Atlantic. Frontiers in Marine Science, doi:10.3389/fmars.2020.572166

Perez, J.A.A., Kitazato, H., Sumida, P.Y.G., Sant'Ana, R., Mastella, A.M., (2018). Benthopelagic megafauna assemblages of the Rio Grande rise (SW atlantic). *Deep-Sea Res. Part A* Oceanogr. Res. Pap. 134, 1–11. https://doi.org/10.1016/j.dsr.2018.03.001.

Periasamy R. & Ingole B., (2022) Three New Carnivorous sponge species (Demospongiae: Cladorhizidae) from the Seamounts of the Central Indian Ridge. Zootaxa 5162 (5), 451-486

Periasamy R., Palayil, J,K. & Ingole B., (2022) A new report on the deep-sea sponge-associated Spongicoloides weijiaensis Xu, Zhou & Wang, 2017 (Decapoda: Spongicolidae) from the Southwest Indian Ocean Ridge. Zootaxa 5195 (3), 267-277

Periasamy R., Kurian, PJ. & Ingole B., (2023a) A new deep-water coral species *Telestula ridgensis* sp. nov (Scleralcyonacea: Sarcodictyonidae) from the seamount of the Central Indian Ridge. Zootaxa 5254 (2), 231-244

Periasamy R., Kurian, PJ. & Ingole B., (2023b) Two new deep-water species of squat lobsters (Crustacea: Anomura: Galatheoidea) from the Central and Southwest Indian Ridge. Zootaxa 5231 (2), 165-178.

Periasamy R., Palayil, J,K. & Ingole B., (2023c) First record of sponge-associated deep-sea polychaete (Polynoidae: Bathymoorea) on the ultraslow-spreading Southwest Indian Ridge. Deep Sea Research Part I: Oceanographic Research Papers 191, 103923

Periasamy R., Kurian, PJ. & Ingole B.,(2023d) Two new bamboo corals species (Octocorallia: Keratoisididae) from the seamounts of slow-spreading Central Indian Ridge. Deep Sea Research Part I: Oceanographic Research Papers 201, 104158Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. and Weyer, N., 2019. The ocean and cryosphere in a changing climate. *IPCC special report on the ocean and cryosphere in a changing climate*, *1155*, pp.10-1017.

Priede I.G., Muller-Karger F. E., Niedzielski T., Gebruk A.V., Jones D.O.B. & Colaço A. (2022) Drivers of Biomass and Biodiversity of Non-Chemosynthetic Benthic Fauna of the Mid-Atlantic Ridge in the North Atlantic. *Frontiers in Marine Science* 9: 10.3389/fmars.2022.866654

Radziejewska T, Błażewicz M, Włodarska-Kowalczuk M, Jóźwiak P, Pabis K and Węsławski JM (2022) Benthic biology in the Polish exploration contract area of the Mid-Atlantic Ridge: The knowns and the unknowns. A review. *Front. Mar. Sci*. 9:898828. doi: 10.3389/fmars.2022.898828

Ramirez-Llodra, E., Hilario, A., Paulsen, E., Costa, C.V., Bakken, T., Johnsen, G. and Rapp, H.T., 2020. Benthic communities on the Mohn's treasure mound: implications for management of seabed mining in the Arctic mid-ocean ridge. *Frontiers in Marine Science*, *7*, p.490.

Ramirez-Llodra, E., Meyer, H.K., Bluhm, B.A., Brix, S., Brandt, A., Dannheim, J., Downey, R.V., Egilsdóttir, H., Eilertsen, M.H., Gaudron, S.M. and Gebruk, A., 2024. The emerging picture of a diverse deep Arctic Ocean seafloor: From habitats to ecosystems. *Elementa: Science of the Anthropocene*, *12*(1).

Rastelli, E. Cinzia Corinaldesi, Antonio Dell'Anno, Michael Tangherlini, Marco Lo Martire, Manabu Nishizawa, Hidetaka Nomaki, Takuro Nunoura, Roberto Danovaro, (2019) Drivers of Bacterial α- and β-Diversity Patterns and Functioning in Subsurface Hadal Sediments, Frontiers in Microbiology, 10.3389/fmicb.2019.02609, 10,

Riehl, T., Lins,L., Brandt, A., (2018) The effects of depth, distance, and the Mid-Atlantic Ridge on genetic differentiation of abyssal and hadal isopods (Macrostylidae). *Deep Sea Research Part II: Topical Studies in Oceanography.*148, 74-90. https://doi.org/10.1016/j.dsr2.2017.10.005

Røyseth, V., Hurysz, B.M., Kaczorowska, A.K., Dorawa, S., Fedøy, A.E., Arsın, H., Serafim, M.S.M., Myers, S.A., Werbowy, O., Kaczorowski, T. and Stokke, R., 2023. Activation mechanism and activity of globupain, a thermostable C11 protease from the Arctic Mid-Ocean Ridge hydrothermal system. *Frontiers in Microbiology*, *14*, p.1199085.

Sanei, H., Outridge, P. M., Oguri, K., Stern, G. A., Thamdrup, B., Wenzhöfer, F., Wang, F. & Glud, R. N. (2021) High mercury accumulation in deep-ocean hadal sediments. Scientific Reports. 11, 1, 8 p., 10970

SEAFO (2015) Conservation Measure 30/15 on Bottom Fishing Activities and Vulnerable Marine Ecosystems in the SEAFO Convention Area. CM30-15, South East Atlantic Fisheries Organisation. Sakopmund, Namibia. http://www.seafo.org/Documents Accessed 18 October 2024

SIOFA, (2024) Conservation and Management Measure for the Interim Management of Bottom Fishing in the Agreement Area (Interim Management of Bottom Fishing). CM 01 (2024) . Southern Indian Ocean Fisheries Agreement, Le Port, La Reunion. https://siofa.org/management/CMM/01(2024) Accessed 18 October 2024

Southeast Atlantic Fisheries Organization, 2016. Conservation Measure 30/15 on Bottom Fishing Activities and Vulnerable Marine Ecosystems in the SEAFO Convention Area

SPRFMO, (2023) Conservation and Management Measure for the Management of Bottom Fishing in the SPRFMO Convention Area. CMM 03-2023. South Pacific Regional Fisheries Management Organisation, Wellington, New Zealand, https://www.sprfmo.int/fisheries/conservation-and-management-measures/ Accessed 18 October 2024

Stefanoudis, P.V., Licuanan, W.Y., Morrison, T.H., Talma, S., Veitayaki, J., Woodall, L.C. (2021) Turning the tide of parachute science. Current Biology, 31 (4), R184-R185, https://doi.org/10.1016/j.cub.2021.01.029.

Sutton PJH, Rickard GJ, Roemmich DH. 2024. Southwest Pacific Ocean Warming Driven by Circulation Changes. Geophysical Research Letters 51: e2024GL109174

Taranto, G.H., González-Irusta, J.M., Dominguez-Carrió, C., Pham, C.K., Tempera, F., Ramos, M., Gonçalves, G., Carreiro-Silva, M. and Morato, T., 2023. Spatial distributions, environmental drivers and co-existence patterns of key cold-water corals in the deep sea of the Azores (NE Atlantic). *Deep Sea Research Part I: Oceanographic Research Papers*, *197*, p.104028.

Vecchione M and Bergstad OA (2022) Numerous Sublinear Sets of Holes in Sediment on the Northern Mid-Atlantic Ridge Point to Knowledge Gaps in Understanding Mid-Ocean Ridge Ecosystems. *Front. Mar. Sci*. 9:812915. doi: 10.3389/fmars.2022.812915

Weston, J. N. J. & Jamieson, A. J. (2022) Exponential growth of hadal science: perspectives and future directions identified using topic modelling. ICES Journal of Marine Science. 79, 4, p. 1048-1062 15 p.

Zhang, X., Xu, Y., Xiap, W., Zhao, M., Wang, Z., Wang, X., Xu, L., Luo, M., Li, X., Fang, J., Fang, Y., Wang, Y., Oguri, K., Wenzhöfer, F., Rowden, A. A., Mitra, S. & Glud, R. N., (2022) The hadal zone is an important and heterogeneous sink of black carbon in the ocean. *Communications Earth & Environment* 3, 25 (2022). https://doi.org/10.1038/s43247-022-00351-7

Zhou P. and Peng X. (2023). Delving into the deep: China launches global collaboration program for advancing hadal science. *The Innovation Geoscience* 1(2), 100028. https://doi.org/10.59717/j.xinn-geo.2023.100028

Zhou, Y.-L., Paraskevi Mara, Dean Vik, Virginia P. Edgcomb, Matthew B. Sullivan, Yong Wang, (2022) Ecogenomics reveals viral communities across the Challenger Deep oceanic trench, Communications Biology, 10.1038/s42003-022-04027-y, **5**, 1,

Zhulay, I., Iken, K., Renaud, P.E. and Bluhm, B.A., 2019. Epifaunal communities across marine landscapes of the deep Chukchi Borderland (Pacific Arctic). *Deep Sea Research Part I: Oceanographic Research Papers*, *151*, p.103065.

Supplementary material

Region	***New data***	***Human Pressures***	**Protection measures**
Arctic Ocean	Chukchi Borderland plateau	Fisheries Exploration for mineral resources (chap. 7); Climate change	Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean entered into force on 25 June 2021 The Norwegian government to regulate fisheries in the Yermak plateau, northwest of Spitsbergen/Svalbard~~Svalbard~~

North Atlantic Ocean,	Puerto Rico Trench Vema Fracture zone (11°N) survey Hatton-Rockall Bank Azores plateau	Fisheries Exploration for mineral resources (chap. 7); Climate change Pollution	Nine areas on the Hatton-Rockall Bank are closed to all bottom fishing gears (NEAFC, 2024) -Three areas between the Azores and Iceland including the Charlie-Gibbs Fracture Zone are closed to bottom fishing until 2027 (NEAFC, 2024) when they will be reviewed. -Development of nMAR draft REMP (ISA document 2022).
South Atlantic Ocean	Rio Grande Rise, São Paulo Plateau Walvis Ridge.	Fisheries Exploration for mineral resources (chap. 7); Climate change *offshore hydrocarbons (chap. 19);* *Pollution*	-Ascension Island and Tristan da Cunha MPA- fully protected against fishing and mining -Fishing closure areas in the Walvis Ridge (SEAFO) -Valdivia Bank closed to bottom trawling (SEAFO, 2015). - six areas on the Southern Mid-Atlantic Ridge and the Wüst seamount segment of the Walvis Ridge (SEAFO, 2015) - Brazil's sponsored cobalt crust exploration contract with ISA in the Rio Grande Rise terminated. The region claimed as extended Brazilian EEZ.
Indian Ocean,	Sunda trench	Fisheries Exploration for mineral resources (chap. 7); Climate change *Pollution*	-Amirante to Fortuna Banks Fully protection Fishing closure at the Atlantis Bank of the Broken Ridge Plateau in the east and Walter's Shoal on the Madagascar Plateau in the west (SIOFA, 2024). Development of the Central Indian Basin and western Indian Ocean ridge systems REMP (, ISA 2024)

North Pacific Ocean	Northwest Hawaiian Ridge. Mariana Trench. Emperor Though	Fisheries Exploration for mineral resources (chap. 7); Climate change *Pollution* "Concentrations of discarded cables from scientific expeditions to the Mariana Trench"	Development of NW Pacific draft REMP (ISA document 2022) Northwest Hawaiian Ridge protected as part of the US EEZ Hawaiian Papahānaumokuākea National Monument Fishery targetting North Pacific armorhead _*Pentaceros wheeleri*_ and splendid alfonsino _*Beryx splendens*_ is managed by North Pacific Fishery Commission (NPFC)
South Pacific Ocean	East and West Pacific Trenches.	Fisheries Exploration for mineral resources (chap. 7); Climate change *Pollution*	-Palau MPA- fully protected Coco Islands and Christmas Islands MPA- Fully Protected -Cook Islands Marae Moana management zones, 50km exclusion zones around the islands for deep-sea mineral exploration -NZ. No bottom trawling allowed along the Kermadec Ridge and complete protection 12 M around each island on the ridge. -Australia. A network of Marine Parks offshore where uses are managed, including areas closed to fishing. -SPRFMO spatial management planning includes the Challenger Plateau, Lord Howe Rise and West Norfolk Ridge. -Bottom trawling prohibited in areas of the Tasman Rise, Lord Howe Rise, Challenger Plateau and Norfolk Ridge (SPRFMO, 2023).

			-Bottom trawling prohibited on part of the Three Kings Ridge. (SPRFMO, 2023)
Southern Ocean	East Scotia Ridge South Sandwich Trench,	Fisheries Climate change *Pollution*	Ross Sea MPA. General Protection Zones where no fishing is allowed. -The Ross Sea region MPA prohibits all commercial fishing on the Antarctic Continental shelf and slope and on a segment of the Pacific Antarctic Ridge. (CCAMLR, 2023) In the Southern Ocean, all commercial fishing prohibited in the South Orkney Islands Southern Shelf MPA (CCAMLR, 2023)

Section 4

Sub-chapter 5p: Hydrothermal Vents and Cold Seeps

[=cross-chapter linkages]

Coordinating Author: Lisa A. Levin

Authors: Ana Colaco, Elva Escobar, Nadine Le Bris, Anna Metaxas, Paraskevi Nomikou, Samuel O. Popoola, Julia Sigwart, Paolo Sumida, Verena Tunnicliffe, Hiromi Watanabe, Yadong Zhou

1. Key Points

- Discovery of new sites, novel habitats, new species, and new chemosynthetic symbioses continues at a rapid pace for vents and seeps.
- Pressures are growing from climate change, fisheries and seabed mining, but protection for vents and seeps remains limited.
- New recognition, quantification and valuation of critical ecosystem services provided by vents and seeps heighten conservation imperatives.
- Inequities remain in knowledge and capacity transfer, particularly for Indigenous Peoples and Low- and Middle Income Countries

2. Introduction and context

2.1-. Summary of baseline state provided by WOA I and II.

Hydrothermal vents and cold seeps host high microbial and animal biomass supported by chemosynthesis, involving microbe-animal symbioses, and contribute to broader productivity and fisheries in surrounding systems. They occur at mid-ocean ridges, volcanic arcs and hotspot-associated volcanic intraplate, and back-arc spreading centers (vents) and on passive continental margins and subduction zones (seeps). Both vents and seeps exhibit high spatial and temporal variability of constraining environmental factors imposing physiological adaptations. Late successional systems including cold-water corals and inactive sulfide communities may persist over centuries. The high levels of endemism provide significant species discovery, and provide model systems for understanding adaptation to extreme conditions, critical climate regulating services, as well as biotechnology and biomedical potential (e.g., Bruno and others, 2019).

Technological advances have enabled discovery of thousands of sites in the past decades, as well as development of deep oil, gas and gas hydrate activities (seeps), and new mining exploration contracts (vents) issued in the Atlantic and Indian Oceans. Additional pressures include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. There is growing recognition of the need for vent and seep protection. Conservation actions to date include scientific and industry codes of conduct, protected areas and International Union for the Conservation of Nature Red List designations (Le Bris and others, 2017, 2021).

2.2. Scope of the Coverage.

Here, we synthesize recent regional exploration and discovery of vents and seeps, key advances in knowledge and understanding of processes and threats, description of environmental change, social implications, and knowledge and capacity gaps.

3. Description of environmental change since WOA II

3.1 Changes in the overall status.

Climate change. Rising ocean temperatures [S4.C3] caused past gas hydrate destabilization (El bani Altuna and others, 2021). The flux of methane from seabed seeps to the atmosphere is increasing in the Arctic and Antarctic (Workman and others, 2024). In a warming ocean, present-day connectivity pathways may be disrupted due to shorter larval duration (thus smaller dispersal distance) and vertical position shifts (Rakka and others, 2021), changing current patterns (magnitude or direction) (Levin and others 2020) or loss of suitable habitat (Morato and others, 2020).

Resource Exploration/Exploitation. Intense research occurs at some vent sites with likely impacts (Juniper and others 2019). Recovery from a small, induced disturbance at a Mid-Atlantic Ridge vent found altered community structure after two years with implications for deep-sea mining (Marticorena and others, 2021). As of 2024, the International Seabed Authority (ISA) has signed seven exploration contracts for vent deposits in the Atlantic and Pacific Oceans [S5A.C7]. Exploration licenses are active in Tonga, Japan and Papua New Guinea, while Norway has initiated approvals. Exploitation of active vents may cause losses of species, functions and connectivity (Alfaro-Lucas and others, 2024; Tunnicliffe and others, 2024) while knowledge of the ecological value of inactive/extinct sulphides is limited (Van Dover and others, 2020). Offshore oil and gas development continues [S5A.3B], likely affecting associated methane seeps.

Bottom trawling [S5A.C1c] exerts pressure on cold seep faunas as commercial species often congregate near seeps (e.g., Sen and others, 2019; Turner and others, 2020). Foundation species were reduced at New Zealand seeps (Jones 2023) and trawl nets were tangled on carbonates on the Canadian Pacific Margin (DFO 2018). In Norway, broken carbonates and trawl marks had limited recolonization (Bellec and others, 2024). Hydrocarbon exploration on continental margins [S5A.3Cb] has located methane seep communities (e.g., Dueñas and others, 2021; Bravo and others, 2024). Extraction will likely diminish the methane supply that fuels chemosynthesis as observed by Boles and others (2023).

3.2 Factors contributing to the change observed.

The changes are driven by rising populations and industry development increasing fishing pressure [S5A.C1c], energy demand [S5A.3B], and emissions (causing warming) [S4.C3], as well as rising metal demand and geostrategic contexts [S5A.C7], in part for electrification of transport.

3.3. Impacts and interactions of the change with other marine system components

Discoveries of large nursery areas of deep-sea species near vents and seeps (e.g., Barry and others, 2023) suggest that changes in these systems can influence recruitment to non-vent species, including from higher trophic levels.

3.4 The social, economic and cultural aspects associated with the change (since WOA II)

As potential exploitation draws closer, societal awareness is growing, often with strong disagreements with state or ISA actions (e.g., van Putten and others, 2023; Gilbert, 2024). Mining at vents may intersect with sites of cultural heritage significance (Turner and others, 2020) [S5B.C5].

3.5 Implications for the 2030 Agenda for Sustainable Development and for the BBNJ Treaty.

Protection supports Sustainable Development Goal (SDG) 14 through sustainable management (Target 14.2) and strengthening resilience using MPAs (Target 14.5). The ISA (ISA/27/C/8) declares support for SDG14 through its regulatory framework for seabed mining, which requires trade-offs with SDG 7 (energy) and SDG 8 (industry). A Draft Regional Environmental Management Plan (ISA/27/C/38) reflects Target 14.2 by classifying active hydrothermal vents as needing protection. Current Mining Code development aims to prevent environmental harm while mining in vent areas. Protection of vents and seeps, plus the ecosystem functions and services they provide, can help meet the Global Biodiversity Framework targets. For the Agreement on the Conservation and Sustainable Use of Marine Biological Diversity in Areas Beyond National Jurisdiction (ABNJ; BBNJ treaty) all four components are relevant.

4. Region-specific changes - New Discoveries and New Pressures.

Figure 1 depicts previously known and recently discovered (since 2018) deep vents and seeps.

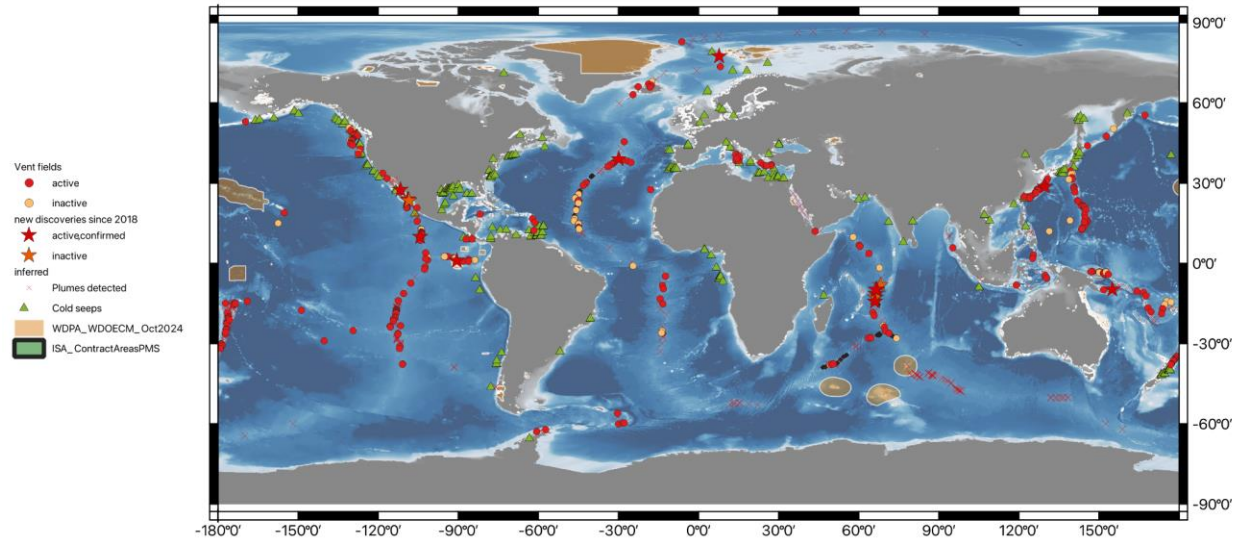


Figure 1. Global map of confirmed active (red symbols) or reported inactive vent fields (orange symbols) and cold seeps (green triangles). For vents, stars denote vent fields discovered in 2018-2024. Vent field locations are from the InterRidge Vent Database (Beaulieu and Szanfranski 2020) completed by recent references (Zhou et al. 2018; Soule et al. 2018; Paduan et al. 2019; Ryu et al. 2019; Jang et al. 2023, Boulart et al. 2022; McDermott et al. 2022; Borhrman et al. 2022; Zhou et al. 2022; Chen et al. 2024; Dang et al. 2024; Lecoeuvre et al. 2021). Seep site data listed in the Biogeography of Deep-Water Chemosynthetic Ecosystems Database (ChEssBase 2019) were completed from other inventories (Olu et al. 2010; Quattrini et al. 2015; Baumberger et al. 2018; Feng et al. 2018; Etiope et al. 2019; McDonald et al., 2020; Aguillar et al. 2024).

Brown polygons represent designed MPAs from Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], October 2024, Cambridge, UK: UNEP-WCMC and IUCN (2024) Available at:www.protectedplanet.net. Bathymetry is the GEBCO One Minute Grid map

from https://www.gebco.net/data_and_products/gridded_bathymetry_data/. This map was built using QGIS 2.18.20.

At shallow vents and seeps (<200 m; not mapped in Fig. 1), species may coexist alongside photosynthetic algae and seagrass, and have greater exposure to anthropogenic changes including warming, ocean acidification, bottom fishing, pollution, or invasive species (Ramirez-Lodra and others, 2010; Åström and others, 2018). New technologies were increasingly used for analysing deep sea biota, revealing magnificent vent assemblages (e.g., Gerdes and others, 2021; Ramirez-Llodra and others, 2024; Sun and others, 2020). Vent and seep faunas show heterogeneity linked to depth, surface production, oxygen minimum zones and geology (Seabrook and others, 2024).

4.1 The Arctic Ocean

First found in the 1990s, cold seep discovery continues in the Arctic (e.g. Waghorn and others, 2022; Sen and others, 2019; Serov and others, 2024), as well as two recently discovered vent fields (Stensland and others, 2019; Sahlström and others, 2023) and many new vent species (Eilertsen and others, 2024) [S4.5o].

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

New vents were discovered on the Mid-Atlantic Ridge (Butterfield and others, 2023). Other new vents discovered south of Iceland at the Reykjanes Ridge were noticeably lacking typical vent macrofauna (Taylor and others, 2021). In the NW Atlantic margin, acoustic imaging revealed ~1139 unique methane flare sites; most are shallower than 400 m, but some extend to 1400 m (Ruppel and others, 2024). A newly discovered squat lobster in the Gulf of Mexico is the first W. Atlantic seep endemic (Rodriguez-Flores and others, 2024).

4.3 The South Atlantic Ocean and the Wider Caribbean

Seeps in the West Atlantic, Caribbean and off Columbia are associated with linear diapir systems, salt diapirs resulting from salt tectonics, regions of mud volcanism, and compact seafloor mounds; most knowledge is still associated with the oil and gas industry, with limited access to the science community and faunal studies are limited (Aguilar Pérez and others, 2024). Argentina's first methane seeps (~500 m) are reported with dense infaunal assemblages (Bravo and others, 2024).

4.4 The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

New discoveries include a rare serpentinite-hosted field (Lecoeuvre and others, 2021) and the first actively diffusing vent system in the Red Sea (Van der Zwan and others, 2023); both host unique microbial communities without typical vent macrofauna. Faunal studies described over 30 new taxa and indicate within-region biogeographic discontinuity (e.g. Jang and others, 2023). Two new seep communities were reported in the northern Indian Ocean with biogeographic affiliations with the West Pacific vent/seep communities (Mazumdar and others, 2019), and a new active cold seep site occurs in the Bay of Bengal (Sangodkar and others, 2023).

4.5 The North Pacific Ocean

Serpentine-hosted seep communities at mud volcanoes on the Mariana Forearc, where methane-rich fluids are highly alkaline (pH >12), support many novel species (Chen and others, 2023, 2024a) [S4.5l]. New NE Pacific vent and seep sites continue to be discovered (Galkin and others, 2019) notably including 1600 methane flares mapped in the Canadian Pacific (DFO 2018) and 8 new seeps off Washington and Oregon (Seabrook and others, 2024). Low temperature ridge-flank hydrothermal springs in the NE Pacific support deep-sea octopus nurseries (Barry and others, 2023).

4.6 The South Pacific Ocean and Equatorial Pacific Ocean

A newly discovered vent site in the Southwest Pacific may contribute to faunal connectivity (Boulart and others, 2022). Other new vent sites in the Galapagos Rift expand records of vent species (Chen and others, 2024b).

4.7 The Southern Ocean

Three new deep sea vent sites have been reported in the Atlantic region of the Southern Ocean (Bohrmann 2019; Linse and others, 2022). Major new seepage sites in the Ross Sea indicates likely widespread climate-sensitive phenomena around Antarctica (Seabrook and others, 2023).

5. Remaining Key Knowledge and Capacity Changes and any new gaps

5.1 Advances in technology

Many technological advances have improved understanding of chemosynthetic ecosystems, such as: i) evolving molecular tools to support systematics and studies of adaptations to extreme environments and genetic connectivity (e.g., Zeng and others 2020), ii) photogrammetry methods for 3D reconstructions to aid habitat change studies (e.g., Van Audenhaege and others, 2024), iii) neural network approaches to image classification (Vega and others, 2024), and iv) novel computer algorithms for seep identification (Vrolijk and others, 2021; Ruppel and others, 2024).

5.2 Novel habitats and processes.

Important new findings include subseafloor vent faunal habitats (Bright and others, 2024) and off-axis hydrothermalism (McDermott and others, 2022, Parsons and others 2024) and novel chemo-symbioses (Goffredi and others, 2020, 2021) and inactive vent species (Chen and others, 2024a). Microbial processes are implicated in primary productivity at inactive vent deposits (Achberger, and others, 2024), in carbon cycling and nutrient export (Versteegh and others, 2023), and in trophic networks in vent communities (Murdock and others, 2021). A comprehensive genomic catalogue of microbes from seeps (Han and others, 2023) enables exploration of functional processes such as biogeochemical cycling.

5.3 Dynamics, succession and sphere of influence

Long-term observations and experiments reveal high stability and slow recovery of vent ecosystems in slow-spreading ridges following disturbance (Van Audenhaege and others, 2022, Marticorena and others, 2021). Evidence that vents and seeps affect the ocean outside their perimeters accumulates, such as iron from rising vent plumes inducing phytoplankton blooms in the Southern Ocean (Ardyna and others, 2019), and enhanced faunal abundance on the seafloor (Klunder and others, 2020). At seeps, input from both chemosynthesis and photosynthesis support distinctive infaunal communities in an intermediate zone between methane seeps and background (Ashford and others, 2021).

5.4 Stepping stones

Population connectivity could enhance resilience to disturbance. Highly divergent gene flow directions and ranges exist among closely allied vent species (e.g., Breusing and others, 2023; Methou and others, 2024). A novel, but isolated, Arctic vent ecosystem in a region with imminent mineral exploration provides evidence for historical connectivity (Eilertsen and others, 2024). Range analyses divide the Indian Ocean into three vent provinces that suggest separate management areas (Zhou and others 2022). In the Northwest Pacific, the Okinawa Trough has high endemicity (Brunner and others, 2022) while connectivity along the volcanic arcs appears limited for many species (Giguère and Tunnicliffe 2021). Most vent species are known only within one limited region; for a few species, the Manus Basin is the key region for cross-equator linkages (Brunner and others, 2022, Tunnicliffe and others, 2024). At both vents and seeps, some widespread species form localized genetic units with rare long-distance dispersal events (Jollivet and others, 2024).

5.5 Ecosystem services

Hydrothermal vents provide regulating services such as biogeochemical cycling of manganese, iron and nitrogen and carbon fixation. Provisioning services include marine genetic resources (e.g., Fuelzyme ®, Bravakos and others, 2021, Giordano, 2020) [S5A.C5] and potential metals from mining [S5A.C7]. Supporting services include nutrient transfers to the deep sea and nursery areas at both active and inactive vents. Cultural values flow from scientific research (e.g., models for extraterrestrial life), and creative inspiration (DOSI, 2023). Cold seeps provide provisioning services through commercial fish/crustacean species and regulating services through carbon sequestration (Le and others, 2022). This new understanding heightens conservation imperatives.

5.6 Consequences of environmental impacts, governance challenges, conservation status.

About half of known vent sites fall in Areas Beyond National Jurisdiction where many are under mining exploration contracts; regulations on the conservation status of vents within contract areas are under development. Of all other vents, 17% are covered by non-targeted conservation interventions while 8% benefit from vent-specific actions (Menini and others, 2023). For new and updated areas, see Table 1. Four southwest Pacific States initially declared a moratorium on deep-sea mining (MSG Secretariat, 2020); today 32 states have taken a position against deep-seabed mining in international waters. Thomas and others (2021) find the limited distribution of most vent molluscs is the key vulnerability, with notable extinction threat in mining contract areas. However, regular distribution assessment updates are needed. Conservation is in place for very few cold seeps although many are vulnerable to anthropogenic disturbance and climate change (Le and others, 2022, Bellec and others, 2024). An economic valuation identified highest willingness to pay to conserve Costa Rican seeps with endemic species (Pereira and others, 2024). Governance in the ABNJ is problematic due to fragmented and variable approaches (Menini and others, 2023), and protections remain limited.

TABLE 1: Emerging threats, risks and conservation measures since 2019

Basin	Threat actions	Other Risks	Conservation measures	Citations
Arctic	Norway approved (but paused in Dec. 2024) exploration for extraction of polymetallic sulphides	Warming waters could bring colonists to seeps and vents northward challenging endemic species.		Delivorias, A. 2024. Åström, E.K. and others, 2020.
North Atlantic and Mediterranean	Exploration of three ISA contract areas in progress in active vent sites.	Bottom contact fishing on shallower vent areas. Marine litter (mostly plastics) in vent habitats from abandoned fishing gear	Luso Hydrothermal Field MPA; Portugal. ISA considers REMP proposal to protect all active vents from mining in contract areas.	Governo dos Açores. 2022. International Seabed Authority, 2022. Consoli, P. and others, 2021.
Western Tropical Atlantic and Caribbean		Submarine slides caused by methane hydrate destabi-lization in a warming ocean. Lack of literacy and capacity to address impacts		Ruffine, L. and others, 2023. Amon D. and others, 2022.
South Atlantic	Oil and gas exploration in deep water continues off		Ascension Island MPA; (UK). Covers 750 km of	Ascension Island Government, 2021.

	Argentina near newly discovered seeps.		ridge crest with known vent sites.	Bravo M. and others, 2024.
Northeast Pacific	Notable climate-induced deoxygenation in the MPA (Ross et al. 2020) may affect shallow vents and larvae	Bottom contact fishing on shallower vent areas. Deep seabed mining could affect vents.	Tang.g̱wan-ḥačxwiqak-Tsigis (ṮḥT) MPA now including all confirmed hydrothermal vents in Canada and some methane seeps.	Canada Gazette, 2024. Ross, T. and others, 2020.
Northwest Pacific		Microplastic accumulation in cold seep animals	Northern part of Central (Naka) Mariana Ridge and West Mariana Ridge MPA; Japan. Includes three vent sites.	Teng, J. and others, 2023. Watanabe H.K. & Yamakita T, 2022. Government of Japan, 2020.
Southwest Pacific	Potential renewal of seabed exploitation licence for polymetallic sulphides at Solwara, Manus Basin, Papua New Guinea			Monga Bay, 2024.
Indian Ocean	Exploration of four ISA mining contract areas in progress at active vent sites.	Microplastic accumulation in vent animals		Park, B. and others, 2024.
Global	Seabed mining	Ocean warming and acidification	Assessment of hydro-thermal vent species against IUCN Red List criteria. Of these, 114 fall in Vulnerable, Endangered or Critically Endangered catagories.	Thomas, E.A. and others, 2021.

5.7 Previously identified gaps that remain to be addressed.

Many knowledge gaps identified in WOA II (Le Bris and others, 2021) remain, including the distribution, biogeography and connectivity of vent and seep biota, resilience and time and space scales of recovery from disturbance (trawling, mining, climate change) and vent and seep roles in biogeochemical cycles. Capacity gaps are being identified (Bell and others, 2023) and addressed (Johannes and others, 2023), but limited access to funding, research vessels, low-cost instruments, and taxonomic expertise remain, creating global inequity. SIDS for example, although often in close proximity, have limited access to hydrothermal vents and seeps. Currently several international programmes offer training opportunities and philanthropic foundations offer some research vessel support.

5.8 Newly recognized knowledge gaps.

Regional gaps in location of new sites, and in novel habitats, functions, symbioses and other mutualistic interactions among species, and genetic resource potential at vents and seeps exist. Additional key gaps include vent-seep-organic fall connectivity and stepping-stone functions

including the role of inactive and ecotone/transition vent (Boschen and Colaco, 2021; Neufeld and Metaxas, 2022) and seep (Pereira and others, 2021) sites, and animal-microbe interactions at active vents (Murdock and others, 2021), seeps (Pereira, 2024), and inactive sites.

6. REFERENCES

Achberger, Amanda M., and others. Inactive hydrothermal vent microbial communities are important contributors to deep ocean primary productivity. Nature Microbiology, vol. 9, No. 3, pp. 657-668, 2024.

Aguilar Pérez, Maria Isabel, and others. Review of cold seeps in the Western Atlantic, focusing on Colombia and the Caribbean. Frontiers in Marine Science, vol. 11, art. 1430377, 2024.

Alfaro-Lucas, Joan, and others. High functional variability across the world's deep-sea hydrothermal communities. Proceedings of the National Academy of Sciences of the United States of America., vol. 121, art. e2403899121, 2024.

Amon, Diva, and others. My Deep Sea, My Backyard: a pilot study to build capacity for global deep-ocean exploration and research. Philosophical Transactions of the Royal Society B, vol. 377, art. 20210121, 2022.

Ardyna, Mathieu, and others. Hydrothermal vents trigger massive phytoplankton blooms in the 691 Southern Ocean. Nature Communications, vol. 10, art. 2451, 2019.

Ascension Island Government. The Ascension Island Marine Protected Area Management Plan 2021-26. Ascension Island Government Conservation and Fisheries Directorate, 2021.

Ashford, Oliver, and others. A chemosynthetic ecotone – 'chemotone' – in the sediments surrounding deep-sea methane seeps. Limnology and Oceanography. vol. 66, No. 5, pp. 1687-1702, 2021.

Åström, Emmelie K. L., and others. Methane cold seeps as biological oases in the high-Arctic deep sea. Limnology and Oceanography, vol. 63, pp. S209-S231, 2018.

Åström, Emmelie K. l. and others. Cold seeps in a warming Arctic: Insights for benthic ecology. Frontiers in Marine Science, vol 7, art 244, 2020.

Barry, James P., and others, Abyssal hydrothermal springs—Cryptic incubators for brooding octopus. Science Advances, vol. 9, No. 34, art. eadg3247, 2023.

Baumberger, Tamara, and others. Mantle-derived helium and multiple methane sources in gas bubbles of cold seeps along the Cascadia Continental Margin. Geochemistry, Geophysics, Geosystems, vol. 19, pp. 4476–4486, 2018.

Beaulieu, Stace E. and Kamil M. Szafranski. InterRidge Global Database of Active Submarine Hydrothermal Vent Fields. Version 3.4 PANGAEA https://doi.pangaea.de/10.1594/PANGAEA.917894.

Bell, Katherine L.C., and others. Exposing inequities in deep-sea exploration and research: results of the 2022 Global Deep-Sea Capacity Assessment. Frontiers in Marine Science. vol. 10, art. 1217227, 2023.

Bellec, Valerie Karin, and others. New cold seep sites on the continental slope southwest to Svalbard. Frontiers in Earth Science, vol. 12, art.1328357, 2024.

Boschen, Rachel and Ana Colaco.Northern Mid-Atlantic Ridge hydrothermal habitats: A systematic review of knowledge status for environmental management. Frontiers in Marine Science, vol. 8, art. 657358, 2021.

Bohrman, Gerhard. The Expedition PS119 of the Research Vessel Polarstern to the Eastern Scotia Sea in 2019. Berichte zur Polar-und Meeresforschung, Reports on polar and marine research, vol. 736, 2019.

Bohrmann, Gerhard, and others. Discovery of the first hydrothermal field along the 500-km-long Knipovich Ridge offshore Svalbard (the Jøtul field). Scientific Reports, vol. **14**, art. 10168, 2024.

Boles, James R. and others. Hydrocarbon production reduces natural methane seeps in the Santa Barbara channel. Marine and Petroleum Geology, vol, 151, art. 106187, 2023.

Boulart, Cedric, and others. Active hydrothermal vents in the Woodlark Basin may act as dispersing centres for hydrothermal fauna. Communications Earth & Environment, vol. 3, No. 1, p.64, 2022.

-

Bravakos, Panos, and others. Genomic adaptation of *Pseudomonas* strains to acidity and antibiotics in hydrothermal vents at Kolumbo submarine volcano, Greece. Sci Rep vol. 11, 1336, 2021.

Bravo, Maria Emilia, and others. Discovery of deep-sea cold seeps from Argentina host singular trophic linkages and biodiversity. Deep-sea Research Part I, vol. 211, art. 104361, 2024.

Breusing, Corinna., J. and others. Differential patterns of connectivity in Western Pacific hydrothermal vent metapopulations: A comparison of biophysical and genetic models. Evolutionary Applications, vol. 16, No. 1, pp.22-35, 2023.

Bright, Monica, and others. Animal life in the shallow subseafloor crust at deep-sea hydrothermal vents. Nature Communications, vol. 15, art. 8466, 2024.

Brunner, Otis, and others. Species assemblage networks identify regional connectivity pathways among hydrothermal vents in the Northwest Pacific. Ecology and Evolution, vol. 12, No. 12, art. e9612, 2022.

Bruno, Renato, and others. Worms' antimicrobial peptides. Marine Drugs, vol. 17, No. 512, 2019.

Butterfield, David A., and others. Discovery of three hydrothermal vent fields on the Mid-Atlantic Ridge with Falkor (too). AGU Fall Meeting Abstracts Vol. 2023, No. 1281, p. OS11B-1281, 2023.

Canada Gazette, 2024. Part II, Volume 158, Number 13. https://gazette.gc.ca/rp-pr/p2/2024/2024-06-19/html/sor-dors122-eng.html .

Chen, Chong, and others. Unexpected discovery of a serpentinite-hosted chemosynthetic ecosystem on Asùt Tesoru Seamount, Mariana Forearc. Marine Ecology, vol. 44, No. 5, art. e12759, 2023.

Chen, Chong, and others. Serpentinite-hosted chemosynthetic community of South Chamorro Seamount, Mariana Forearc. Marine Ecology, vol. 45 art. e12808, 2024a.

Chen, Chong, and others. Hydrothermal vent fauna of the Galápagos Rift: updated species list with new records. Marine Biodiversity, vol. 54, No. 2, art.16, 2024b.

ChEssBase, Ocean Biogeographic Information System: ChEssBase (CoML). Accessed via http://www.gbif.org/dataset/83b90d28-f762-11e1-a439-00145eb45e9a on 2015-05-06, 2019.

Consoli, Pierpaolo, and others. Marine litter pollution associated with hydrothermal sites in the Aeolian archipelago (western Mediterranean Sea). Science of the Total Environment, vol. 773, art. 144968, 2021.

Deep Ocean Stewardship Initiative (DOSI). “Hydrothermal Vent Ecosystems” - Information Sheet. Deep-Ocean Stewardship Initiative. 2023. https://www.dosi-project.org/wp-content/uploads/vents-ecosystems-info-sheet.pdf

Delivorias, A. Norway to mine part of the Arctic seabed. PE 757.616, EPRS, 2024. https://www.europarl.europa.eu/RegData/etudes/ATAG/2024/757616/EPRS_ATA(2024)757616_EN.pdf.

Department of Fisheries and Oceans (DFO). 2018. Assessment of Canadian Pacific Cold Seeps against Criteria for Determining Ecologically and Biologically Significant Areas. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/002

Dueñas Luisa F., and others. Fauna associated with cold seeps in the deep Colombian Caribbean. Deep–Sea Research vol. 173, art. 103552, 2021.

Eilertsen, Mari H., and others. Diversity, habitat endemicity and trophic ecology of the fauna of Loki's Castle vent field on the Arctic Mid-Ocean Ridge. Scientific Reports, vol. 14, No. 1, art. 103, 2024.

El bani Altuna, N., and others. Deglacial bottom water warming intensified Arctic methane seepage in the NW Barents Sea. Communications, Earth and Environment, vol. 2, art. 188, 2021.

Etiope, Giuseppe, and others. Gridded maps of geological methane emissions and their isotopic signature. Earth System Science Data, vol. 11, No. 1, pp. 1-22, 2019

Feng, Dong, and others. Cold seep systems in the South China Sea: An overview. Journal of Asian Earth Sciences, vol. 168, pp. 3–16, 2018.

Galkin, Sergei V., and others. Comprehensive research of ecosystems of hydrothermal vents and cold seeps in the Bering Sea (Cruise 82 of the R/V Akademik MA Lavrentyev). Oceanology, vol. 59, pp. 618-62, 2019.

Gerdes, Klaas, and others. Megafauna of the German exploration licence area for seafloor massive sulphides along the Central and South East Indian Ridge (Indian Ocean). Biodiversity Data Journal, vol. 9, art. e69955, 2021.

Giguère Thomas, N. and Verena Tunnicliffe. Beta diversity differs among hydrothermal vent systems: Implications for conservation. PLoS ONE, vol. 16, art. e0256637, 2021

Gilbert, Natasha. First approval for controversial sea-bed mining worries scientists. Nature, vol. 625, pp. 435-436, 2024.

Giordano, Daniela. Bioactive molecules from extreme environments. Marine drugs, vol. 18, No. 12, art.640, 2020.

Goffredi, Shana K., and others. Mixotrophic chemosynthesis in a deep-sea anemone from hydrothermal vents in the Pescadero Basin, Gulf of California. BMC Biology, vol. 19, art. 8, 2021.

Goffredi, Shana K., and others. Methanotrophic bacterial symbionts fuel dense populations of deep-sea feather duster worms (Sabellida, Annelida) and extend the spatial influence of methane seepage. Science Advances, vol. 6, art. eaay8562, 2020.

Government of Japan. Ministry of the Environment, Designation of offshore seabed natural environment conservation areas, 2020. https://www.env.go.jp/press/108741.

Governo dos Açores. Portaria n.o 68/2019, de 26 de setembro - aprova o Regulamento para o exercício da pesca na zona marítima do campo hidrotermal LUSO, 2019.

Han, Yingchun, and others. A comprehensive genomic catalog from global cold seeps. Scientific Data, vol. 10, art. 596, 2023.

International Seabed Authority. Regional environmental management plan for the Area of the northern Mid-Atlantic Ridge with a focus on polymetallic sulphide deposits. ISBA /27/C/38, 56 pp, 2022.

Jang, Sook-Jin, and others. Geographical subdivision of *Alviniconcha* snail populations in the Indian Ocean hydrothermal vent regions. Frontiers in Marine Science, vol.10, pp.1139190, 2023.

Johannes Kristen N., and others. Seafloor observation scenario exploration tool enabling representative exploration of the global deep seafloor. Frontiers in Marine Science, vol. 10 art. 251562, 2023.

Jollivet Didier, and others. Preferential pathways of dispersal and role of the AMOC in connectivity. Ref. WP1. iAtlantic Deliverable 1.5. iAtlantic. 2024.

Jones, McKenzie Margaret. Global and Regional Variations in Methane Seep Communities MSc Thesis, Victoria University of Wellington. 118 pp., 2023.

Juniper, S. Kim, and others. Remote monitoring of a deep-sea marine protected area: The Endeavour Hydrothermal Vents. Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 29, pp. 84-102, 2019.

Klunder, Lise and others. A molecular approach to explore the background benthic fauna around a hydrothermal vent and their larvae: Implications for future mining of deep-Sea SMS deposits. Frontiers in Marine Science, vol. 7, 10.3389/fmars.2020.00134, 2020.

Le, Jennifer Tran., and others. Using deep-sea images to examine ecosystem services associated with methane seeps, Marine Environmental Research, vol. 181, art. 105740, 2022.

Le Bris, Nadine and others. The First World Ocean Assessment - WOA I _Chapter 45. Hydrothermal vents and cold seeps. 2017.

Le Bris, Nadine and others. The Second World Ocean Assessment - WOA II_Chapter 7P: Hydrothermal vents and cold seeps. 2021.

Lecoeuvre, Aurelien, and others. Microbial ecology of the newly discovered serpentinite-hosted Old City hydrothermal field (southwest Indian ridge). The ISME journal, vol. 15, No. 3, art. 818-832, 2021.

Levin Lisa A, and others. Climate change considerations are fundamental to management of deep-sea resource extraction. Global Change Biology, vol. 26, art. 4664, 2020

Linse, Katrine, and others. Megabenthos habitats influenced by nearby hydrothermal activity on the Sandwich Plate, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, vol. 198, art. 105075, 2022

MacDonald, Ian R., and others. The asphalt ecosystem of the Southern Gulf of Mexico: Abyssal habitats across space and time. In: Murawski, S., et al. Scenarios and Responses to Future Deep Oil Spills. Springer, Cham, pp. 132-146, 2020

Marticorena, Julien, and others. Recovery of hydrothermal vent communities in response to an induced disturbance at the Lucky Strike vent field (Mid-Atlantic Ridge). Marine Environmental Research, 168, art. 105316, 2021.

Mazumdar, Asis, and others. The first record of active methane (cold) seep ecosystem associated with shallow methane hydrate from the Indian EEZ. *Journal of Earth System Science, vol.* 128, pp.1-8, 2019.

McDermott, Jill M., and others. Discovery of active off-axis hydrothermal vents at 9 54′ N East Pacific Rise. Proceedings of the National Academy of Sciences, vol. 119, No. 30, art. e2205602119, 2022

Menini, Elisabetta, and others. Towards a global strategy for the conservation of deep-sea active hydrothermal vents. npj Ocean Sustainability, vol. 2, No. 1, p.22, 2023.

Methou, Pierre, and others. Genetic connectivity and isotopic niches of alvinocaridid shrimps from chemosynthetic habitats in Aotearoa/New Zealand, with a new *Alvinocaris* species. Marine Ecology Progress Series, vol. 739, pp. 85-109, 2024.

MSG Secretariat, 2020. https://msgsec.info/wp-content/uploads/documentsofcooperation/2023-Aug-24-UDAUNE-DECLARATION-on-Climate-Change-by-Members-of-MSG.pdf

Monga Bay, 2024. https://news.mongabay.com/2024/09/not-merely-exploration-png- deep-sea-mining-riles-critics-surprises-officials/

Morato, Telmo, and others. Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. Global Change Biology, vol. 26, art. 2181, 2020.

Murdock, Sheryl A., and others. Emergent “core communities” of microbes, meiofauna and macrofauna at hydrothermal vents. ISME Communication vol. 1, art 27, 2021.

Neufeld, Monika and others.Non-vent megafaunal communities on the Endeavour and Middle Valley segments of the Juan de Fuca Ridge, Northeast Pacific Ocean. Frontiers in Marine Science, vol. 9, art. 849976, 2022

Olu, Karine, and others. Biogeography and potential exchanges among the Atlantic Equatorial Belt cold-seep faunas. PLOS One, vol. 5, art. e11967, 2010.Paduan, Jennifer B., and others. Discovery of hydrothermal vent fields on Alarcón Rise and in southern Pescadero Basin, Gulf of California. Geochemistry, Geophysics, Geosystems, vol. 19, pp. 4788–4819, 2018.

Park, Byeongyong, and others. Microplastic contamination of a benthic ecosystem in a hydrothermal vent. Environmental Science and Technology, vol. 58, pp. 7636–7642, 2024.

Parsons Patrice, K.F., and others. Hydrothermal seepage of altered crustal formation water seaward of the Middle America Trench, offshore Costa Rica. Geochemistry, Geophysics, Geosystems, vol. 25, art. e2023GC011246, 2024.

Pereira, Olívia Soares and others. The dynamic influence of methane seepage on macrofauna inhabiting authigenic carbonates. Ecosphere vol. 12, No. 10, art 303744, 2021.

Pereira, Olivia Soares, and others. Understanding and valuing human connections to deep-sea methane seeps off Costa Rica. Ecological Economics, vol 223, art. 108228, 2024.

Pereira, Olivia Soares. Diversity and trophic dynamics, resilience, and value of hardground invertebrates at methane seeps and on mineral-rich slopes in the deep Eastern Pacific. PhD Dissertation. University of California, San Diego., La Jolla, California, 2024.

Quattrini Andrea M, and others. Exploration of the canyon-incised continental margin of the Northeastern United States reveals dynamic habitats and diverse communities. PLoS ONE vol. 10, No. 10, art. e0139904, 2015

Rakka, Maria, and others. Embryo and larval biology of the deep-sea octocoral Dentomuricea aff. meteor under different temperature regimes. Peer J, vol. 9, 2021.

Rarez-Llodra, Eva, and others. Deep, diverse and definitely different: unique attributes of the world's largest ecosystem, Biogeosciences, vol. 7, art. 2851-2899, 2010.

Ramirez-Llodra, Eva, and others. The emerging picture of a diverse deep Arctic Ocean seafloor: From habitats to ecosystems. Elementa: Science of the Anthropocene, vol. 12, No. 1, 2024.

Rodruiguez-Flores, Paula Carolina, and others. Integrative taxonomy reveals a new species of deep-sea squat lobster (Galatheoidea, Munidopsidae) from cold seeps in the Gulf of Mexico. Zoosystems Evolution, vol. 100, pp. 1243-1257, 2024. Ross, Tetyana., and others. Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. Global Change Biology, vol. 26, No. 11, pp. 6424-6444, 2020.

Ruffine, Livio, and others. Environmental challenges related to methane hydrate decomposition from climate change scenario and anthropic activities: State of the art, potential consequences and monitoring solutions. Earth-Science Reviews, vol. 246, art. 104578, 2023.

Ruppel, Carolyn D., and others. Methane seeps on the U.S. Atlantic margin: An updated inventory and interpretative framework. Marine Geology,vol. 471, art. 107287, 2024.

Ryu, Taewoo, and others. The first reference transcriptome assembly of the stalked barnacle, *Neolepas marisindica*, from the Onnuri Vent Field on the Central Indian Ridge. Marine Genomics, vol. 48, art. 100679, 2019.

Sahlström, Fredrik, and others. Mineralogical distribution and genetic aspects of cobalt at the active Fåvne and Loki's Castle seafloor massive sulfide deposits, Arctic Mid-Ocean Ridges. Ore Geology Reviews, vol. 153, art. 105261, 2023.

Sangodkar, Nitisha, and others. Macrofaunal distribution, diversity, and its ecological interaction at the cold seep site of Krishna-Godavari Basin, East Coast of India. Microbial Ecology, vol. 85, No. 1, art. 61-75, 2023.

Seabrook, Sarah, and others. Emergent Antarctic seafloor seeps: A tipping point reached? ResearchSquare, 2023. DOI: https://doi.org/10.21203/rs.3.rs-3657723/v1.

Seabrook, Sarah, and others. Ubiquitous but unique: Water depth and oceanographic attributes shape methane seep communities. Limnology and Oceanography, vol. 69, No. 5, pp. 1218-1232, 2024.

Sen, Arunima, and others. Atypical biological features of a new cold seep site on the Lofoten-Vesterålen continental margin (northern Norway). Scientific Reports, vol. 9, No. 1, art. 1762, 2019.

Serov, Pavel, and others. Geological and glaciological controls of 21,700 active methane seeps in the northern Norwegian Barents Sea. Frontiers in Earth Science, vol. 12, art. 1404027, 2024.Soule, Samuel Adam, and others. Exploration of the northern Guaymas Basin. Oceanography, vol. 31, No. 1, pp.39-41, 2018.

Stensland, Anne, and others. He along the ultraslow spreading AMOR in the Norwegian-Greenland Seas. Deep Sea Research Part I: Oceanographic Research Papers, vol. 147, pp. 1-11, 2019.

Sun, Jin, and others, Nearest vent, dearest friend: biodiversity of Tiancheng vent field reveals cross-ridge similarities in the Indian Ocean. Royal Society Open Science, vol. 7, No. 3, art. 200110, 2020.

Taylor James, and others. The discovery and preliminary ecological and faunal descriptions of three new Steinahóll vent sites, Reykjanes Ridge, Iceland. Frontiers in Marine Science, vol. 8 art. 520713, 2021.

Teng, Jia, and others. First record of microplastics in *Gigantidas platifrons* (Mytilidae: Bathymodiolus) and *Shinkaia crosnieri* (Munidopsidae: Shinkaia) from a cold-seep in the South China Sea. Marine Pollution Bulletin, vol. 185, art. 114523, 2023.

Thomas, Elin A., and others. A global Red List for hydrothermal vent molluscs. Frontiers in Marine Science, vol. 8, art. 13022, 2021.

Tunnicliffe, Verena and others. Hydrothermal vent fauna of the western Pacific Ocean: Distribution patterns and biogeographic networks. Diversity and Distributions, vol. 30, No. 2, art. 313794, 2023.

Turner, Phillip, J., and others. Methane seeps on the US Atlantic margin and their potential importance to populations of the commercially valuable deep-sea red crab, *Chaceon quinquedens*. Frontiers in Marine Science, vol.7, art.75, 2020.

Van Audenhaege, Loïc., and others. 2024. Monitoring ecological dynamics on complex hydrothermal structures: A novel photogrammetry approach reveals fine-scale variability of vent assemblages. Limnology and Oceanography, vol. 69, No. 2, pp. 325-338, 2024.

Van der Zwan, Froukje M., and others. Widespread diffuse venting and large microbial iron-mounds in the Red Sea. Communications Earth & Environment, vol. 4, no. 1, art.496, 2023.

Van Dover, Cindy L., and others. Research is needed to inform environmental management of hydrothermally inactive and extinct polymetallic sulfide (PMS) deposits. Marine Policy, 121, art. 104183, 2020.

van Putten, E. Ingrid, and others. History matters: societal acceptance of deep-sea mining and incipient conflicts in Papua New Guinea. Maritime Studies, vol. 22, No. 3, art. 32, 2023.

Vega, Pedro, J.S., and others. Convolutional neural networks for hydrothermal vents substratum classification: An introspective study. Ecological Informatics, vol. 80, art.102535, 2024.

Versteegh, Emma A., and others. Multiple nutritional strategies of hydrothermal vent shrimp (*Rimicaris hybisae*) assemblages at the Mid-Cayman Rise. Deep–Sea Research, vol. 192, art. 103915, 2023.

Vrolijk Peter, and others. Using a ladder of seeps with computer decision processes to explore for and evaluate cold seeps on the Costa Rica active margin. Frontiers In Earth Science, vol. 9, art. 601019, 2021.

Waghorn, Kate, and others. Svyatogor Ridge—A Gas Hydrate System Driven by Crustal Scale Processes. *World Atlas of Submarine Gas Hydrates in Continental Margins*, pp. 247-254, 2022.

Watanabe, Hiromi and Takehisa Yamakita. Designation of offshore seafloor Natural Environment Conservation Area in the Japanese EEZ. Deep-Sea Life, 18, p. 22. 2022. https://www.dosi-project.org/wp-content/uploads/DSL18_final.pdf

Workman, Evelyn, and others. Methane emissions from seabed to atmosphere in polar oceans revealed by direct methane flux measurements. Journal of Geophysical Research: Atmospheres, vol. 129, art. e2023JD040632, 2024.

Zeng, Xiang, and others. Genome sequencing of deep-sea hydrothermal vent snails reveals adaptations to extreme environments. GigaScience, vol. 9, No. 12, art. Giaa139, 2020.

Zhou, Yadong, and others. Delineating biogeographic regions in Indian Ocean deep-sea vents and implications for conservation. Diversity and Distributions, vol. 28, No. 12, pp. 2848-2870, 2022.

Section 4

Sub- chapter 5q: Sargasso Sea

Keynote points

- The Sargasso Sea is an iconic high seas ecosystem internationally recognized as a fundamentally important part of the global ocean.
- The Sargasso Sea has been consistently identified as an area of the high seas that would benefit from internationally legally binding protection (IUCN 2008; UNESCO 2016–). The adoption of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement) on 19 June 2023 (A/CONF.232/2023/4) provides an opportunity to further this ambition.
- *Sargassum* continues to inundate beaches in more southern latitudes, and new research suggests these blooms are driven by anthropogenic nutrient inputs into the system.
- The first satellite-tagging evidence of the European eel migrating to the Sargasso Sea emphasizes the importance of the area for these economically important fish. An increased understanding of the ecology of commercial tuna and tuna-like species and awareness of the use of the area by endangered and threatened species is increasing the need for EAFM (ecosystem approach to fisheries management).
- Ship traffic has increased on the Sargasso Sea over time and de facto shipping routes have been established by shipping companies. This increased traffic carries risks to cetaceans of collisions and noise pollution.
- The increasing activity in the Sargasso Sea demonstrates the importance of addressing the cumulative impacts of human activities on the high seas.

Introduction and context

The present chapter builds on developments and knowledge of the previous baseline state as reported in chapter 50 of the first WOA and chapter 7Q of the second WOA (United Nations, 2016; 2021), and summarised in this section. The oceanography of the Sargasso Sea within the North Atlantic Gyre is well understood from two of the longest-running time series of oceanographic data, Hydrostation S and the Bermuda Atlantic Time-series Study (BATS).

The Sargasso Sea supports a unique surface ecosystem based upon floating aggregations of two species of *Sargassum (S. natans and S. fluitans)* and their role as feeding and nursery areas for pelagic fishes, juvenile

turtles (for more information see WOA chapter 4f) and seabirds (for more information see WOA chapter 4g). The Sargasso Sea is the only known spawning area for the European eel (*Anguilla anguilla*) and the American eel (*Anguilla rostrata*). The Sargasso Sea acts as a migratory corridor for several species of sharks, rays, turtles and cetaceans. A number of the species inhabiting the Sargasso Sea are endangered or threatened.

The Sargasso Sea remains a fundamentally important part of the global ocean due to the ecosystems it supports and its role in global-scale ocean processes, particularly in carbon sequestration. It contributes significantly to local as well as global economies both directly from fisheries for highly migratory species (tunas, swordfish) and harvesting of Anguillid eels, whale and turtle tourism, and indirectly from its role in climate regulation, conservation of genetic diversity and nutrient cycling (Laffoley and others, 2011; Pendleton and others, 2015). It is threatened by climate change, pollution, increased fishing effort, and international shipping.

The conservation work of the Sargasso Sea project began in 2010, but it has been boosted recently by two major grants: the GEF-UNDP-IOC project (under the FAO Common Oceans Program) on “Strengthening the stewardship of an economically and biologically significant high seas area – the Sargasso Sea", and the FFEM SARGADOM project are financing a socio-ecosystem diagnostic analysis (SEDA) that underpins this chapter. In addition, the significance of the BBNJ Agreement is outlined, including the Agreement’s impact on the conservation of the Sargasso Sea.

Description of environmental change since the second World Ocean Assessment

Location

The Sargasso Sea is a pelagic ecosystem bounded by the currents of the North Atlantic gyre. The Sargasso Sea Commission acts as steward of the ecosystem under an area of collaboration defined in the 2014 Hamilton Declaration. New work from the Duke University Marine Geospatial Ecology Laboratory emphasizes the dynamic nature of the Sargasso Sea, represented by a ‘maximum feature extent’ with shared biogeographical characteristics (Cleary and others 2023) (see Figure 4.5q.1).

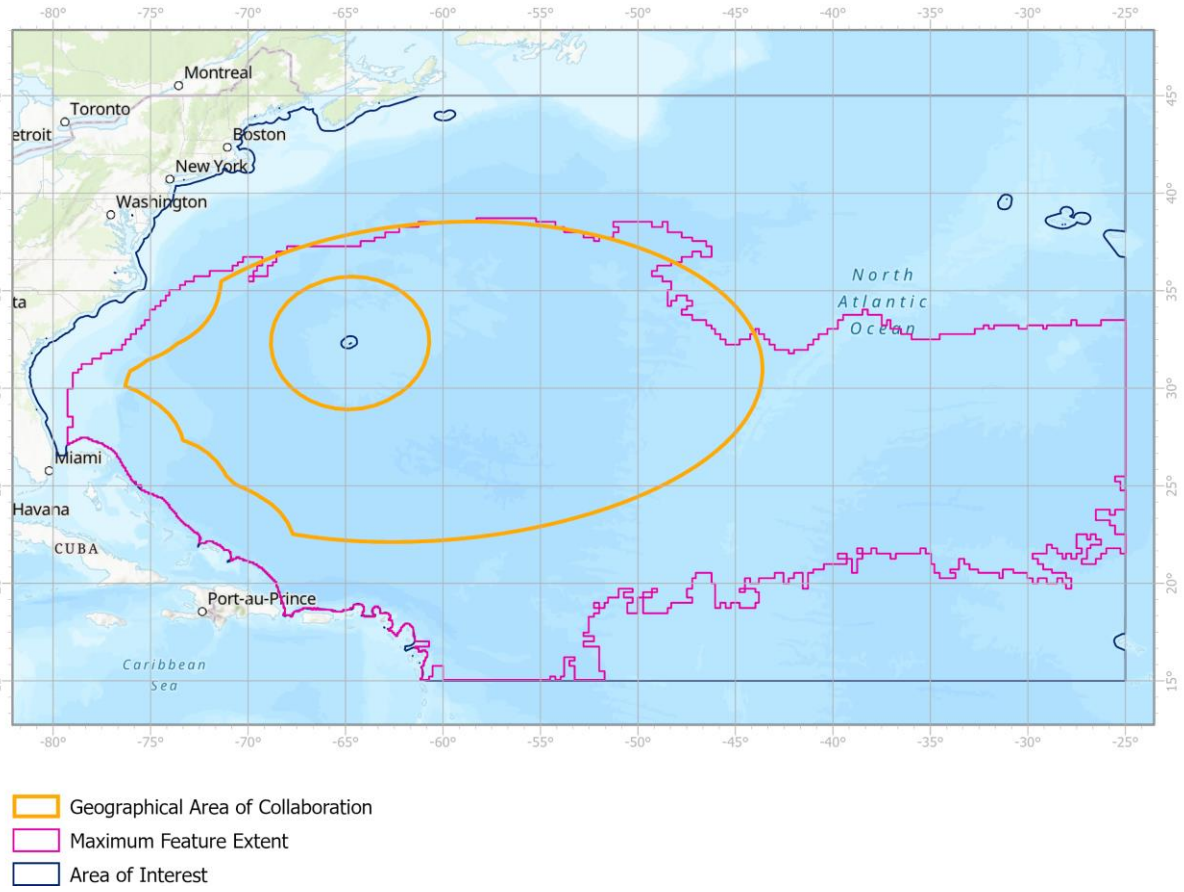


Figure 4.5q.1. For more information on how the figure was created, see Cleary and others 2023 and Smith and others 2023. Credit Smith and others 2023.

Ocean time series

Continued monitoring of the Sargasso Sea from Hydro-station S and BATS (which are long-standing ocean quality monitoring sites) has shown that the last forty years have seen significant surface ocean warming of ~1.2°C, lengthening of summertime and shortening of wintertime conditions, slow-down of subtropical mode water formation, salinification due to reorganization of the global water cycle, and uptake of anthropogenic carbon dioxide such that ocean acidification in the 2020s of the Sargasso Sea are outside the range observed in the 1980s and before (Bates and Johnson, 2020, 2023; Stevens and others, 2020). Marine photosynthesis has also changed with knock on effects for the higher trophic level ecology of the Sargasso Sea (Lomas and others, 2022), and the marine ecosystem may have also changed in concert with these physical changes (Bates and others, 2023).

In terms of chemical oceanography, since the late 1980s, waters in this subtropical region of the North Atlantic Ocean have lost oxygen at a rate of ~2% per decade (~8% over the past 40 years) (Bates and Johnson, 2020; Bates and Johnson, 2023). From the early 2000s to the present, rates of primary production have decreased by >25% (Lomas and others, 2022; D'Alelio and others, 2020). Notably, over the past several decades, carbon export to the deep ocean has remained steady while primary production has decreased (Lomas and others, 2022) with significant changes in ecosystem community structure (Bates and others, 2023).

Sargassum

More broad information on algae can be found in WOA III chapter 4i. Increased sea surface temperature has implications for the *Sargassum* ecosystem. Graba-Landry and others (2020) showed that elevated temperature impacts the survival of a *Sargassum* algae (S. swartsii) and while it remains to be seen specifically how temperature impacts the two dominant *Sargassum* species of the Sargasso Sea, warming patterns revealed in the analyses suggest broader implications for the integrity of *Sargassum* mats (Graba-Landry and others, 2020).

Although *Sargassum* supports a thriving ecosystem in the Sargasso Sea, it has economic and ecological impacts when it inundates beaches, as discussed in the 2016 and 2021 WOA chapters. Blooms of *Sargassum* in the North Equatorial Recirculation Region (NERR) are hypothesized to be linked to anthropogenic nutrient inputs into the ocean via the Orinoco and Amazon Rivers, and anthropogenic climate change (McGillicuddy and others, 2023).

Sargassum in the NERR is morphologically different from the *Sargassum* in the Sargasso Sea (Alleyne and others, 2023). *S. natans I* and *S. fluitans III* are the most predominant variations in the Sargasso Sea, while *S. natans VIII* is the most predominant in the NERR - and this morphological type has also been found to support a less diverse rafting community (Schell and others, 2015), which could threaten the Sargasso Sea if *S. natans VIII* eventually invades a more northern area.

Fisheries

More broad information on medium and large scale fisheries can be found in WOA III chapter 1a. The first direct evidence of European eel migration to the Sargasso Sea using satellite tags was published in 2022

(Wright and others). Interest in the conservation and sustainable management of the species continues to grow due to its economic importance for human consumption.

The Western Central Atlantic Ocean is among the least fished UNFAO Fishing Areas in the world (Figure 4.5q.2). The landing volume and value in this portion of the high seas since 2010 has remained relatively low and stable, where catches consist of large pelagic species, primarily albacore tuna, swordfish and blue sharks. The Sargasso Sea only represents 0.47% of the volume of fisheries catches across the International Convention for the Conservation of Atlantic Tuna (ICCAT) convention area (Vousden, and others, forthcoming). ~~The Taiwanese and Spanish distant-water pelagic longline fleets and the US Atlantic pelagic longline fleet accounted for 81% of the landings in the Sargasso Sea between 2010-2021 (Vousden, and others, forthcoming).~~

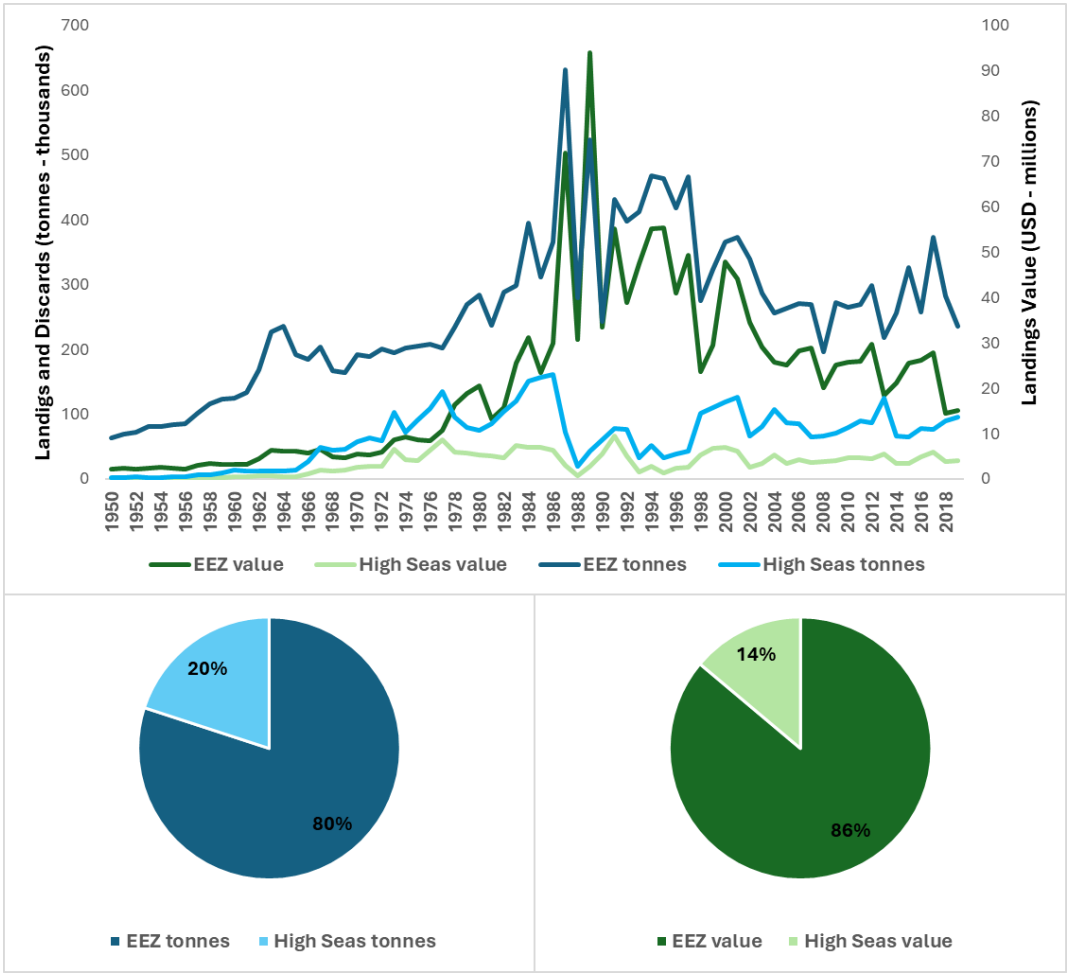


Figure 4.5q.2*: fisheries landings volume and value in UNFAO Fishing Area 31 across the High Seas and the Exclusive Economic Zones (1950-2019). Source: Sea Around Us (https://www.seaaroundus.org/).*

The US Atlantic pelagic longline fleet generated around US$10 million in profit without subsidies. However, without subsidies, the Spanish pelagic longline fleet would have lost between US$1.5 and 2.78m, without subsidies, the other fleets would have lost between US$4.49 -US$7.25 million a year.

~~, and the Taiwanese pelagic longline fleet some US$2.99-4.47 million a year (estimates from Sala and others, 2018).~~ The majority of fishing in Sargasso Sea seems to be unprofitable without subsidies.~~.~~

The Northwest Atlantic Fisheries Organization (NAFO) has extended the closure of seamounts in the northwest sector of the Sargasso Sea to bottom trawling until 2026. This closure was first introduced in 2007, with the closure being enlarged in 2022 to include all the Corner Rise seamounts. An adjacent advisory closure in the WECAFC area was adopted in 2016 (WECAFC, 2016).

~~In 2007 Northwest Atlantic Fisheries Organization (NAFO) closed the seamounts in the northwest sector of the Sargasso Sea to bottom trawling. In 2016, the closure area was extended to cover the Corner Rise seamounts and the exploratory fishing exception was removed. In 2022 this ban was extended in 2026 (NAFO, 2021).~~

The Subtropical Convergence Zone (STCZ) where warm and cold water masses meet, occurs between 22° and 30°N in the southern sector of the Sargasso Sea and has been shown to be a significant seasonal spawning area for three species (albacore tuna, swordfish, white marlin) managed by ICCAT (Luckhurst and Arocha, 2015), and important areas for the reproductive cycle of blue marlin and porbeagle shark (Luckhurst and others, 2006; Campana and others, 2010). The first record of eggs and juveniles of the rare roundscale spearfish in the Sargasso Sea was reported by Freese and others in January 2025.

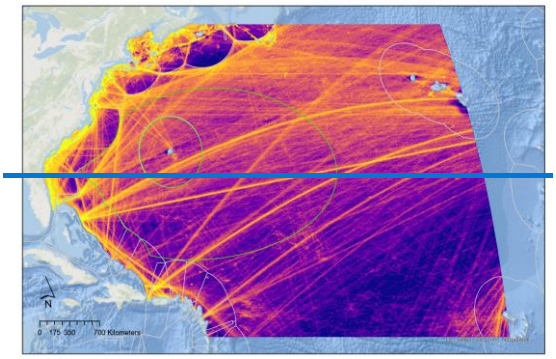
Deep sea

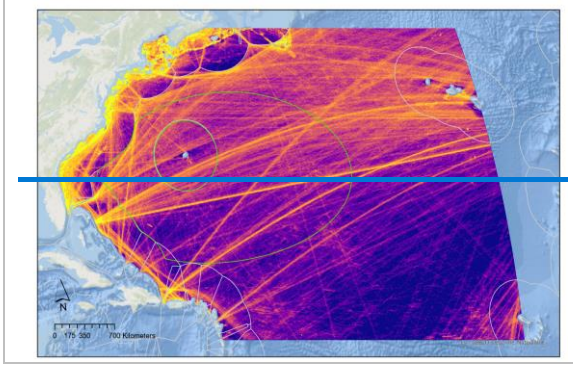
Pioneering scientific studies in the northwestern margins of the Sargasso Sea have been pivotal in understanding patterns of abundance, biomass and diversity in deep-sea ecosystems. Below the epipelagic zone sampling of mesopelagic and bathypelagic communities of fish suggests they may form a single Central North Atlantic province spanning the entire Sargasso Sea (Backus and others, 1977). Benthic communities show a decline in abundance and biomass with depth (Sutton and others, 2010). Falling Sargassum affects the deep sea ecosystem and some organisms are specially adapted to feed on this macroalgae (Peoples and others, 2024). Coral and sponge habitats on seamounts are associated with distinct communities of fish and other associated organisms.

France, Russia and Poland have mining exploration contracts awarded by the International Seabed Authority for seabed massive sulphides on the Mid-Atlantic Ridge (https://www.isa.org.jm/exploration-contracts/). Active vents in this region are often associated with vent-endemic fauna. The Lost City site is a unique hydrothermal vent system and may be of high scientific importance as the physico-chemical conditions may resemble those of the ancient Earth when genesis of life occurred (Johnson, 2019; Brazelton and others, 2022). Documentation of the species and ecology of each active vent ecosystem and surrounding non-vent ecosystems which are currently unexplored, will be required before management plans can be designed for potential mining of any of these sites, in accordance with the draft ISA Regional Environmental Management Plan.

Shipping

Vessel traffic in the Sargasso Sea ranges from highly concentrated shipping routes across the middle North Atlantic to the less intensively occupied fishing grounds around the Gulf of Maine and the coast of Labrador (Figure 4.5q.3).





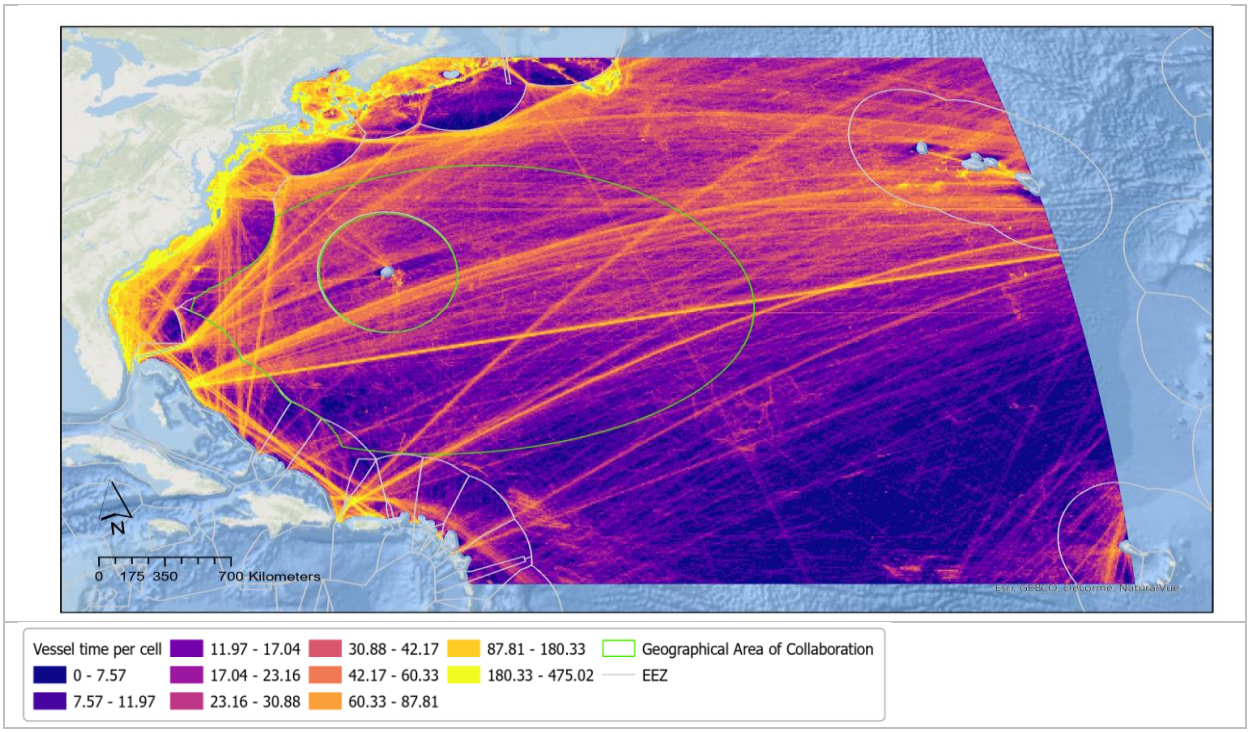


Figure 4.5q.3. *Summary of vessel traffic (vessel time in hours) in2021 (. Credit Smith and others, 2023.*

Several corridors experiencing particularly high vessel volume can be identified consistently across time (Smith and others, 2023). Vessels transiting these the major routes connect ports primarily in the U.S., United Kingdom, Panama, the Netherlands, Spain, Gibraltar and Egypt (Smith and others, 2023).

With the presence of these prominent vessel traffic lanes through the center of the Sargasso Sea, it is important to consider the potential environmental impacts of this traffic for cetaceans, many species of which are known to migrate through the area, especially humpback whales – including effects from noise pollution and collisions (see Smith and others, 2023, and reference to Important Marine Mammal Areas (IMMA) below).

Institutional arrangements and partnerships

High seas ocean governance is more fully explored in WOA III section 3 – Ocean Governance. As outlined in the 2021 WOA chapter, the Sargasso Sea faces a unique challenge in its conservation: it is located in an area beyond national jurisdiction (ABNJ). The Sargasso Sea Commission was established pursuant to the 2014 Hamilton Declaration on Collaboration for the Conservation of the Sargasso Sea to fill this lacuna in

the regime. It has 10 Government Signatories[24] who are pledged to work collaboratively to conserve the iconic ecosystem of the Sargasso Sea.

The BBNJ Agreement represents a major change in the international legal landscape for the high seas since the inception of the Sargasso Sea project in 2010. The Agreement opens up a new pathway for ~~internationally recognized~~ Area-Based Management Tools (including marine protected areas) for the high seas.

The UNDP GEF-IOC/FFEM supported Socio-Ecosystem Diagnostic Analysis (SEDA) for the Sargasso Sea – the first for a high seas ecosystem – will provide the basis for a Strategic Action Programme (SAP) for the Sargasso Sea. The SAP will reflect the agreement of the Sargasso Sea stakeholders on a mechanism for more effective stewardship and conservation of this unique ecosystem.

The 2011 description of the Sargasso Sea as an ecologically or biologically significant area (EBSA) is a scientific determination but hopes that States and competent international organizations would utilize it to deliver conservation benefits, have not materialized (Roe and others, 2022). Nevertheless, the Sargasso Sea Commission's achievements are still considerable (Freestone, 2021). In 2023 the Commission cohosted with IMO a workshop on Particularly Sensitive Sea Areas (PSSAs) on the high seas, an IMO tool designed to reduce pressures from international shipping. In 2024 it supported an IUCN/International Marine Mammal Area (IMMA) workshop resulting in the designation of an important humpback whale north/south migratory corridor across the North Atlantic as an IMMA in 2025. The Convention on Migratory Species (CMS) is developing a single species action plan for the European eel, in consultation with Range States and relevant IGOs and NGOs, as per mandate from COP14 (Decision 14.109).[25] ~~The Convention on Migratory Species COP has also mandated the Commission to develop a single species action plan for the European eel.~~ Under the FFEM SARGADOM project, the Commission is developing tools for remote monitoring of the high seas with partners including Global Fishing Watch (Freestone, 2024).

[24] The Azores, The Bahamas, Bermuda, British Virgin Islands, Cayman Islands, Canada, Dominican Republic, Monaco, United Kingdom and the United States.

[25] At CMS COP 14~~3~~ in Samarqand, Uzbekistan, February 2024. Decision 14.109. ~~Gandhinagar, India, February 2020. UNEP/CMS/COP13/Doc.26.2.9~~https://www.cms.int/sites/default/files/document/cms_cop14_decisions_e.pdf

Remaining key knowledge and capacity changes and any new gaps

Climate change and its accompanying effects of ocean acidification and changes to ocean circulation (for eg Ditlevsen and Ditlevsen 2023) are the impacts with the furthest reaching consequences for the Sargasso Sea, which could fundamentally change the Sargassum ecosystem and affect the distribution of larvae and the migration of fish and other species. Plastics and other pollutants are also a constant threat.

Fishing effort remains low in the Sargasso Sea, but research shows most fishing activity requires heavy subsidies to reach the area (Vousden, and others, forthcoming). Anguillid eels remain economically important, but mostly encounter threats during the inshore stage of their life cycle.

Ship traffic has increased on the Sargasso Sea over time and de facto shipping routes have been established by shipping companies. With the risk of ship strikes to cetaceans, more research and discussion are needed on the impacts of international shipping in the Sargasso Sea, and the need and/or feasibility of conservation measures related to international shipping in the area.

Gaps in knowledge for the area include bycatch, IUU, movements of highly migratory species, plastics, impacts from deep sea mining and deep sea ecology. The cumulative impacts of all threats to the Sargasso Sea discussed are likely to combine to be greater than the sum of their parts, and the full effects of cumulative impacts are unknown.

The BBNJ Agreement represents a seismic shift in the international regime for the high seas, with the potential to streamline the conservation of the Sargasso Sea. While area-based management tools do not necessarily protect against non-spatial threats, they can remove anthropogenic pressures on the ecosystem, providing greater resilience in a changing climate, and increasing the potential for sustainable ecosystem benefits.

Citations

Alleyne, Kristie S. T., and others. Seasonal variation in morphotype composition of pelagic Sargassum influx events is linked to oceanic origin. Scientific Reports, vol 13, art 3753, 2023.

Backus, R. H., and others. Atlantic mesopelagic zoogeography. Pt. 7. Order Iniomi (Myctophiformis)., Fishes of the Western North Atlantic. R. H. Gibbs, ed-in-chief.Mem. Sears Fdn. Mar. Res., 1:266-287., 1977.

Bates, Nicholas R., and Johnson, Rodney J. Acceleration of ocean warming, salinification, deoxygenation and acidification in the surface subtropical North Atlantic Ocean. Nature Communications in Earth and Environment, vol 1, no 33, 2020

Bates, Nicholas R., and Johnson, Rodney J. Forty years of ocean acidification observations (1983-2023) in the Sargasso Sea at the Bermuda Atlantic Time-series Study (BATS) site. Frontiers in Marine Science, vol 10, 2023.

Bates, Nicholas R., and others. Oceanography of the Sargasso Sea: An update concerning the scientific case for protection of the Sargasso Sea. 2023.

BBNJ Agreement. 2023. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (New York, 17 June 2023, not yet in force) UN Doc A/CONF.232/2023/4* (19 June 2023).

Brazelton, William J., and others, 2022. Metabolic Strategies Shared by Basement Residents of the Lost City Hydrothermal Field. Applied Environmental Microbiology. Vol 13, iss 88. 2022.

Campana, Steven E, and others. Subtropical pupping ground for a cold-water shark. Journal of Fisheries and Aquatic Sciences, vol 67, pp. 769-773, 2010.

Cleary, Jesse, and others. Preparatory Data Discovery and Analysis to Support Enhanced Management and Governance of the Sargasso Sea: A Description of the Feature in Space and Time. A Report Submitted to Sargasso Sea Commission. Duke Marine Geospatial Ecology Lab, 2023.

D'Alelio, Domenico and others. Machine learning identifies a strong association between warming and reduced primary productivity in an oligotrophic ocean gyre. Scientific reports, vol **10**, art 3287, 2020.

Ditlevsen, P., and Ditlevsen, S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications* vol 14, art 4254, 2023.

Freese, Marko, and others. Genetically confirmed first records of an egg and a juvenile roundscale spearfish, *Tetrapturus georgii*. Journal of Fish Biology, 2025.

Freestone, David. The Sargasso Sea Commission: An Evolving New Paradigm for High Seas Ecosystem Governance? Frontiers in Marine Science 8:668253, 2021. doi: 10.3389/fmars, 668253 1-10, 2021.

Freestone, David, and others. High Seas in the Cloud: The Role of Big Data and Artificial Intelligence in supporting High Seas Governance – The Sargasso Sea Pilot Project. Frontiers of Marine Science: Policy and Practice Reviews, 1-13, 2024.

Graba-Landry, Alexia, and others. Impaired growth and survival of tropical macroalgae (*Sargassum* spp.) at elevated temperatures. Coral Reefs, vol 39, pp. 475–486, 2020.

IUCN. High Seas Gems: Hidden Treasures of Our Blue Earth, 2008 https://iucn.org/sites/default/files/import/downloads/high_seas_gems_booklet_finaloct08.pdf

Johnson, David E. Protecting the lost city hydrothermal vent system: All is not lost, or is it? Marine Policy 103593. 2019

Laffoley, Dan, and others. The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic. 2011.

Lomas, Michael W., and others. Adaptive carbon export response to warming in the Sargasso Sea. Nature Communications, vol 13, art 1211, 2022.

Luckhurst, Brian E, .and Arocha, Freddy. Evidence of spawning in the southern Sargasso Sea of fish species managed by ICCAT – albacore tuna, swordfish and white marlin. Collection Volume of Scientific Papers ICCAT, vol 72 no 8, pp. 1949 – 1969, 2016.

Luckhurst, Brian, E., and others. Evidence of blue marlin (*Makaira nigricans*) spawning in Bermuda waters and elevated mercury levels in large specimens. Bulletin of Marine Science, Vol 79, pp. 691–704, 2006.

McGillicuddy, Dennis J., and others. Nutrient and arsenic biogeochemistry of Sargassum in the western Atlantic. Nature Communications, vol 14, art 6250, 2023.

NAFO. NAFO Agrees to Further Measures to Protect Vulunerable Marine Ecosystems (VMEs) at its 43rd Annual Meeting. https://www.nafo.int/Portals/0/PDFs/press/pressrelease_AM2021.pdf?fbclid=IwAR090SGcDplB6jeXJb8CZlZ4qEgujuuofqdm2zRZsvcjyAFHSqo2wG4U-dk 2021.

Pendleton, Linwood, and others. Assessing the value of marine and coastal ecosystem services in the Sargasso Sea. 2014.

Peoples, Logan M., and others. A deep-sea isopod that consumes Sargassum sinking from the ocean's surface. Royal Society. Vol 291, iss. 2030. 2024.

Roe, Howard S. and others. The Sargasso Sea High Seas EBSA After Ten Years: Is It Still Relevant and How Has It Helped Conservation Efforts?. Frontiers in Marine Science, vol 9, 2022.

Sala, Enric and others. The economics of fishing the high seas. Science advances, vol 4 issue 6, 2018.

Sargasso Sea Commission. The Hamilton Declaration. https://www.sargassoseacommission.org/meet-the-commission/hamilton-declaration 2014.

Schell, Jeffrey M., and others. Recent Sargassum Inundation Events in the Caribbean: Shipboard Observations Reveal Dominance of a Previously Rare Form. Oceanography vol 28, no 3, 2015.

SeaAroundUs. We present fisheries and fisheries-related data at spatial scales that have ecological and policy relevance, such as by Exclusive Economic Zones, High Seas, or Large Marine Ecosystems. https://www.seaaroundus.org/ 2024.

Smith, Beatrice and others. Preparatory Data Discovery and Analysis to Support Enhanced Management and Governance of the Sargasso Sea: A Technical Report on the State of the Ecosystem and Human Use Pressures. Duke Marine Geospatial Ecology Lab. 2023.

Stevens, Samuel W., and others. A recent decline in North Atlantic subtropical mode water formation. Nature Climate Change, vol 10, art 4, pp. 335-341, 2020.

Sutton, Tracey T., and others. Diversity and community structure of pelagic fishes to 5000 m depth in the Sargasso Sea. Deep Sea Research Part II: Topical Studies in Oceanography. Vol 57, iss. 24-26, 2010.

UNESCO. World Heritage in the High Seas: An Idea Whose Time Has Come. World Heritage Report 44, 2016.

Vousden, David, and others. Socio-ecosystem diagnostic analysis for the Sargasso Sea. Forthcoming.

Wright Rosalind M, and others. First direct evidence of adult European eels migrating to their breeding place in the Sargasso Sea. Sci Rep vol 12, art 15362, 2022.

Western Central Atlantic Fishery Commission. Recommendation WECAFC/16/2016/4. Report of the Sixteenth session of the Commission Guadeloupe, 20–24 June 2016. Food and Agriculture Organization of the United Nations Subregional Office for the Caribbean. FAO Fisheries and Aquaculture Report Nº 1162. Bridgetown, Barbados, FAO. 137 pp.

~~aotFAO Fisheries and Aquaculture Report Nº 1162. Bridgetown, Barbados, FAO. 137 pp.~~

Section 4
Sub-chapter 5r: Fjord systems

1 Keynote points

- Fjords are ecologically carbon organic-rich regions and home to Indigenous Peoples and local communities.

- Global warming is already affecting both northern and southern hemisphere fjords (via warming, deoxygenation and acidification).

- The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors and processes in Fjords systems.

2 Introduction

The fjord systems of the world are characterized by a deep basin connecting directly or indirectly with the open sea at the mouth (Matthews and Heimdal, 1980). Fjords are often long, narrow, deep, and steep-sided inlets, frequently branched and sinuous, or straight, and may contain one or more submarine sills (a shallow dome of bedrock that forms at the mouth of a fjord)). The presence and size of these sills at the fjord's mouth can restrict the exchange of water between the fjord and the coastal ocean, often leading to highly stratified conditions that result in low-oxygen bottom waters. Main fjord regions occur along the coasts of North and South America (above 42° latitude); many sub-Antarctic islands including the Kerguelen Islands ~~Islands~~ and South Georgia Island ~~(South Georgias)~~, the southwest coast of New Zealand's South Island; Antarctica; the Russian and Canadian Arctic Archipelagos, Svalbard Norway, Iceland, Greenland; and northern Europe, including the west coast of Scotland (Pickard, 1961, 1973; Syvitski and others, 1987; Cottier and others., 2010) (Fig. 1). Fjord systems are large transitional coastal zones, encompassing many distinct climate-hydrological-oceanographic interconnected systems, that are strongly influenced by interactions with mountain ranges, freshwater input, local to hemispheric-scale

atmospheric weather patterns, glacier ice fields and the open ocean (i.e., Pacific, Atlantic) (Bianchi and others, 2020; Hunt and others, 2024). These transitional coastal zones are characterized by a complex geography including the presence of several marine habitats such as bays, estuaries, gulfs, islands, fjords and channels. Inner coastal waters are influenced by freshwater flux by rivers, which are fed from precipitation, and/or snow, glacier and sea ice melting. The interaction of this freshwater with oceanic waters can generate strong horizontal and vertical salinity, density and nutrient gradients (chapter 3: Trends in the Physical and Chemical State in the Ocean). Fjords are also carbon cycle hotspots where the largest amount of organic carbon per unit area is buried in sediments, making them key ecosystems for carbon cycle regulation over time (Smith and others, 2015; Faust and Knies, 2019; Cui and others, 2022; Smeaton and Austin, 2022; Watts and others, 2024; Bertrand, 2025). At present, coastal fjord regions are increasingly experiencing anthropogenic impacts due to global processes (e.g. climate change), and regional activities (e.g. eutrophication) in inshore waters. According to the framework established in the third World Ocean Assessment, the present chapter focuses for the first time on several fjord systems of the world (Fig. 1), with particular emphasis on recent studies in mainland Norway, Svalbard ~~(Spitsbergen)~~, Greenland, Patagonia and Pacific North America.

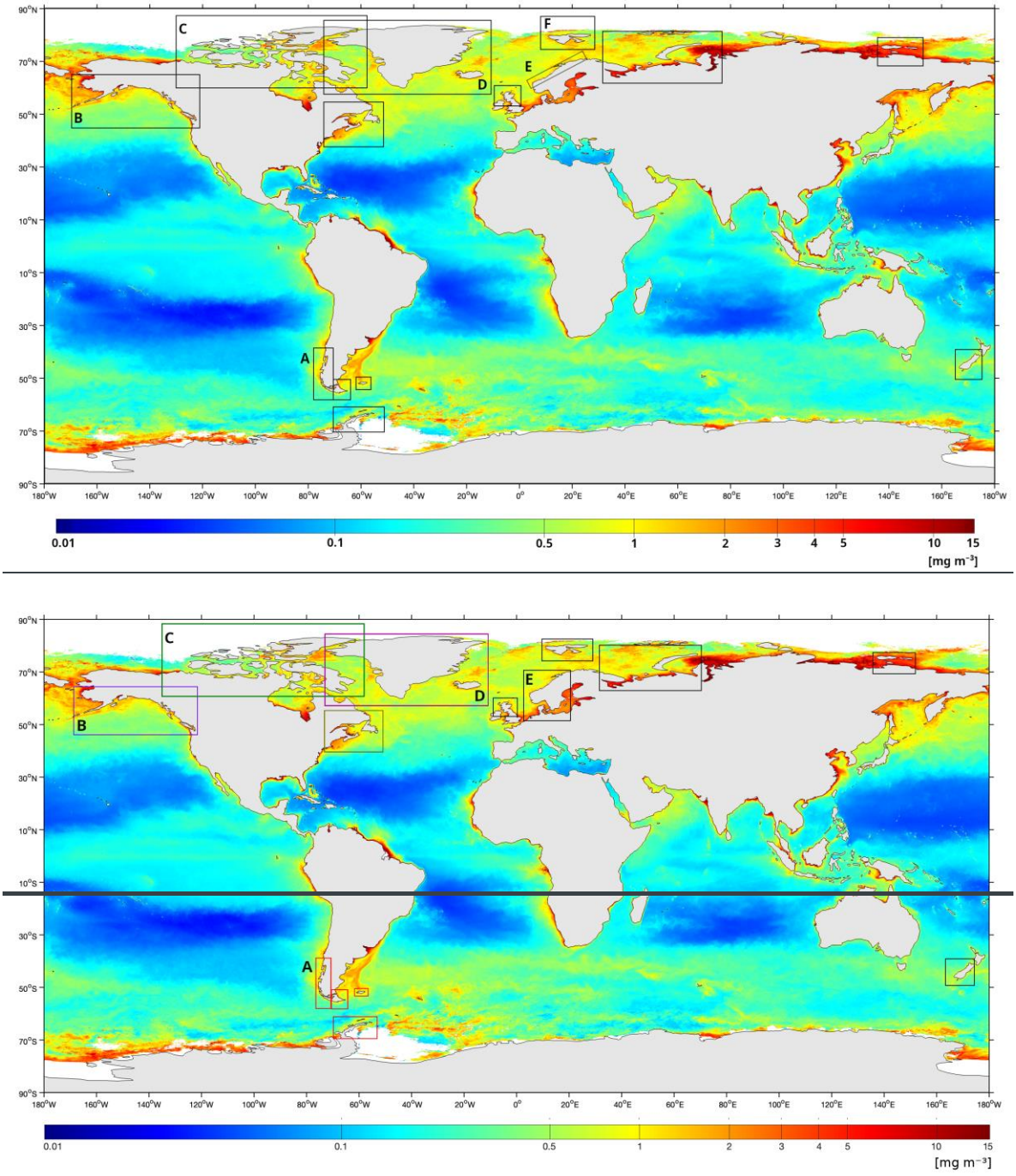


Figure 1. Map showing the global distribution of fjord systems overlaid with map showing chlorophyll-a concentrations. Fjord systems of the world, with particular emphasis on recent studies in Patagonia (A),

Pacific North America (B), Canadian Arctic Archipelago (C), ~~Svalbard (Spitsbergen) (C),~~ Greenland margins (D), ~~and~~ mainland Norway (E~~D~~), and Svalbard (F).

3 Descriptions of the overall status

3.1 Mainland Norway

Mainland Norway has thousands of fjords along the coast (58°-72°N). Fjords on the west coast are influenced by two distinct water masses: the low-salinity Norwegian Coastal Water in the upper layer and the high-salinity Atlantic Water in the lower layer beneath. The vertical structure and horizontal extent of coastal water show seasonal oscillations due to prevailing wind conditions, where alongshore northerly (southerly) winds can cause coastal upwelling (downwelling) (Sætre and others, 1988; Skarðhamar and Svendsen, 2005). Norwegian fjords are affected by land-fjord-shelf interactions such as river water input carrying organic matter and nutrients to the fjords and further to the shelf and some glaciated fjords have meltwater runoff. Some fjords have a shallow sill that prevents frequent renewal of the deep water due to the low salinity (low density) surface layer. Strong stratification and limited vertical mixing can result in long residence times of deep-water masses, which can lead to a decrease in oxygen levels and create challenging environments for local ecosystems (Aksnes and others, 2019; Darelius, 2020; Johnsen and others, 2024).

Fjords are productive due to nutrient-rich freshwater runoff from rivers and land promoting primary and secondary production. Diatom-spring blooms are most common in Norwegian fjords and as food for zooplankton. Periodically, spring blooms of the calcium carbonate forming coccolithophore had been reported in several Norwegian fjords (Kristiansenet and others, 2014), observed from space (NASA; Modis). Large copepods are an important food source for fish (e.g. Atlantic coastal cod) and shrimps (Zimmermann and others, 2023). Some fjords have unique cold-water corals (Ruggeberg and others, 2011). Fixation of CO_2 by phytoplankton is a significant factor controlling the partial pressure of CO_2 (pCO_2), with the development of spring blooms in northernmost fjords. Decreased CO_2 uptake is observed in autumn due to a combined reduction of the mixed layer with the entrainment of high-CO_2 subsurface water, reduced biological production and increased surface water temperatures (Aalto and others, 2021). Time series data reveal that the North Atlantic Oscillation (NAO) significantly influences river discharge, temperature, and precipitation in central Norway, making terrigenous input and erosional processes in the fjord hinterland highly sensitive to atmospheric variability. Additionally, marine carbonate productivity is the primary source of calcite and Ca in all three fjords (Faust and others, 2014, 2017).

3.2 Svalbard (Spitsbergen)

Most fjords on the west coast of Svalbard ~~(Spitsbergen)~~ exhibit a typical fjord circulation associated with a three-layer structure: a fresh surface layer in summer; a layer of intermediate water, transformed

Atlantic Water in the middle to outer part; and local fjord water in the deeper part of the fjord (Hop and others, 2006; Cottier and others, 2005; Nilsen and others, 2008; Skogseth and others, 2020). The summer surface layer is mainly formed by freshwater from glacial meltwater and river runoff (Svendsen and others, 2002). East coast fjords are mostly impacted by cold Arctic water and thicker sea ice than are found in the west coast fjords. Due to the sill depth, some fjords with a shallow sill depth such as Billefjorden have limited inflow of water from outside the fjord to renew the bottom water and creates Arctic conditions in the inner parts (Søreide and others, 2008, 2022).

Mountains surrounding the fjords have different bedrock compositions where weathering supplies minerals and ions to the fjord (Dragańska-Deja, 2024), which impacts the marine chemistry (alkalinity) and carbonate system (ocean CO_2 uptake) (Fransson and others, 2015; 2016; Ericson and others, 2019). Glacier runoff contributes to surface stratification and nutrient supply. Sub-glacial melting impacts the presence and supply of nutrients and other bio-essential substances (iron) derived from the bedrock/sediment at the bottom and transported by vertical mixing (Hopwood and others, 2020). High primary production blooms in Kongsfjorden (usually in April-June) are initiated due to shallow surface stratification and are often dominated by diatoms (e.g. Hegseth and others, 2019) and when the surface layer becomes more mixed and warmer the blooms are dominated by other species such as *Phaeocystis pouchetii* (e.g. Hoppe and others, 2024). Submarine melt in Arctic/Svalbard fjords is typically driven by the presence of warm water such as Atlantic Water and its derivative coastal water masses (Svendsen and others, 2002; Straneo and others, 2012). This melting causes low-density water to rise to the surface in the inner fjord, with positive responses on phytoplankton growth (diatoms), zooplankton (large copepods), fish, birds and sea mammals (Søreide and others, 2008; Lydersen and others, 2014; Halbach and others, 2019; Assmy and others, 2023). On the other hands, sediments carried by glacial meltwater can induce light availability, thereby limiting primary production (Hopwood and others, 2020; Dragańska-Deja and others, 2024). Sea ice is important for ice algae (mainly diatoms) which play an important role as an early food source for many marine invertebrates such as polychaetae and roundworms (Nematoda) that are known to reside within sea ice (Søreide and others, 2008). Glacial surface melt is largest in summer and limited during winter, while subglacial freshwater generated all year round through geothermal and frictional heat and delayed release of subglacially-stored freshwater (Vonnahme and others, 2023). Recent research in Kongsfjorden, Svalbard, reveals how freshwater runoff from marine- and land-terminating glaciers affects the biogeochemical cycles of carbon, nutrients, and trace elements in the Arctic fjord system. The data show that intense carbonate weathering in proglacial catchments adds dissolved carbonates to fjord waters, mitigating the reduced buffering capacity from glacial runoff

(Schmidt and others., 2025). Also observed in other west-Spitsbergen fjords such as Tempelfjorden (Fransson and others, 2015; 2020). Work in Smeerenburgfjorden, Kongsfjorden, and Van Keulenfjorden, of Western Svalbard, revealed that benthic recycling of glacially derived dissolved iron into seawater, followed by partial re-oxidation and deposition, facilitates iron transport across the fjords and potentially into adjacent shelf waters. This new data on biogeochemical processes and carbon cycling in a climate-sensitive, high-latitude fjord region, aids in predictions of future Arctic ecosystem changes (Wehrmann and others, 2014).

3.3 Greenland Glacial Fjords

Kalaallit Nunaat (Greenland) is characterized by hundreds of glacial fjords, distributed around its perimeter, that connect the ocean with the ice sheet. Many of these fjords are associated with marine-terminating glaciers that discharge icebergs that move through the fjords and into the coastal ocean. Meltwater released into the fjords from glacier melt, iceberg melt, and tundra runoff constitute a significant freshwater export into the coastal ocean (Bamber and others, 2018). One key feature of Greenland's glacial fjords is the release of large volumes of summer surface melt at the grounding zone of marine terminating glaciers, hundreds of meters below sea-level (Moon and others, 2017; Beaird and others, 2018). The large density difference between this freshwater and the ocean water give rise to turbulent, rising plumes, which play a key role in driving the fjord circulation, increase melting of the glacier face and upwell deep nutrients (Slater and others, 2015; Meire and others, 2017; Hopwood and others, 2018; Cape and others, 2019). Estimating the dissolved silica (dSi) flux from the Greenland Ice Sheet has been difficult, with existing estimates differing by an order of magnitude. A new study indicates a modest dissolve Si flux from runoff, with smaller contributions from melting icebergs and suspended particles (Hopwood and others, 2025). The confluence of Arctic and Atlantic- origin waters flow along-side with the Arctic waters inshore and the Atlantic waters on the continental slope (Straneo and others, 2012). Greenland fjords are characterized by seasonal sea-ice coverage varying significantly with latitude and between east and West Greenland. Sea ice plays a vital role for Indigenous Peoples and local communities, supporting traditional livelihoods like fishing and hunting (Krupnik and others, 2010).

Large phytoplankton blooms occur in spring as solar radiation increases and sea-ice retreats (Vernet and others, 2021). The mixing of different water types and nutrient upwelling associated with glacial plumes contributes to a continued high productivity in the fjords with marine-terminating glaciers during summer (Meire and others, 2023; Juul-Pedersen and others, 2015). These high primary production blooms, often dominated by diatoms, provide a valuable food source for attracting large zooplankton communities and

consequently for lower trophic level forage fish species such as capelin (Grønkjær and others, 2019, Laidre and others, 2008). These rich marine ecosystems are not only of ecological importance but also of socio-economic importance for commercial fisheries (Boje and others, 2014; Meire and others, 2017) as well as local fishing and hunting activities (Schiøtt and others, 2022, Straneo and others, 2022).

3.4 Patagonian fjords

Along the Chilean Patagonia (41 – 54°S), the coast is characterized by a complex geography including the presence of fjords and channels. Northern Patagonia (41 – 47°S) showed high freshwater input by large rivers (up to 600 $m^3 s^{-1}$) along the coast characterized by waters of low salinity and high silicic acid concentration (Jacob and others, 2014; Cuevas and others, 2019). Such discharges affect the nutrient content and their stoichiometric ratio (N:P:Si), as well as the water column structure showing a strong haline stratification (León-Muñoz and others, 2024). Their interaction with the Subantarctic Water (SAAW), generate strong horizontal and vertical salinity (and density) gradients (Saldías and others, 2019) that contribute to maintain the phytoplankton community under high nutrient availability within the euphotic zone (Iriarte and others, 2014). The interplay between river discharges and oceanic water masses, as the principal nutrient sources, leads the maximum peak of chlorophyll-a to occur in the inner coastal waters during the austral spring-summer months (Iriarte and others, 2007). The pronounced salinity gradient by the riverine freshwater input can be extended to the offshore region, reaching as far as ~80°W, generating a strong relationship between stratification, nutrient content, and surface total chlorophyll *a* biomass (Galán and others, 2021). In contrast, southern Patagonia (47 – 54°S) is strongly affected by western winds (which have maximum intensity during summer) and the fluvial influence is lower compared to snow and glacial melting processes (Garreaud and others, 2009; Aguayo and others, 2024). These conditions promote a deeper mixed layer, low silicic acid and nitrate concentrations (Cuevas and others, 2014), and high content of suspended sediments, which affect the light availability in the upper layer, mainly in the inner waters (González and others, 2013; Jacob and others, 2014). The biogeochemistry of Patagonia's fjords is shaped by complex, changing factors, including fjord geomorphology, local climate, interactions of multiple water masses and atmospheric modes (Crosswell and others, 2022; Linford and others, 2023; Rebolledo and others, 2015; Sepúlveda and others, 2009). Despite this complexity, studies of water columns, surface sediments, and downcore organic carbon emphasize the heterogeneity of carbon inputs and fate (González and others, 2019; Rojas and Silva, 2005; Sepúlveda and others, 2011; Silva and others, 2011).

3.5 Pacific North America fjords

In North America, fjords are located on all three ocean coasts - the Atlantic, Arctic, and Pacific Oceans but here we focus on Pacific North American fjords, which span Washington state (USA), British Columbia (Canada), and Alaska (USA). These fjords are part of the Northeast Pacific Coastal Temperate Rainforest Ecoregion (NPCTR), which includes prehumid and seasonal rainforests (Bidlack and others, 2021; Hunt and others, 2024). The Pacific North American fjords are fringed by mountain ranges - the Olympic range in western Washington, and the coast mountain range (aka the Cascade Range) that runs throughout Washington, British Columbia and Alaska. Freshwater flows from the coastal mountains to the coast via thousands of small coastal rivers and 5 large continental rivers (Giesbrecht and others, 2021). Rivers are observed at the heads of most fjords and the seasonality of the river depends on whether the source of the freshwater is rain, snow, or glacial melt (Morrison and others, 2012). In British Columbia, there are 42 fjords that are longer than 18.5 km and of these, the outer sill depth ranges from 6 m to 490 m, the maximum depth ranges to 75 m to 730 m, and the length ranges from 33 km to 130 km (Pickard, 1961). In most cases there are 3 water types in fjords - deep water (greater than sill depth) that in most fjords is seasonally modified by deep water renewal (Farmer and Freeland, 1983), intermediate water (above sill and below surface water) that can be modified by wind-driven or advective processes (Jackson and others, 2022) and surface water that is driven by estuarine circulation (Pickard, 1961). Recent research pointed out that the ecosystem within fjords is different than surrounding waters, with high phytoplankton concentrations (Marchese and others, 2022) that are dominated year-round by diatoms (Johannessen and others, 2019; Del Bel Belluz and others, 2024) and very abundant and diverse zooplankton populations (Pata and others, 2022).

4 Region-specific changes

4.1 Mainland Norway

Freshwater input is increasing to the coastal zone which is an important area for fisheries (cod, salmon, shrimp) and aquaculture. Cod egg dispersion models show negative impacts of increased low-density water with low oxygen (Stenevik and others, 2008). There is recent evidence that coastal waters in mainland Norway are becoming lighter due to climate change, resulting in a stronger stratification in the fjord basins with reduced mixing and consequent deoxygenation in fjords (Johnsen and others, 2024). An estimated increase of 0.6°C in temperature in the fjord basins after 1990 showed that basin water renewal occurred less frequently in most fjord basins along the Norwegian coast (Johnson and others, 2024). Masfjorden in southern Norway is one of the fjords showing recent oxygen-depleted basin water (Pitcher

and others, 2021). Impacts of ocean acidification: some glaciated fjords have meltwater runoff that dilutes buffering ions (and alkalinity), increases CO_2-uptake, and increases ocean acidification (Aalto and others, 2021; Jones and others, 2020). Human activities such as shipping, aquaculture (sub-chapter 1d: Small-Scale Aquaculture), fishing and pollution (e.g. mining waste; Chapter 6: Pressures) and climate stressors such as ocean warming and acidification, negatively impacting the fjords. Because of the unique and diverse environment, several such fjords have recently become Marine Protected Areas.

4.2 Svalbard

Ocean warming of 0.7° C per year in winter and 0.6° C per year in summer is observed on the shelf of western Spitsbergen and Isfjorden (Skogseth and others, 2020) and a decline in sea ice is reported in Kongsfjorden (Pavlova and others, 2019; Gerland and others, 2020). Glaciers in Svalbard are melting and retreating, and freshwater input to the coastal zone is increasing (Kohler and others, 2007; Geyman and others, 2022) due to warming (e.g. Foss and others, 2024). Fjords in Svalbard experience increased ocean acidification due to increased glacial discharge and meltwater-induced CO_2 uptake (e.g. Fransson and others, 2016; Cantoni and others, 2020). These waters are further modified by accumulated dissolved inorganic carbon from sea-ice brine rejection and respiration of organic matter which further contributes to acidification (Ericson and others, 2019; Fransson and others, 2016, 2015). Studies in Kongsfjorden (west Spitsbergen) showed inter-annual variability in biogeochemical properties with lower aragonite saturation (Ω_{ar}) and pH (indicators of ocean acidification) in cold years with extensive sea-ice cover, relative to warm years with a greater influence from warm and saline Atlantic Water inflow (Fransson and others, 2016). Differences in phytoplankton spring bloom composition in Kongsfjorden was observed in contrasting years where in a cold year with more sea ice the spring bloom was dominated by diatoms and in a warm year with less sea ice, the spring bloom was dominated by haptophyte (Søreide and others, 2010; Assmy and others, 2023). In years with less surface stratification, warmer water and deeper mixed layer the blooms were dominated by species such as *Phaeocystis pouchetii* (Hoppe and others, 2024). Moreover, the reported decreased sea ice presence in Svalbard fjords (Pavlova and others, 2019) will lead to less ice algae and earlier phytoplankton blooms (Søreide and others, 2008), resulting in changes in the diversity of sea-ice protist (e.g diatoms) and ice-associated fauna (Hop and others, 2020). In sediments of Kongsfjorden in Svalbard benthic remineralization could increase nutrient sources like iron (Fe). Interannual variations in primary productivity, expected to intensify with global warming, and changes in glacial sediment delivery will affect benthic Fe and Sulphur cycling. Over time, this may lead to decreased benthic Fe fluxes. With glacial retreat and shifts in productivity, fjords like Kongsfjorden may become less

efficient carbon sinks, burying less organic matter in deep sediments (Herbert and others, 2022). Seepage of methane is reported in most Svalbard fjords and natural gas below the permafrost, with methane flares measured in Isfjorden, Kongsfjorden, and VanMijenfjorden (Hodson and others, 2024). With warming, permafrost thawing and methane release into the fjords will likely increase with impacts on carbon cycling in the fjords and shelves. Knowledge gaps on the methane dynamics in Svalbard still exist (Hodson and others, 2024).

4.3 Greenland's Margins

Climate change, including the rapid warming of the Arctic, is resulting in significant changes over Greenland and along its coastal margins. These changes include the retreat of glaciers, increased surface melt (Mankoff and others, 2021, 2020), reduced sea ice (Cooley and others, 2020) and warming air temperatures (Box and others, 2009). These trends are superimposed with long-term modes of variability, such as the Arctic and North Atlantic Oscillations and the Atlantic Multidecadal Oscillation, that account for a significant fraction of the variability in this region (Hanna and others, 2021). Records of physical and chemical properties, and of ecosystem and fisheries variability, in the fjords and in the coastal region are, however, scarce – making it challenging to quantify change that has already occurred. Proxy records derived from fjord sediment archives offer valuable insights into past changes beyond the instrumental era (Heikkilä and others, 2022). Fjord sediments simultaneously record changes in sea ice, ice-sheet discharge, ice-ocean interactions and associated ecosystem responses (Ribeiro and others, 2017, Vermassen and others, 2019). Proxy-data studies from Greenland fjords from both West and East Greenland have revealed multi-decadal changes in the inflow of Atlantic-derived warm water and its relationship with glacier dynamics (Andresen and others, 2012, Vermassen and others, 2019b). They also have revealed that present-day impacts of freshwater discharge on fjord productivity are unprecedented in centuries to millennia (Oksman and others, 2022, Oksman and others, 2024). The increase in the upwelling of nutrients associated with subglacial discharge may be partly offset by the retreat of glaciers into shallower water – thus reducing the ability to upwell deep nutrients (Meire and others, 2017; Hopwood and others, 2020). Sea-ice decrease is impacting wintertime travel and fishing, which Indigenous Peoples and local communities rely on for sustenance and threatens the future viability of key polynya ecosystems (Ribeiro and others, 2021). Sea-ice cover serves as winter refuges for marine mammal species that are harvested by Indigenous People in Greenland fjords (Heide-Jørgensen and others, 2013). At the same time, reduced sea-ice resulted in increased primary productivity as light limitations are

reduced and wind-induced mixing increased (Baffin Bay and the Arctic Ocean; York and others, 2020; Frey and others, 2020).

4.4 Patagonia

The Patagonia region is undergoing an increasing anthropogenic affectation due to global phenomena, including hydrological anomalies, glacier retreatment, climatological shifts (Aguayo and others, 2019; 2024; Garreaud and others, 2009) and regional productive activities such as large-scale aquaculture farms (salmon and mussels) allocated along inshore waters (Navedo and Vargas, 2021). In northern Patagonia (41 – 44°S), climate change projections forecast 20% less rainfall in the next decade (Aguayo and others, 2019), which affect negatively the annual dynamics of large river streamflows, water chemistry (silicic acid) and pelagic (mollusk larvae) and benthic organisms inhabiting fjords systems (van Leeuwen and others, 2021) as well as the physical support (weakening of haline stratification and increase of sea surface temperature; Leon-Muñoz and others, 2024). Recurrent harmful microorganisms' events observed in coastal and oceanic regions off northern Patagonia since 2016, coincided with the synergy of remote climatic phenomena (El Niño) and global warming that led to very dry conditions, higher than normal solar radiation, high sea surface temperatures, and reduced wind velocities (León-Muñoz et al., 2018; Mardones and others, 2023). Significant mass loss (65%) in the Patagonia icefields (47 – 55°S) may continue in the future (Minowa and others, 2022; Aguayo and others, 2024), where ocean-terminating and land-terminating fjords are likely exposed to increasing freshwater runoff (freshening effect) and increasing rain precipitation (Garreaud and others, 2013). Patagonian fjords and inner seas are affected by human-induced global changes, including climate-ocean events, altered freshwater inputs, harmful algal blooms, settlement, aquaculture, glacial melt, and coastal hypoxia (Dussaillant and others, 2019; González and others, 2019; Iriarte, 2018; Linford and others, 2024; Quiñones and others, 2019).

4.5 Pacific North America

Data of temperature, salinity and oxygen have been collected since 1951 in British Columbia fjords. Recent work found that deep water warmed by 1.2 to 1.4°C and lost 0.4 to 0.7 mL L^{-1} of oxygen from 1951 to 2020 (Jackson and others, 2021). These changes are explained by the upwelling of offshore water that was warmed by the 2014-2016 marine heatwave to fjords via deep water renewal (Jackson and others, 2018; Alin and others, 2024); the 2014-2016 marine heat wave water lingered in deep fjord water until

2020 (Jackson and others, 2021). Waters in fjords are often acidic (Hare and others, 2020) and impacted by random events (Alin and others, 2024).

Glaciers in British Columbia are melting rapidly, and it is predicted that the volume of glacial ice will shrink by ~70% by 2100 relative to 2005 (Clarke and others, 2015). In addition to altering the amount of freshwater transported to the ocean, as the glaciers melted, they caused extreme events such as the 2020 outburst flood that destroyed salmon habitat and advected tons of inorganic and organic sediments into Bute Inlet (Geertsma and others, 2022). There is evidence that these changes to the seasonality and amount of freshwater that enters fjords are impacting the timing of the spring bloom (Wolfe and others, 2015; Hunt and others, 2024; Del Bel Belluz and others, 2024), as well as zooplankton dynamics (Tommasi and others, 2013).

5 Outlook

General awareness of fjords and the key ecosystem services offered by them are essential to determine actions on management under natural disturbances as well as present and projected climate change scenarios. Linking physical-ecological and socio-economic structures and their ecosystems functions are key to propose and incorporate both mitigation and adaptation processes such as nature-based solutions and “climate refugees”. Long-term monitoring approaches designed and coordinated by scientists and stakeholders must be undertaken in existing and future marine and terrestrial protected areas located in fjord systems. This chapter as well as others such as Cold-water corals and sponges (sub-chap. 5e), Estuaries and Deltas (chap. 5F) and Small-scale Aquaculture (sub-chap. 5a) pointed out that fjord regions are under threat from intensive human activities (including land-use, aquaculture, dams, tourism) and impacts of climate change (including warming, freshening, ice loss, permafrost thawing, erosion, sea-level rise).

6 Remaining key knowledge and capacity changes and any new gaps

- A critical knowledge gap exists for fjords habitats, as only a small percentage of the world's fjords have been studied.
- Change from marine-terminating glaciers to land-terminating glaciers would determine changes in surface and sub-glacial melt, sediment supply that limits light, stronger stratification and nutrient limitation for primary production, changes in species composition, and ultimately the dynamic of carbon flux.
- How methane emissions from melting Ice sheets and glaciers in the Arctic are contributing to the global carbon cycle is so far not known.
- The resilience of fjord systems to changes in hydrologic (precipitation, melting, runoff) and oceanographic (water masses, stratification, nutrient stoichiometry) to present conditions remain a major gap.
- Advances in modelling research, such as in relation to the impacts of freshening, coastal acidification, sea surface warming, and deoxygenation processes, are lacking and need to be compared with *in situ* studies approaches.

All authors declare no use of Artificial Intelligence in the writing process of this chapter.

7 References

Aalto NJ, and others (2021) Drivers of Atmosphere-Ocean CO_2 Flux in Northern Norwegian Fjords. Frontiers Marine Science, doi: 10.3389/fmars.2021.69209, 2021.

Aguayo, Rodrigo, and others. The glass half-empty: Climate Change drives lower freshwater input in the coastal system of the Chilean northern Patagonia. Climatic Change, https://doi.org/10.1007/s10584-019-02495-6, 2019.

Aguayo, Rodrigo, and others. Unravelling the sources of uncertainty in glacier runoff projections in the Patagonian Andes (40 – 56S). The Cryosphere, vol. 18, 5383-5406, doi.org/10.5194/tc-18-5383-2024.

Aksnes, D. L., and others. Multi-decadal warming of Atlantic water and associated decline of dissolved oxygen in a deep fjord. Estuarine, Coastal and Shelf Science, 228, https://doi.org/10.1016/j.ecss.2019.106392, 2019.

Alin, S.R., and others. Seasonality and response of ocean acidification and hypoxia to major environmental anomalies in the southern Salish Sea, North America (2014–2018). Biogeosciences, vol. 21, 1639-1673, https://doi.org/10.5194/bg-21-1639-2024, 2024.

Andresen, C., and others. Rapid response of Helheim Glacier in Greenland to climate variability over the past century. Nature Geoscience, vol. 5, 37–41, 2012.

Assmy Philipp, and others. Seasonal plankton dynamics in Kongsfjorden during two years of contrasting environmental conditions. Progress in Oceanography, vol. 213, 102996, https://doi.org/10.1016/j.pocean.2023.102996, 2023.

Bamber, J. L., and others. Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results. Journal of Geophysical Research: Oceans, vol. 123, 1827-1837, 2018.

Beaird, N. L., and others. Export of strongly diluted Greenland meltwater from a major glacial fjord. Geophysical Research Letters, vol. 45, 4163–4170, doi: 10.1029/2018GL077000, 2018.

Bertrand, S. Biogeochemistry of riverine organic matter inputs to the Patagonian fjords and implications for fjord organic carbon budgets. Journal of Geophysical Research, Biogeosciences, vol. 130, 2025.

Bianchi, Thomas, S., and others. Fjords as aquatic critical zones (ACzs). Earth-Science Reviews, vol. 203, https://doi.org/10.1016/j.earscirev.2020.103145, 2020.

Bidlack, A.L., and others. Climate-Mediated Changes to Linked Terrestrial and Marine Ecosystems across the Northeast Pacific Coastal Temperate Rainforest Margin. BioScience, vol. 71, 581-595, https://doi.org/10.1093/biosci/biaa171, 2021.

Boje, J., and others. Seasonal migration, vertical activity, and winter temperature experience of Greenland halibut *Reinhardtius hippoglossoides* in West Greenland waters. Marine Ecology Progress Series, vol. 508, 211-222, 2014.

Box, J. E., and others. Greenland ice sheet near-surface air temperature variability: 1840–2007, J. Climatology, vol. 22, 4029– 4049, doi:10.1175/2009JCLI2816.1, 2009.

Cantoni, C., and others. Glacial drivers of marine biogeochemistry indicate a future shift to more corrosive conditions in an Arctic fjord. Journal of Geophysical Research: Biogeosciences, vol. 125, 2020. e2020JG005633. https://doi.org/10.1029/2020JG005633.

Cape, Mattias, and others. Nutrient release to oceans from buoyancy-driven upwelling at Greenland tidewater glaciers. Nature Geoscience, vol. 12, 34-39, 2019.

Clarke, G., and others. Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, vol. 8, 372-377, https://doi.org/10.1038/ngeo2407, 2015.

Cooley, S.W., and others. Coldest Canadian Arctic communities face greatest reductions in shorefast sea ice. Nature Climate Change, vol. 10**,** 533–538, https://doi.org/10.1038/s41558-020-0757-5, 2020.

Cottier, F.R., and others., Artctic fjords: a review of the oceanographic environment and dominant physical processes. Geological Society of London, vol. 344, 35-50, 2010.

Cottier FR, and others. Water mass modification in an Arctic fjord through cross-shelf exchange: the seasonal hydrography of Kongsfjorden, Svalbard. Journal of Geophysical Research: Oceans, 110:C12005, 2005.

Crosswell, J. R., and others. Geophysical controls on metabolic cycling in three Patagonian fjords. Progress in Oceanography, vol. 207, 2022. https://doi.org/10.1016/j.pocean.2022.102866.

Cuevas, Antonio, and others. Interplay between freshwater discharge and oceanic waters modulates phytoplankton size-structure in fjords and channel systems of the Chilean Patagonia. Progress in Oceanography, vol. 173, 103-113, 2019.

Cui, X., and others. Global fjords as transitory reservoirs of labile organic carbon modulated by organo-mineral interactions. Science Advances, vol. 8, 2022.

Darelius, E. On the effect of climate trends in coastal density on deep water renewal frequency in sill fjords—A statistical approach. Estuarine, Coastal and Shelf Science, vol. 243, https://doi.org/10.1016/j.ecss.2020.106904, 2020.

Del Bel Belluz, Justin, and others. Phytoplankton community composition links to environmental drivers across a fjord to shelf gradient on the central coast of British Columbia. Frontiers in Marine Science, https://doi.org/10.3389/fmars.2024.1458677, 2024.

Draganska-Deja, Katarzyna. Characterization of suspended particles at different glacial bays at Spitsbergen. Oceanologia, vol. 6, 239-249, 2024. doi.org/10.1016/j.oceano.2023.12.001.

Draganska-Deja, Katarzyna, and others. Productivity of Spitsbergen fjords ecosystems in summer-Spatial changes of in situ primary production in Kongsfjorden and Hornsund in the period 1994 – 2019. Ecology and Evolution, vol. 14, 2024. https://doi.org/10.1002/ece3.11607.

Ericson Y., and others. Marine CO_2 system variability in a high arctic tidewater-glacier fjord system, Tempelfjorden, Svalbard. Continental Shelf Research, vol. 181, 1-13, https://doi.org/10.1016/j.csr.2019.04.013, 2019.

Farmer, D.M., and Freeland, H.J. The physical oceanography of Fjords. Progress in Oceanography, vol. 12, 147-220, https://doi.org/10.1016/0079-6611(83)90004-6, 1983.

Faust, J. C., and others. Terrigenous input to a fjord in central Norway records the environmental response to the North Atlantic Oscillation over the past 50 years. The Holocene, vol. 24, 1411–1418, 2014. https://doi.org/10.1177/0959683614544052

Faust, J. C., and others. Geochemical characterization of northern Norwegian fjord surface sediments: A baseline for further paleo-environmental investigations. Continental Shelf Research, vol. 148, 104–115, 2017. https://doi.org/10.1016/j.csr.2017.08.015.

Faust, J. C., and Knies, J. Organic matter sources in North Atlantic fjord sediments. Geochemistry, Geophysics, Geosystems, vol. 20, 2872–2885, 2019.

Foss, Ø., and others, 2024. Ocean warming drives immediate mass loss from calving glaciers in the high Arctic. Nature Communication, vol. 15, 2024. https://doi.org/10.1038/s41467-024-54825-7.

Fransson, Agneta, and others. Effect of glacial drainage water on the CO_2 system and ocean acidification state in an Arctic tidewater-glacier fjord during two contrasting years. Journal of Geophysical Research: Oceans, 120, https://doi.org/10.1002/2014JC010320, 2015.

Fransson, Agneta, and others. Late winter-to-summer change in ocean acidification state in Kongsfjorden, with implications for calcifying organisms. Polar Biology, vol. 39, 1841–1857, 2016.

Fransson, Agneta. and others. Influence of glacial water and carbonate minerals on wintertime sea-ice biogeochemistry and the CO_2 system in an Arctic fjord in Svalbard. Annals of Glaciology, 2020. https://doi.org/10.1017/aog.2020.52.

Frey K. E., and others. “Arctic Ocean Primary Productivity: The Response of Marine Algae to Climate Warming and Sea Ice Decline”, in *Arctic Report Card 2020*, R. L. Thoman, J. Richter-Menge, and M. L. Druckenmiller, eds. (https://doi.org/10.25923/vtdn-2198, 2020)

Galán, Aexander, and others. Argo float reveals biogeochemical characteristics along the freshwater gradient off western Patagonia. Frontiers in Marine Science, doi:10.3389/fmars.2021.613265, 2021.

Garreaud, René, and others. Present-day south american climate. Paleogeography, Paleoclimatology, Paleoecology, vol. 281, 180-195, doi:10.1016/j.palaeo.2007.10.032, 2009.

Garreaud, René, and others. Large-scale control on the Patagonian climate. Journal of Climatology, vol. 26, 215–230, doi.org/ 10. 1175/ JCLI-D- 12- 00001.1, 2013.

Geertsma, M., and others. The 28 November 2020 landslide, tsunami, and outburst flood -–A Hazard cascade associated with rapid deglaciation at Elliott Creek, British Columbia, Canada. Geophysical Research Letters, 49, e2021GL096716, 2022.

Gerland, and others. Long-term monitoring of landfast sea ice extent and thickness in Kongsfjorden, and related applications (FastIce), in Van den Heuvel, F, Hübner, C, Błaszczyk, M, Heimann, M, Lihavainen, H eds., SESS Report 2019. Longyearbyen: Svalbard Integrated Arctic Earth Observing System: 160–167, 2020.

Geyman, E.C., and others. Historical glacier change on Svalbard predicts doubling of mass loss by 2100. Na*ture, 6*0**1,** 374–379, https://doi.org/10.1038/s41586-021-04314-4, 2022.

Giesbrecht, IJW and others. Watershed Classification Predicts Streamflow Regime and Organic Carbon Dynamics in the Northeast Pacific Coastal Temperate Rainforest - Giesbrecht - 2022 - Global Biogeochemical Cycles, 2021.

González, Humberto, and others. Land-ocean gradient in haline stratification and its effects on plankton dynamics and trophic carbon fluxes in Chilean Patagonian fjords. Progress in Oceanography, vol. 119, 32 – 47, http://dx.doi.org/10.1016/j.pocean.2013.06.003, 2013.

González, H., and others. Organic matter distribution, composition and its possible fate in the Chilean North-Patagonian estuarine system. Science of The Total Environment, vol. 657, 1419–1431, 2019. https://doi.org/10.1016/j.scitotenv.2018.11.445.

Grønkjær, P, and others. Feeding ecology of capelin (*Mallotus villosus*) in a fjord impacted by glacial meltwater (Godthåbsfjord, Greenland). Polar Biology, vol. 42, 81–98, 2019.

Halbach, L., and others. Tidewater glaciers and bedrock characteristics control the phytoplankton growth environment in an Arctic fjord. Frontiers in Marine Science, vol. 6, 254, https://doi.org/10.3389/fmars.2019.00254, 2019.

Hanna, E, and others. Greenland surface air temperature changes from 1981 to 2019 and implications for ice-sheet melt and mass-balance change. International Journal Climatology, vol. 41, 1336– 1352, https://doi.org/10.1002/joc.6771, 2021.

Hare, A., and others. Contrasting marine carbonate systems in two fjords in British Columbia, Canada: Seawater buffering capacity and the response to anthropogenic CO_2 invasion. PLOS ONE, https://doi.org/10.1371/journal.pone.0238432, 2020.

Hegseth, E.N., and others. Phytoplankton seasonal dynamics in Kongsfjorden, Svalbard and the adjacent shelf, in Hop, H, Wiencke, C eds., The ecosystem of Kongsfjorden, Svalbard. Cham, Switzerland: Springer: 173–227. Advances in Polar Ecology; vol. 2, 2020.

Heide-Jørgensen MP, and others. The significance of the north water polynya to arctic top predators. Ambio, vol. 42, 596-610, doi: 10.1007/s13280-012-0357-3, 2013.

Heikkilä, M., and others. Predicting the future of coastal marine ecosystems in the rapidly changing Arctic: the potential of palaeoenvironmental records. Anthropocene, https://doi.org/10.1016/j.ancene.2021.100319, 2022.

Herbert, C., and others. Tight benthic-pelagic coupling drives seasonal and interannual changes in iron-sulfur cycling in Arctic fjord sediments (Kongsfjorden, Svalbard). Journal of Marine Systems, vol. 225, 2022.

Hodson A, and others. Methane in Svalbard. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, 106-137, 2025. https://doi.org/10.5281/zenodo.14425572.

Hop H, and others. Physical and biological characteristics of the pelagic system across Fram Strait to Kongsfjorden. Progress in Oceanography, vol. 71, 182–231, 2006.

Hop H, and others. Changes in sea-ice protist diversity with declining sea ice in the Arctic Ocean from the 1980s to 2010s. Frontiers in Marine Science, vol. 7, 243, 2020.

Hoppe C. J. M., and others. The effects of biomass depth distribution on phytoplankton spring bloom dynamics and composition in an Arctic fjord. Elementa: Science of the Anthropocene, vol. 12, 2024. https://doi.org/10.1525/elementa.2023.00137.

Hopwood, Mark, and others. Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland. Nature Communications, vol. 9, 3256, doi:10.1038/s41467-018-05488-8, 2018.

Hopwood, Mark, and others. Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? The Cryosphere, vol. 14, 1- 37, 2020.

Hopwood, Mark, and others. A close look at dissolved silica dynamics in Disko Bay, west Greenland. Global Biogeochemical Cycles, vol. 39, 2025..

Hunt, B.P.V., and others. Advancing an integrated understanding of land-ocean connections in shaping the marine ecosystems of Coastal Temperate Rainforest ecosystems. Limnology and Oceanogrpahy, 2024..

Iriarte, José Luis, and others. Oceanographic Processes in Chilean Fjords of Patagonia: from small to large-scale studies. Progress in Oceanography, vol. 129, 1- 7, 2014.

Iriarte, José Luis, and others. Spatial and temporal variability of chlorophyll and primary productivity in surface waters of southern Chile (41.5 – 43S). Estuarine, Coastal and Shelf Science, 74, 471-480, 2007.

Iriarte, José Luis. Natural and Human Influences on Marine Processes in Patagonian Subantarctic Coastal Waters. Frontiers in Marine Science, vol. 5, 2018.. https://doi.org/10.3389/fmars.2018.00360.

Jackson, Jennifer, and others. Warming From Recent Marine Heatwave Lingers in Deep British Columbia Fjord. Geophysical Research Letters, vol. 45, 9757-9764, https://doi.org/10.1029/2018GL078971, 2018.

Jackson, Jennifer, and others. Identification of a Seasonal Subsurface Oxygen Minimum in Rivers Inlet, British Columbia. Estuaries and Coasts, vol. 45, 754-771, https://doi.org/10.1007/s12237-021-00999-y, 2022.

Jackson, Jennifer, and others. Deep Waters in British Columbia Mainland Fjords Show Rapid Warming and Deoxygenation from 1951 to 2020. Geophysical Research Letters, vol. 48, e2020GL091094, https://doi.org/10.1029/2020GL091094, 2021.

Jacob, Barbara, and others. Springtime size-fractionated primary production across hydrographic and PAR-light gradients in Chilean Patagonia (41-50°S). Progress in Oceanography, vol. 129, 75-84, 2014.

Johannessen, S.C., and others. Rain, Runoff, and Diatoms: the Effects of the North Pacific 2014–2015 Warm Anomaly on Particle Flux in a Canadian West Coast Fjord. Estuaries and Coasts, vol. 42, 1052–1065, https://doi.org/10.1007/s12237-018-00510-0, 2019.

Johnsen I.A, and others. Coastal alterations influence deep water renewal in Norwegian sill fjords. Estuarine, Coastal and Shelf Science, vol. 297, 108604, https://doi.org/10.1016/j.ecss.2023.108604, 2024.

Jones, E. M., and others. Seasonal dynamics of carbonate chemistry, nutrients and CO_2 uptake in a sub-Arctic fjord. Elemental Science of Anthropocene, vol. 8, 41, 2020.

Juul-Pedersen, Thomas, and others. Seasonal and interannual phytoplankton production in a sub-Arctic tidewater outlet glacier fjord, SW Greenland. Marine Ecology Progress Series, vol. 524, 27-38, 2015.

Kohler, J., and others. Acceleration in thinning rate on western Svalbard glaciers. Geophysical Research Letters, vol. 34, doi:10.1029/2007GL030681, 2007

Kristiansen S., and others. An *Emiliania huxleyi* dominated subsurface bloom in Samnangerfjorden, Western Norway. Importance of hydrography and nutrients. Sarsia, vol. 79, 357-368, 2014.

Krupnik, I., and others. SIKU: Knowing Our Ice. Springer, Dordrecht, https://doi.org/10.1007/978-90-481-8587-0, 2010.

Laidre, K.L., and others. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. Ecological Applications, vol. 18, 97-125, 2008.

Leon-Muñoz, Jorge, and others. Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). Scientific Reports, DOI: 10.1038/s41598-018-19461-4, 2018.

León-Muñoz, Jorge, and others. Hydrographic shifts in coastal waters reflect climate-driven changes in hydrological regimes across Northwestern Patagonia. Scientific Reports, doi.org/10.1038/s41598-024-71008-y, 2024.

Linford, P., and others. Oceanographic processes driving low-oxygen conditions inside Patagonian fjords. Biogeosciences, vol. 21, 1433–1459, 2024. https://doi.org/10.5194/bg-21-1433-2024.

Lydersen, C., and others. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. Journal of Marine Systems, vol. 129, 452-471, 2014.

Mankoff, K.D., and others. Greenland ice sheet mass balance from 1840 through next week. Earth System Science Data, vol. 13, 5001–5025, DOI: 10.5194/essd-13-5001-2021, 2021.

Mankoff, K.D., and others. Greenland liquid water discharge from 1958 through 2019. Earth System Science Data, vol. 12, 2811–2841, DOI: 10.5194/essd-12-2811-2020, 2020.

Marchese, C., and others. Bioregionalization of the coastal and open oceans of British Columbia and Southeast Alaska based on Sentinel-3A satellite-derived phytoplankton seasonality. Frontiers in Marine Science, vol. 9, https://doi.org/10.3389/fmars.2022.968470, 2022.

Matthews, J.B.L. and Heimdal, B.R. "Pelagic productivity and food chain in fjord systems", in *Fjord Oceanography* Freeland, H.J., Farmer D.M. and Levings, C.D, eds. (Springer, Boston, MA. https://doi.org/10.1007/978-1-4613-3105-6_34, 1980).

Minowa, M., and others. Effects of topography on dynamics and massloss of lake terminating glaciers in southern Patagonia. Journal of Glaciology, DOI:https://doi.org/10.1017/jog.2023.42, 2022.

Navedo, Juan and Vargas-Chacoff, Luis. Salmon aquacullture threatens Patagonia. Science, vol. 372, 694, 2021.

Nilsen, F., and others. Fjord-shelf exchanges controlled by ice and brine production: the interannual variation of Atlantic Water in Isfjorden, Svalbard. Continental Shelf Research, vol. 28, 1838–1853, https://doi.org/10.1016/j.csr.2008.04.015, 2008.

Meire, M., and otrhers. Marine-terminating glaciers sustain high productivity in Greenland fjords. Global Change Biology, vol. 23, 5344-5357, 2017.

Meire, L.orenz, and others. Glacier retreat alters downstream fjord ecosystem structure and function in Greenland. Nature Geoscience, vol. 16, 671-674, 2023.

Moon, T., and others. Subsurface iceberg melt key to Greenland fjord freshwater budget. Nature Geoscience, vol. 11, 49–54, doi:10.1038/s41561- 017-0018-z, 2017.

Morrison, J., and others. A Method for Estimating Monthly Freshwater Discharge Affecting British Columbia Coastal Waters. Atmosphere-Ocean, vol. 50, 1-8, https://doi.org/10.1080/07055900.2011.637667, 2011.

Oksman, M., and others. Impact of freshwater runoff from the southwest Greenland Ice Sheet on fjord productivity since the late 19th century. The Cryosphere, vol. 16, 2471-2491, 2022.

Oksman, M., and others. Climate variability and glacier dynamics linked to fjord productivity changes over the last ca. 3300 years in Nuup Kangerlua, Southwest Greenland. Paleoceanography and Paleoclimatology, 2024.

Pata, P.R., and others. Persistent zooplankton bioregions reflect long-term consistency of community composition and oceanographic drivers in the NE Pacific. Progress in Oceanography, vol. 206, https://doi.org/10.1016/j.pocean.2022.102849, 2022.

Pavlova, O., and others. "Changes in Sea-Ice Extent and Thickness in Kongsfjorden, Svalbard (2003–2016)", in Hop, H. and Wiencke, C., eds.: The Ecosystem of Kongsfjorden, Svalbard. Advances in Polar Ecology, Springer, Cham. https://doi.org/10.1007/978-3-319-46425-1_4, 2019.

Pickard, G.L. Oceanographic Features of Inlets in the British Columbia Mainland Coast Journal of the Fisheries Board of Canada, https://doi.org/10.1139/f61-062, 1961.

Pickard, G.L. "Water structure in Chilean fjords", in Fraser, R., ed.: Oceanography of the South Pacific. New Zealand National Commission for UNESCO Wellington, 1973.

Pitcher G.C., and others. System controls of coastal and open ocean oxygen depletion. Progress in Oceanography, vol. 197, https://doi.org/10.1016/j.pocean.2021.102613, 2021.

Quiñones, Renato, and others. Environmental issues in Chilean salmon farming: a review. Reviews in Aquaculture, vol. 11, 375–402, 2019. https://doi.org/10.1111/raq.12337.

Rebolledo, L., and others. Late Holocene precipitation variability recorded in the sediments of Reloncaví Fjord (41°S, 72°W), Chile. Quaternary Research, vol. 84, 21–36, 2015. https://doi.org/10.1016/j.yqres.2015.05.006.

Ribeiro, Sophia, and others. Sea ice and primary production proxies in surface sediments from a High Arctic Greenland fjord: Spatial distribution and implications for palaeoenvironmental studies. AMBIO, vol. 46, 106, 2017.

Ribeiro, Sophia, and others. Vulnerability of the North Water ecosystem to climate change. Nature Communications, vol. 12, 4475, 2021.

Rojas, N., and Silva, N. Early diagenesis and vertical distribution of organic carbon and total nitrogen in recent sediments from southern Chilean fjords (Boca del Guafo to Pulluche Channel). Investigaciones Marinas, vol. 33, 2005. https://doi.org/10.4067/S0717-71782005000200005.

Rüggeberg, A., and others. Water mass characteristics and sill dynamics in a subpolar cold-water coral reef setting at Stjernsund, northern Norway, Marine Geology, Vol. 282, 5-12, https://doi.org/10.1016/j.margeo.2010.05.009, 2011.

Saldías, Gonzalo, and others. Freshwater structure and its seasonal variability off western Patagonia. Progress in Oceanography, vol. 174, 143-153, doi: 10.1016/j.pocean.2018.10.014, 2019.

Schiøtt, S., and others. Inuit and local knowledge on the marine ecosystem in Ilulissat Icefjord, Greenland. Human Ecology, 1-15, 2022.

Sepúlveda, J., and others. Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jacaf Fjord, 44°S). Quaternary Research, vol. 72, 400–409, 2009. https://doi.org/10.1016/j.yqres.2009.06.010

Sepúlveda, J., and others. Sources and distribution of organic matter in northern Patagonia fjords, Chile (~44–47°S): A multi-tracer approach for carbon cycling assessment. Continental Shelf Research, vol. 31, 315–329, 2011. https://doi.org/10.1016/j.csr.2010.05.013.

Silva, Nelson, and others. Land–ocean distribution of allochthonous organic matter in surface sediments of the Chiloé and Aysén interior seas (Chilean Northern Patagonia). Continental Shelf Research, vol. 31, 330–339, 2011. https://doi.org/10.1016/j.csr.2010.09.009

Skarðhamar J. and H. Svendsen. Circulation and shelf-ocean interaction off North Norway. Continental Shelf Research, vol. 25, 1541-1560, 2005.

Smeaton, C., and Austin, W. E. N. Understanding the role of terrestrial and marine carbon in the mid-latitude fjords of Scotland. Global Biogeochemical Cycles, vol. 36, 2022.

Schmidt, C. E., and others. The contrasting role of marine- and land-terminating glaciers on biogeochemical cycles in Kongsfjorden, Svalbard. Global Biogeochemical Cycles, vol. 39, 2025.

Stenevik, E. K., and others. Buoyancy and vertical distribution of Norwegian coastal cod (*Gadus morhua*) eggs from different areas along the coast. ICES Journal of Marine Science, vol. 65, 1198–1202, 2008.

Svendsen H, and others. The physical environment of Kongsfjorden– Krossfjor den, an Arctic fjord system in Svalbard. Polar Research, vol. 21, 133–166, 2002.

Syvitski, J.P.M., and others. Fjords: Processes and Products. Springer-Verlag, N.Y., 1987

Sætre, R., and others. Wind effects on the lateral extension of the Norwegian Coastal Water. Continental Shelf Research, vol. 8, 239-253, 1988.

Skogseth R, and others. Variability and decadal trends in the Isfjorden (Svalbard) ocean climate and circulation – An indicator for climate change in the European Arctic. Progress in Oceanography, vol. 187, https://doi.org/10.1016/j.pocean.2020.102394, 2020.

Smith, R.W., and others. High rates of organic carbon burial in fjord sediments globally. Nature Geoscience, vol. 8, 450-453, 2015.

Slater, D. A., and others. Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. Geophysical Research Letters, vol. 42, 2861–2868, 2015.

Straneo, F., and others. An interdisciplinary perspective on Greenland's changing coastal margins. Oceanography, vol. *35*, 106-117, 2022.

Straneo, F., and others. Characteristics of ocean waters reaching Greenland's glaciers. Annals of Glaciology, vol. 53, 202-210, 2012.

Søreide JE, and others. Seasonal mesozooplankton patterns and timing of life history events in high-arctic fjord environments. Frontiers in Marine Science, doi: 10.3389/fmars.2022.933461, 2022.

Søreide, J. E., and others.Timing of Blooms, Algal Food Quality and Calanus Glacialis Reproduction and Growth in a Changing Arctic. Global Change Biology, vol. 16, 3154–3163, doi:10.1111/j.1365-2486.2010.02175.x, 2010.

Søreide J.E, and others. Seasonal feeding strategies of Calanus in the high-Arctic Svalbard region. Deep-Sea Research II, 55, 2225– 2244, 2008.

Tommasi, D.A.G., and others. The seasonal development of the zooplankton community in a British Columbia (Canada) fjord during two years with different spring bloom timing. Marine Biology Research, vol. 9, 129-144, https://doi.org/10.1080/17451000.2012.708044, 2013.

Van Leeuwen, SM., and others. Climate change, marine resources and a small Chilean community: making the connections. Marine Ecology Progress Series, vol. 680: 223-246, https://doi.org/10.3354/meps13934, 2021.

Vermassen, F., and others. A reconstruction of warm-water inflow to Upernavik Isstrøm since 1925 CE and its relation to glacier retreat. Climate Past, vol. 15, 1171–1186, https://doi.org/10.5194/cp-15-1171-2019, 2019.

Vermassen, F., and others. Evaluating ice-rafted debris as a proxy for glacier calving in Upernavik Isfjord, NW Greenland. J. Quaternary Science, vol. 34, 258-267, https://doi.org/10.1002/jqs.3095, 2019.

Vernet, María, and others. Spatial variability in rates of net primary production (NPP) and onset of the spring bloom in Greenland shelf waters. Progress in Oceanography, vol. 198, 2021.

Vonnahme, T.R., and others. Impact of winter freshwater from tidewater glaciers on fjords in Svalbard and Greenland; A review. Progress in Oceanography, 2023.

Zimmermann F., and others. Fine-scale spatial variation of northern shrimp and Atlantic cod across three Norwegian fjord systems and implications for management. Estuarine, Coastal and Shelf Science, vol. 292, https://doi.org/10.1016/j.ecss.2023.108435, 2023.

Watts, E.G., and others. Burial of organic carbon in Swedish Fjord sediments: Highlighting the importance of sediment accumulation rate in relation to fjord redox conditions. Journal of Geophysical Research-Biogeosciences, vol. 129, 2024.

Wehrmann M., and others. Iron and manganese speciation and cycling in glacially influenced high-latitude fjord sediments (West Spitsbergen, Svalbard): Evidence for a benthic recycling-transport mechanism Geochimica et Cosmochimica Acta, vol. 141, 628-655, 2014.

Wolfe, A., and others. Impact of advection loss due to wind and estuarine circulation on the timing of the spring phytoplankton bloom in a fjord. ICES Journal of Marine Science, vol. 73, 1589-1609, https://doi.org/10.1093/icesjms/fsv151, 2015.

York A.V., and others. Changes at the edge: trends in sea ice, ocean temperature and ocean color at the Northwest Atlantic/Southern Arctic interface. Annals of Glaciology, 1–15, doi:10.1017/aog.2020.66, 2020.

Section 4
Chapter 6: Pressures: Invasive species

Writing Team: Thomas W Therriault (CAN-Global, North Pacific), Chad L Hewitt (AU-NZ-Global, South Pacific), Bella Galil (ISR-Med), Graeme Inglis (NZ-South Pacific, SIDS), Evangelina Schwindt (ARG-South Atlantic), Alejandro Bortolus (ARG-South Atlantic), ~~Tammy~~ Tamara B Robinson (RSA-South Atlantic/Indian), Susana Carvalho (SA-Red Sea), Henn Ojaveer (EST-Baltic/North Seas), Jihno Chae (KOR-North Pacific)

1.0: Key Findings

- Globally, non-indigenous species (NIS) continue to spread, exacerbated by climate change and human activities, negatively impacting some of the most vulnerable marine ecosystems ~~with some of the most sensitive ecosystems now being impacted by invasive species~~
- NIS introductions ~~have resulted in newly documented, significant~~continue to negatively impacts ~~on~~ native species and habitats, affecting ~~with~~ global ecological, socio-economic, cultural and human health values~~impacts~~
- Preventing introductions is ~~essential~~ crucial, however, ~~but there are few~~ limited mandatory global or regional regulations or policies ~~in place~~exist
- A significant gap remains in s~~S~~ystematic monitoring and information sharing ~~for~~ about NIS ~~remains a significant gap~~ at multiple temporal and spatial scales, ~~which~~ undermining~~es~~ management and response efforts~~, including response~~
- ~~-~~

The lack of long-term studies on NIS impacts hinders risk identification and reduces the effectiveness of post-invasion management efforts~~Long-term studies on the impacts of many NIS impair risk identification and the success of post-invasion management efforts~~

- ~~-~~

2.0: Introduction

Non-indigenous species (NIS) occur globally with identity, abundance, and richness affected by biotic and abiotic factors (Figure 1). The ~~continued~~ ongoing accidental or intentional introduction of species~~, either intentionally or unintentionally, has significant negative consequences for~~significantly impacts marine ecosystems, ~~contributing~~ creating~~to~~ biotic homogenization and threatening biodiversity,~~;~~ ecosystem services,~~;~~ human health,~~;~~ and ~~numerous~~ other socio-economic ~~endpoints~~ outcomes (Schwindt and others, 2022; Ojaveer and others, 2023; Roy and others, 2024; Simberloff and others, 2024; Zaiko and others, 2024). Any ~~NIS~~ species ~~has the potential to~~may become invasive under

favorable conditions (Williamson, 1996; UNEP, 2002) so~~.~~ ~~Therefore, adopting a precautionary approach,~~ this chapter ~~considers~~ adopts a precautionary approach by considering all NIS while acknowledging some native species can also become invasive (e.g., Crown of Thorns Seastar; Hoey and others, 2016; Guareschi and others, 2024).

Information on NIS varies, ~~spatially and temporally~~ with strong biases in the breadth and depth of taxonomic coverage and expertise, favoring larger, more conspicuous species or those with economic consequences (Watkins and others, 2021; Schwindt and others, 2022). As noted in WOA2, there is a lack of, and continuing need for, large-scale systematic surveys for NIS ~~and their impacts~~. The context-dependency of many NIS further impairs our ability to generalize ~~and there are challenges extrapolating NIS impacts to new locations given the context-dependency of many aquatic NIS~~ (Carlton and Schwindt, 2024; Figure 2; Table 1). ~~Predicting~~ Determining which NIS to prioritize for management ~~action~~ is challenging, but there are an increasing number of screening and risk assessment tools to ~~aid in prioritization exercises~~support decision-making (Dahlstrom and others, 2011; Kumschick and Richardson, 2013; Srébalienė and others, 2019; Wilcox and others, 2024).

Global policy documents clearly identify NIS as a major threat to biodiversity. The Kunming-Montreal Global Biodiversity Framework Targets (developed under the Convention on Biological Diversity) directly address NIS. Specifically, Target 6 requires States to minimize the impacts of NIS on biodiversity and ecosystem services through preventative measures that will reduce the rates of introduction and establishment of NIS by at least 50 per cent by 2030. ~~Also, t~~The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) ~~have~~ has recognized the negative impacts of invasive species around the world (IPBES, 2023) and their assessments highlight~~ed~~ several important considerations, including local extinctions caused by marine species such as *Pterois volitans, Caulerpa taxifolia*, and *Mytilus galloprovincialis* (Bacher and others, 2023; Schwindt and others, 2024). Given Marine Protected Areas (MPAs) are one internationally accepted tool to conserve biodiversity it is surprising that there are limited efforts to characterize NIS in MPAs or to better understand their potential impacts (Soares, 2018; Mendez and Schwindt, 2024). Meanwhile, recreational vessels ~~traffic~~, among other vectors, ~~is~~ are creating invasion networks by linking MPAs to invasion hotspots (Iacarella and others, 2020)~~,~~ thus compromising conservation objectives.

As a global ecosystem stressor, NIS can belong to any taxa (see Briski et al., 2024) so there are potential linkages to all sub-chapters in Chapters 4 (Biodiversity) and 5 (Habitats). Some marine plants have been introduced globally, including habitat altering species such as *Spartina* and *Phragmites* (sub-chapter 4h). ~~Similarly, b~~Bivalves, such as Pacific oyster,

have been introduced for aquaculture purposes, but often with negative consequences for native biodiversity (Bacher and others, 2023 (Box 4.11); Di Blasio and others, 2023). ~~while~~ White Spot Syndrome (WSS), a viral disease that affects most of the commercially cultivated marine shrimp species globally (Flegel, 1997; Lotz, 1997), has spread to most shrimp culture countries (Yan and others, 2007). ~~Also,~~ NIS also have been shown to benefit from already stressed or degraded habitats ~~due~~ resulting from ~~to~~ other human impacts, which are linked to sub-chapters in Chapter 6 (Pressures), ~~while~~ and many NIS have socio-economic or cultural impacts (Campbell and Hewitt, 2018; Bortolus and Schwindt, 2022), so there are linkages to Section 5 (Socio-ecological systems).

3.0: Change Since WOA2

Globally, significant gaps remain in the detection, reporting and response to NIS thereby limiting our understanding of ecological, economic, and cultural impacts, which in turn limits our ability to predict NIS impacts in new locations (e.g., Schwindt and others, 2022). The continued introduction and spread of NIS compromises the achievement of up to 11 of the 17 United Nations Sustainable Development Goals ~~-~~and other global conservation efforts. Although vectors and pathways have only been partially characterized globally, commercial shipping, the Suez Canal and other artificial ~~made~~ waterways, aquaculture, recreational boats, and aquarium releases are responsible for most NIS introductions and spread (Bailey and others, 2020; Seebens and others, 2021; Menezes and others, 2022; Guerra-Garcia and others, 2023; Aylagas and others, 2024). M~~, while m~~arine debris/litter ~~has also been implicated in some basins~~is an emerging vector globally (Therriault and others, 2018; Audrézet and others, 2021; Galil, 2023), ~~creating unprecedented links~~with unprecedented pathways already noted between Antarctica and other continents (Dawson and others, 2024).

Biogeographic barriers can limit the natural spread of NIS depending on their permeability, ~~but~~ however, climate change is affecting the strength and location of these barriers (Krumhansl and others, 2023) ~~often necessitating effective management to limit human activities that bridge these barriers~~. Climate change ~~is~~ also result~~s~~ing in more frequent and intense marine heat waves, ~~which are~~ facilitating the spread and impacts of NIS. In the Mediterranean, New Zealand, and temperate regions of Australia~~, and New Zealand~~ the nearshore ecosystem has proven highly vulnerable to recurrent heat-induced mass mortality events over the past four decades (Thomsen and others, 2019; Verdura and

others, 2019, Tait and others, 2021; Wernberg, 2021; Bell and others, 2023) – a scenario that is likely to repeat itself in multiple ocean basins. Most research has documented NIS impacts on ecological, and to a lesser extent, socioeconomic endpoints, but there is growing recognition of cultural impacts of NIS in some ocean basins ~~(see examples in Figure 2, Table 1)~~. Figure 2 and Table 1 provide examples of the types of impacts certain NIS can have but an exhaustive analysis is beyond the scope of this chapter.

4.0: Region-specific Changes

a) Arctic Ocean

There continue to be significant knowledge gaps for the Arctic Ocean with no new reports since WOA2. However, some studies have shown that NIS from polar and sub-polar environments could establish in the Arctic Ocean, especially under multiple climate change projections and increased vessel traffic (Goldsmit and others, 2020). For example, t~~T~~he Red King Crab (*Paralithodes camtschaticus*) originally introduced to establish a ~~fisheries~~ fishery has now spread ~~into~~ to Norway, causing significant ecological and economic impacts (Sundet and Hoel, 2016).

b) The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

By July 2023, 1~~,~~671 NIS and ~~and~~ cryptogenic marine~~/ and~~ oligohaline species in European ~~Seas~~ seas had been reported (Katsanevakis and others, 2023) – likely a significant undercount. By December 2020, 1006 NIS (excluding cryptogenic or data-deficient species) had been reported for the Mediterranean Sea alone, with half representing Erythraean species introduced via the Suez Canal (Galanidi and others, 2023) suggesting ~~a sizable 'invasion debt'~~ invasions will continue. The number of NIS in the Black Sea is unclear, but ~~more~~ recent accounts list 81 NIS, plus 113 cryptogenic, cryptogenic-expanding and data-deficient species (Öztürk, 2021; Băncilă and others, 2022; Shalovenkov, 2022). The number of new NIS to the Baltic Sea was higher during the most recent HELCOM assessment period (13 vs 12 NIS – HELCOM, 2023), while~~.~~ t~~T~~he number of new NIS in the Greater North Sea has varied annually between 3 and ~~-~~5 species from 2018-2021 with a reversal of the long-term increasing trend (ICES, 2022). ~~while t~~The rate of new NIS introductions ~~also~~ has decreased in OSPAR Regions II (Greater North Sea), III (Celtic Seas) and IV (Bay of Biscay and Iberian Coast) (Stæhr and others, 2022).

c) The South Atlantic Ocean and the Wider Caribbean

National scale reassessments have not been conducted since WOA2 but high-profile species such as the ~~sun~~ Sun ~~coral~~ Coral (*Tubastraea* spp.) continue to spread (Dutra and others, 2023). At least ten NIS reported in the Southwest Atlantic are now widely distributed, with another 24 NIS expanding their ranges (Schwindt and others, 2020; Teixeira and Creed, 2020) ~~with~~ and several others predicted to spread further (Schwindt and others, 2022; Soares and others, 2022). In Argentina and Uruguay, six NIS hotspots ~~of NIS~~ were identified, mostly associated with ports and cities (Reyna and others, 2023). In the Southeast Atlantic, almost 100 NIS are now recognized from South African coastlines (Robinson and others, 2020) and although there are efforts to establish routine monitoring programs (Loureiro and others, 2021), detections of new incursions remain largely coincidental.

For the wider Caribbean, a recent assessment reported 33 ~~species~~ NIS (Alidoost Salimi and others, 2021) – likely an underestimate. Along this vast region, ~~the~~ Lionfish (*Pterois* spp.), is probably the most widespread and studied NIS, with ecological, economic, and human health impacts (Côté and others, 2013). ~~while i~~In South Africa, the failure of the first eradication attempt of European green crab (*Carcinus maenas*) populations reinforced the need for preventative management (Mabin and others, 2020).

d) The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

The Red Sea is a major shipping route making it vulnerable to NIS introductions. However, the status of NIS in the region is uncertain due to a lack of monitoring efforts and baseline biodiversity information. Clarke and others (2020) identified 35 NIS for the Arabian Gulf and Sea of Oman, with other species ~~that require~~requiring additional effort~~s~~ to confirm their invasion status. Fernandez and others (2022) conducted an eDNA study from the Gulf of Aqaba and suggested that more than 36% of exact sequence variants detected were non-native. Aylagas and others (2024) and Shchepanik and others (2024) used molecular methods to report 16 new NIS in the Red Sea, including ascidians, bryozoans, and crustaceans as well as Barramundi (*Lates calcarifer*)~~and Mozambique Tilapia~~, ~~two~~ an introduced aquaculture species.

e) The North Pacific Ocean

Large-scale studies of NIS in the North Pacific have not been updated, although several of the 747 reported in WOA2 (Therriault and others, 2021) continue to spread within the basin, and there remains an increasing trend of invasions over time (Bailey and others, 2020). Habitat suitability modeling, identified the southern Salish Sea as an invasion hotspot, along with parts of the outer coasts of Washington and Oregon, with hotspots predicted to shift or expand and new ones likely to appear under a future climate (Lyons and others, 2020). Species like European green crab (*C. maenas*) continue to spread poleward along the west coast of North America with significant impacts on eelgrass (Howard and others, 2019) and other native species (Grosholz and others, 2000). In China, the introduction of *Spartina* to prevent coastal erosion ~~has~~ resulted in extensive spread with dense stands drastically altering the nearshore environment (Chung, 2006; Zhang and others, 2017)~~— impacts that have occurred elsewhere where *Spartina* has invaded~~. China implemented a diverse series of policies, regulations, and ecological restoration projects that have effectively controlled the spread of *Spartina alterniflora* (Li et al., 2022; Luo and Ma, 2025) and by October 2023 had resulted in an 86% removal (Dong and others, 2024).

f) The South Pacific Ocean

Large scale ~~implementation of~~ surveys and surveillance continues to occur in Australia and New Zealand, with increasing baseline evaluations and the development of tools to aid vector management and surveillance in the South Pacific (SPREP 2022). Regardless, ~~but~~ NIS continue to spread (Lane and others, 2022). Despite management of some declared pests (e.g. *Undaria, Asterias, Sabella*) in Australia, ~~Early~~ early ~~Detection~~ detection and ~~Rapid~~ rapid ~~Response~~ response tools generally are lacking. The recent arrival and rapid spread of two habitat-forming subtropical algae in New Zealand, *Caulerpa brachypus* and *C. parvifolia*, caused ~~national~~ National concern about impacts on native habitats, recreational and commercial fisheries, and the spiritual and cultural resources of New Zealand's ~~i~~Indigenous Māori (Evans, 2022). Impact studies of NIS have examined the likelihood of ecosystem impacts ~~of~~ due to key invaders (e.g., Soliman and Inglis, 2018; Atalah and others, 2019; Tait and others, 2020; 2023) and the underlying impacts to social and cultural values (Campbell and Hewitt, 2018; Manaaki te Awanui 2021; Campbell and others, 2024).

g) The Southern Ocean

The Southern Ocean also has significant knowledge gaps with respect to NIS reports. An horizon scanning exercise suggested the Antarctic Peninsula maybe at risk of ballast water and hull fouling introduced invertebrate species ~~Due to its proximity to the South American continental coast, the Antarctic Peninsula region (APR) represents the area at greatest risk of NIS introductions with 113 NIS having some invasion potential and 13 NIS considered high risk, especially marine invertebrates~~ (Hughes and others, 2020). Unless appropriate biosecurity measures are applied~~,~~ the rates of invasions in this region are likely to increase (McCarthy and others, 2022).

5.0: Remaining Key Knowledge and Capacity Changes and Any New Gaps

Critical data gaps and a lack of standardization or frameworks to facilitate comparisons make assessments like these challenging (Carlton and Schwindt, 2024). Further, efforts need to be made to ensure NIS records are freely accessible to the global community by removing access and language barriers. Knowledge brokers could serve this function connecting data holders to managers.

NIS are a major threat to biodiversity yet most biodiversity studies (which are also incomplete for most of the world's ocean) often do not distinguish native from non-native species. Some global registers are attempting to track NIS separately (e.g., World Register of Marine Species, Ocean Biodiversity Information System) but significant gaps remain. New molecular methods are improving our understanding of biodiversity in general (Adams et al., 2023) and NIS broadly (Zhan and others, 2014; Westfall and others, 2020; Lavrador and others, 2024) but a lack of verified DNA barcodes and standard protocols for their application to surveillance has only confounded the problem (Couton and others, 2022; Zaiko and others, 2022; Bowers and others, 2023). Against this background and the accelerated homogenization of the world's oceans, it will be increasingly difficult to ensure NIS are correctly identified.

Prevention is key to limiting the impacts of NIS but such strategies are limited and efforts are needed to prioritize continuous monitoring and early detection. Global efforts have been undertaken to reduce the risk of NIS introductions via the IMO Ballast Water Management Convention and biofouling management guidelines and regional efforts have applied the ICES Code of Practice to reduce risk of NIS introductions from aquaculture activities but many vectors and pathways remain unregulated and the effectiveness of those that are is uncertain (e.g., Outinen and others, 2024). Regional efforts exist to reduce the risk to the North-East Atlantic and the Baltic Sea via the Convention for the Protection

of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the Convention on the Protection of the Marine Environment of the Baltic Sea Area, known as the HELCOM area (Helsinki Convention) in addition to several national efforts (Castro and others, 2018). However, the fragmented and patchwork research and policy environment that differs globally, regionally, and nationally only confounds our ability to identify and respond to NIS risks. One holistic, interdisciplinary approach that has been suggested is the One Biosecurity model (Hulme, 2020, 2021; Hulme and others, 2023; Bray and others, 2024) that aims to reduce risks across ecosystem components by reducing redundancy and increasing collaboration. Such an approach, if applied broadly, would help managers ~~understand~~ identify the NIS that need to be prioritized for early detection, control~~,~~ or management, ~~which~~ all of which require~~s~~ context-specific approaches to ensure their effectiveness.

In most global ocean basins only a few, high risk/high profile NIS receive a bulk of the attention and research effort (Watkins and others, 2021, Ojaveer and others, 2023) limiting our ability to comprehensively identify NIS impacts across a number of impact categories (e.g., socio-economic, cultural), understand how NIS are being redistributed by human activities, and compromising our ability to determine the achievement of SDG goals. Further, most studies have been conducted in coastal waters with limited attention to the deep sea, areas beyond national jurisdictions or polar regions which are much more logistically difficult to access and where baseline information is virtually non-existent but where NIS are known to occur~~,~~ and human activities are increasing. Marine-based industries (fishing, aquaculture, transport, energy, mining, etc.) are increasing at a faster rate than other global industries ~~(OECD placeholder)~~ with NIS implicated in all of these, compromising the achievement of a sustainable blue economy. Thus, prevention and mitigation must be increasing considered as these industries develop to ensure the negative consequences of NIS are fully ~~characterized and accounted for~~considered (Carvalho and others, 2023; Aylagas and others, 2024).

6.0: References

Adams, Clare I.M., and others (2023). Environmental DNA metabarcoding describes biodiversity across marine gradients. *ICES Journal of Marine Science*, vol. 80, No. 4, pp. 953–971.

Alidoost Salimi, Parisa, and others (2021). A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. *Marine Biodiversity Records*, vol. 14, No. 1, p. 11.

Atalah, Javier, and others (2019). The introduced fanworm*, Sabella spallanzanii*, alters soft sediment macrofauna and bacterial communities. *Frontiers in Ecology and Evolution*, vol. 7, p. 481.

Audrézet, François, and others (2021). Biosecurity implications of drifting marine plastic debris: current knowledge and future research. *Marine Pollution Bulletin*, vol. 162, p. 111835.

Aylagas, Eva, and others (2024). Disentangling eukaryotic biodiversity patterns from man-made environments (port and marina) and nearby coral reefs in the Red Sea: A focus on the surveillance of non-indigenous species. *Environmental DNA*, vol. 6, No. 4, p. e583.

Bacher, Sven, and others (2023). Chapter 4: Impacts of invasive alien species on nature, nature's contributions to people, and good quality of life. In: Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, HE, Pauchard, A, Stoett, P, and Renard Truong, T. (eds.). IPBES secretariat, Bonn, Germany.

Bailey, Sarah A., and others (2020). Trends in the detection of aquatic non-indigenous species across global marine, estuarine and freshwater ecosystems: A 50-year perspective. *Diversity and Distributions*, vol. 26, No. 12, pp. 1780–1797.

Băncilă, Raluca I., and others (2022). Alien species of the Romanian and Bulgarian Black Sea coast: state of knowledge, uncertainties, and needs for future research. *Aquatic Invasions*, vol. 17, No. 3, pp. 353–373.

Barclay, Kristina M., and others (2024). Predation scars provide a new method to distinguish native and invasive crab predation on mollusc prey. *Ecology and Evolution*, vol. 14, No. 9, p. e70338.

Bell, James J., and others (2023). Marine heat waves drive bleaching and necrosis of temperate sponges. *Current Biology*, vol. 33, No. 1, pp. 158–163.

Bortolus, Alejandro, and Evangelina Schwindt (2022). Biological invasions and human dimensions: We still need to work hard on our social perspectives. *Ecología Austral,* 32: 767–783. Bortolus, Alejandro, and others (2015). Reimagining South American coasts: unveiling the hidden invasion history of an iconic ecological engineer. *Diversity and Distributions*, vol. 21, No. 11, pp. 1267–1283.

Bowers, Holly A., and others (2021). Towards the optimization of eDNA/eRNA sampling technologies for marine biosecurity surveillance. *Water*, vol. 13, No. 8, p. 1113.

Bray, Jonathan Peter, and others (2024). Bridging aquatic invasive species threats across multiple sectors through One Biosecurity. *BioScience*, vol. 74, No. 7, pp. 440–449.

Briski, Elizabeta, and others (2024). Does non-native diversity mirror Earth's biodiversity? *Global Ecology and Biogeography*, vol. 33, No. 1, pp. 48–62.

Campbell, Marnie L., and Chad L. Hewitt (2018). Which values do non-native marine species affect? A case-study exploration of perceived values at threat in Micronesia. *Frontiers in Marine Science*, vol. 5, p. 247.

Campbell, Marnie L., and others (2024). Critical coastal values impacted by marine bioinvasions: What the public value about marine and coastal areas and what is at stake? *Environmental Science & Policy*, vol. 157, p. 103786.

Carlton, James T., and Evangelina Schwindt (2024). The assessment of marine bioinvasion diversity and history. *Biological Invasions*, vol. 26, No. 1, pp. 237–298.

Carnell, Paul E., and Michael J. Keough (2014). Spatially variable synergistic effects of disturbance and additional nutrients on kelp recruitment and recovery. *Oecologia*, vol. 175, pp. 409–416.

Carvalho, Susana, and others (2023). Hurdles and opportunities in implementing marine biosecurity systems in data-poor regions. *BioScience*, vol. 73, No. 7, pp. 494–512.

Castro, Maria C.T., and others (2018). Ten years of Brazilian ballast water management. *Journal of Sea Research*, vol. 133, 2018, pp. 36–42.

Chung, Chung-Hsin (2006). Forty years of ecological engineering with *Spartina* plantations in China. *Ecological Engineering*, vol. 27, No. 1, pp. 49–57.

Clarke, Stacey A., and others (2020). Identifying potentially invasive non-native marine and brackish water species for the Arabian Gulf and Sea of Oman. *Global Change Biology*, vol. 26, No. 4, pp. 2081–2092.

Côté, Isabelle M., and others (2013). Predatory fish invaders: Insights from Indo-Pacific lionfish in the western Atlantic and Caribbean. *Biological Conservation*, vol. 164, pp. 50–61.

Couton, Marjorie, and others (2022). Water eDNA metabarcoding is effective in detecting non-native species in marinas, but detection errors still hinder its use for passive monitoring. *Biofouling*, vol. 38, No. 4, pp. 367–383.

Dahlstrom, Alisha, and others (2011). A review of international, regional and national biosecurity risk assessment frameworks. *Marine Policy*, vol. 35, No. 2, pp. 208–217.

Dawson, Hannah R.S., and others (2024). Floating debris and organisms can raft to Antarctic coasts from all major Southern Hemisphere landmasses. *Global Change Biology*, vol. 30, No. 8, e17467.

Des, M., and others (2022). Historical and future naturalization of *Magallana gigas* in the Galician coast in a context of climate change. *Science of the Total Environment*, vol. 838, p.156437.

Di Blasio, Laura, and others (2023). Alien Species Associated with New Introductions and Translocations of Commercial Bivalves in Italian Marine Waters. *Sustainability*, vol. 15, No. 4, p.3536.

Dong, Di, and others (2024). Mangroves invaded by *Spartina alterniflora* Loisel: A remote sensing-based comparison for two protected areas in China. *Forests*, vol. 15, No. 10, p. 1788.

Dutra, Beatriz Sant'Anna Vasconcelos Marafiga, and others (2023). When species become invasive research becomes problem oriented: a synthesis of knowledge of the stony coral *Tubastraea*. *Biological Invasions*, vol. 25, No. 7, pp. 2069–2088.

El Zrelli, Radhouan, and others (2021). The macroalgae *Lophocladia lallemandii* and *Sarconema filiforme* and the spaghetti bryozoan *Amathia verticillata* in native seagrass beds in the Gulf of Gabès (southeastern Tunisia, Mediterranean Sea). *BioInvasions Records,* vol. 10, No. 1, pp. 103–108.

Evans, Kate (2022). Killer Algae. *New Zealand Geographic*, 177 (Sep-Oct). Kowhai Media. www.nzgeo.com/stories/killer-algae/.

Falk-Petersen, Jannike, and others (2011). Establishment and ecosystem effects of the alien invasive red king crab (*Paralithodes camtschaticus*) in the Barents Sea–a review. *ICES Journal of Marine Science*, vol. 68, No. 3, pp. 479–488.

Fernandez, Sara, and others (2022). Non-native species in the north Gulf of Aqaba (Red Sea) revealed from environmental DNA. *Frontiers in Marine Science*, vol. 9, p. 940889.

Fisher, Mary C., and others (2024). Invasive European green crab (*Carcinus maenas*) predation in a Washington State estuary revealed with DNA metabarcoding. *PLoS ONE*, vol. 19, No. 5, p. e0302518.

Flegel, Timothy William (1997). Major viral diseases of the black tiger prawn (*Penaeus monodon*) in Thailand. *World Journal of Microbiology and Biotechnology*, vol. 13, pp. 433–442.

Galanidi, Marika, and others (2023). Validated inventories of non-indigenous species (NIS) for the Mediterranean Sea as tools for regional policy and patterns of NIS spread. *Diversity*, vol. 15, No. 9, p. 962.

Galil, Bella S. (2023). A sea, a canal, a disaster: the Suez Canal and the transformation of the Mediterranean biota. In The Suez Canal: past lessons and future challenges (pp. 199–215). Cham: Springer International Publishing.

Gayoso, Ana María, and Vanesa K. Fulco (2006). Occurrence patterns of *Alexandrium tamarense* (Lebour) Balech populations in the Golfo Nuevo (Patagonia, Argentina), with observations on ventral pore occurrence in natural and cultured cells. *Harmful Algae*, vol. 5, No. 3, pp. 233–241.

Ghermandi, Andrea, and others (2015). Jellyfish outbreak impacts on recreation in the Mediterranean Sea: welfare estimates from a socioeconomic pilot survey in Israel. *Ecosystem services*, vol. 11, pp. 140–147.

Gittenberger, A., (2010). Risk analysis of the colonial sea-squirt *Didemnum vexillum* (Kott, 2002) in the Dutch Wadden Sea, a UNESCO World Heritage Site. *GiMaRIS*.

Goldsmit, Jesica, and others (2020). What and where? Predicting invasion hotspots in the Arctic marine realm. *Global change biology*, vol. 26, No. 9, pp. 4752–4771.

Gribben, Paul E., and others (2013). Positive versus negative effects of an invasive ecosystem engineer on different components of a marine ecosystem. *Oikos*, vol. 122, No. 6, pp. 816–824.

Grosholz, Edwin D., and others (2000). The impacts of a nonindigenous marine predator in a California bay. *Ecology,* vol. 81, No. 5, pp. 1206–1224.

Guareschi, Simone, and others (2024). Framing challenges and polarized issues in invasion science: toward an interdisciplinary agenda. *BioScience*: biae084.

Guerra-García, J.M., and others (2023). Quick spreading of the exotic *Laticorophium baconi* (Shoemaker, 1934): another small stowaway overlooked? *Mediterranean Marine Science*, vol. 24, No. 3, pp. 644–665.

HELCOM (2023). State of the Baltic Sea. Third HELCOM holistic assessment 2016-2021. *Baltic Sea Environment Proceedings n°194*. www.helcom.fi/post_type_publ/holas3_sobs.

Hewitt, C.L. (2003). The diversity of likely impacts of introduced marine species in Australian waters. *Records of the South Australian Museum Monographs Series*, vol. 7, pp. 3–10.

Hewitt, Chad L. (2022). Evaluating nonindigenous marine species (NIMS) risks associated with decommissioning oil and gas infrastructure. NDRI Project 1.3: https://ndriaustralia.org/wp-content/uploads/2023/07/NDRI-FINAL-Report-NIS-OG-decommissioning-.pdf

Hoey, Jessica, and others (2016). *Acanthaster planci* invasions: applying biosecurity practices to manage a native boom and bust coral pest in Australia. *Management of Biological Invasions*, vol. 7, No. 3, pp. 213–220.

Holloway, Michael G., and Michael J. Keough (2002). An introduced polychaete affects recruitment and larval abundance of sessile invertebrates. *Ecological Applications, vol.* 12, No. 6, pp. 1803–1823.

Howard, Brett R., and others (2019). Habitat alteration by invasive European green crab *(Carcinus maenas*) causes eelgrass loss in British Columbia, Canada. *Biological Invasions*, vol. 21, No. 12, pp. 3607–3618.

Hughes, Kevin A., and others (2020). Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. *Global change biology*, vol. 26, No. 4, pp. 2702–2716.

Hulme, Philip E. (2020). One Biosecurity: A unified concept to integrate human, animal, plant, and environmental health. *Emerging Topics in Life Sciences*, vol. 4, No. 5, pp. 539–549.

Hulme, Philip E. (2021). Advancing One Biosecurity to address the pandemic risks of biological invasions. *BioScience*, vol. 71, No. 7, pp. 708–721.

Hulme, Philip E., and others (2023). Emerging advances in biosecurity to underpin human, animal, plant, and ecosystem health. *iScience*, vol. 26, No. 9, pp. 107462.

Iacarella, Josephine C., and others (2020). Unwanted networks: Vessel traffic heightens the risk of invasions in marine protected areas. *Biological Conservation*, vol. 245, pp. 108553.

ICES (2022). Greater North Sea ecoregion – Ecosystem overview. In *Report of the ICES Advisory Committee. ICES Advice 2022, Section 7.1*, www. ices-library.figshare.com/articles/report/Greater_North_Sea_ecoregion_Ecosystem_Overview/21731912?file=38559557

IPBES (2023). Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, HE, Pauchard, A, Stoett, P, and Renard Truong, T. (eds.). IPBES secretariat, Bonn, Germany.

Jassim A., and others (2021). Hitchhiking of encrusting organisms on floating marine debris along the west coast of Qatar, Arabian/Persian Gulf. *Science of the Total Environment*, vol. 776, p. 145985

Katsanevakis, Stelios, and others (2023). Marine invasive alien species in Europe: 9 years after the IAS Regulation. *Frontiers in Marine Science*, vol. 10, pp. 1271755.

Kim, Jin Ho, and others (2018). Revealing the distinct habitat ranges and hybrid zone of genetic sub-populations within *Pseudo-nitzschia pungens* (Bacillariophyceae) in the West Pacific area. *Harmful algae*, vol. 73, pp. 72–83.

Kotta, Jonne, and others (2018). Novel crab predator causes marine ecosystem regime shift. *Scientific reports*, vol. 8, No. 1, p. 4956.

Krumhansl, Kira, and others (2023). Permeability of coastal biogeographic barriers to marine larval dispersal on the east and west coasts of North America. *Global Ecology and Biogeography*, vol. 32, No. 6, pp. 945–961.

Kumschick, Sabrina, and David M. Richardson (2013). Species-based risk assessments for biological invasions: advances and challenges. *Diversity and Distributions*, vol. 19, No. 9, pp. 1095–1105.

Lane, Henry, and others (2022). Aquatic disease in New Zealand: synthesis and future directions. *New Zealand Journal of Marine and Freshwater Research*, vol. 56, No. 1, pp. 1–42.

Lavrador, Ana S., and others (2024). Comprehensive DNA metabarcoding-based detection of non-indigenous invertebrates in recreational marinas through a multi-substrate approach. *Marine Environmental Research*, vol. 200, p. 106660.

Lee, Jongmin, and others (2024). Effects of exotic *Spartina alterniflora* invasion on benthic environments in the Yellow Sea. *Marine Pollution Bulletin*, vol. 208, p. 117017.

Li, Huiying, and others (2022). Invasion of *Spartina alterniflora* in the coastal zone of mainland China: Control achievements from 2015 to 2020 towards the Sustainable Development Goals. *Journal of Environmental Management*, vol. 323, p. 116242.

Li, Xiaodong, and others (2019). A review of *Karenia mikimotoi*: Bloom events, physiology, toxicity and toxic mechanism. *Harmful Algae*, vol. 90, p. 101702.

Lotz, J (1997). Viruses, biosecurity and specific pathogen-free stocks in shrimp aquaculture. *World Journal of Microbiology and Biotechnology*, vol. 13, pp. 405–413.

Luo, Xin, and Keming Ma, (2025). A framework for the evaluation and selection of invasive plant management technologies: The case of *Spartina alterniflora* in China. Ecological Frontiers, vol. 45, No. 3, pp. 646–657.

Loureiro, T. G., and others (2021). Dropping plates to pick up aliens: towards a standardised approach for monitoring alien fouling species. *African Journal of Marine Science,* vol. 43, No. 4, pp. 483–497.

Lyons, Devin A., and others (2020). Identifying marine invasion hotspots using stacked species distribution models. *Biological Invasions*, vol. 22, pp. 3403–3423.

Mabin, Clova A., and others (2020). The first management of a marine invader in Africa: The importance of trials prior to setting long-term management goals. *Journal of environmental management*, vol. 261, pp. 110213.

Manaaki te Awanui & NIWA (2021). Te Waharoa. https://express.adobe.com/page/P7C6asxOH2GO9/.

McCarthy, Arlie H., and others (2022). Ship traffic connects Antarctica's fragile coasts to worldwide ecosystems. *Proceedings of the National Academy of Sciences*, vol. 119, No. 3, p. e2110303118.

Mendez, María M., and Evangelina Schwindt (2024). Anthropogenic stressors and rocky shore communities along Atlantic Patagonia: The need of including coastal biodiversity in marine protected areas planning. *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 34, No. 8, p. e4228.

Menezes NM, and others (2022). New non-native ornamental octocorals threatening a South-west Atlantic reef. Journal of the Marine Biological Association of the United Kingdom, vol. 101, No. 6, pp. 911-917.

Newton, Christine, and others (2013). Invasion of the red seaweed *Heterosiphonia japonica* spans biogeographic provinces in the Western North Atlantic Ocean. *PLoS ONE*, vol. 8, No. 4, pp. e62261.

Ojaveer, Henn, and others (2023). Quantifying impacts of human pressures on ecosystem services: Effects of widespread non-indigenous species in the Baltic Sea. *Science of The Total Environment*, vol. 858, part 2, pp. 159975.

Outinen, Okko, and others (2024). Biological testing of ships' ballast water indicates challenges for the implementation of the Ballast Water Management Convention. *Frontiers in Marine Science*, vol. 11, p.1334286.

Öztürk, Bayram (2021). Non-indigenous species in the Mediterranean and the Black Sea. *General Fisheries Commission for the Mediterranean. Studies and Reviews*, vol. 87, pp. I–89.

Perry, R. Ian, and others (2023). Domoic acid in Canadian Pacific waters, from 2016 to 2021, and relationships with physical and chemical conditions. *Harmful Algae*, vol. 129, p. 102530.

Rao, K. S., and others (1989). Success and spread of the exotic fouling bivalve *Mytilopsis sallei* (Recluz) in Indian waters. *Exotic species in India. Asian Fisheries Society, Mangalore*, pp. 125–127.

Reyna, Paola B., and others (2023). Hotspot areas of marine introduced species in the Southwestern Atlantic. *Marine Ecology Progress Series*, vol. 725, pp. 15–28.

Robinson, Tamara B., and others (2020). Coastal invasions: the South African context. In *Biological Invasions in South Africa*, pp. 229–247. Cham: Springer International Publishing.

Ross, D. Jeff, and others (2002). Impact of introduced seastars *Asterias amurensis* on survivorship of juvenile commercial bivalves *Fulvia tenuicostata*. *Marine Ecology Progress Series*, vol. 241, pp. 99–112.

Ross, D. Jeff, and others (2003). Variability in the impact of an introduced predator (*Asterias amurensis*: Asteroidea) on soft-sediment assemblages. *Journal of Experimental Marine Biology and Ecology*, vol. 288, No. 2, pp. 257–278.

Roy, Helen E., and others (2023). Chapter 1: Introducing biological invasions and the IPBES thematic assessment of invasive alien species and their control. In: Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, HE, Pauchard, A, Stoett, P, and Renard Truong, T. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.7430692original.

Roy, Helen E., and others (2024). Curbing the major and growing threats from invasive alien species is urgent and achievable. Nature Ecology & Evolution, vol. 8, pp. 1216–1223

Saburova, Maria, and others (2022). Alien toxic dinoflagellate *Heterocapsa circularisquama* from the western pacific in Kuwait, NW Indian ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 196, p. 105027.

Sadchatheeswaran, Saachi, and others (2015). Changes in habitat complexity resulting from sequential invasions of a rocky shore: implications for community structure. *Biological Invasions*, vol. 17, pp. 1799–1816.

Sánchez, J.A., and D. Ballesteros (2014). The invasive snowflake coral (*Carijoa riisei*) in the Tropical Eastern Pacific, Colombia. *Revista de Biología Tropical*, vol. 62, pp. 199–207.

Schwindt, Evangelina, and others (2020). Past and Future of the Marine Bioinvasions along the Southwestern Atlantic. *Aquatic Invasions*, vol. 15, No. 1, pp. 11–29.

Schwindt, Evangelina, and others (2022). 20 years of marine bioinvasions research: Achievements and challenges for the Southwestern Atlantic. *Ecología Austral*, vol. 32, No. 2, pp. 734–48.

Schwindt Evangelina, and others (2024). Overwhelming evidence galvanizes a global consensus on the need for action against Invasive Alien Species. Biological Invasions, vol. 26, No. 3, pp. 621–626.

Scott, Barry (2022). *Caulerpa Brachypus,* the Invasion by this Non-native Seaweed. Aotea Great Barrier Environmental Trust: Environmental News Issue 45. www.gbiet.org/environmental-news/2022/2/25/environmental-news-issue-45-summer-2022.

Secretariat for the Pacific Regional Environment Programme (SPREP) (2022). Marine Biosecurity Toolkit: Biofouling Assessment Guidance. Samoa. https://brb.sprep.org/marine-biosecurity-toolkit?language_content_entity=en

Seebens, Hanno, and others (2021). Projecting the continental accumulation of alien species through to 2050. *Global Change Biology*, vol. 27, pp. 970–982.

Shalovenkov, N.N (2022). Distribution of alien zoobenthic species on the Black Sea Shelf. *Russian Journal of Biological Invasions*, vol. 13, No. 1, pp. 123–139.

Shchepanik, Hailey N., (2022). Biological characteristics of non-native, wild-caught barramundi (*Lates calcarifer*) aquaculture escapees in the Red Sea and validation of a species-specific environmental DNA quantitative PCR assay. KAUST Research Repository. https://doi.org/10.25781/KAUST-I4557.

Simberloff, Daniel, and others (2024) Systematic and persistent bias against invasion science: Framing conservation scientists. *BioScience*, p.biae029.

Soares, Marcelo (2018). Climate change and regional human pressures as challenges for management in oceanic islands, South Atlantic. *Marine Pollution Bulletin,* vol. 131, pp. 347–355.

Soares Marcelo, and others (2022). Lionfish on the loose: Pterois invade shallow habitats in the tropical southwestern Atlantic. *Frontiers in Marine Science* 9:956848. doi: 10.3389/fmars.2022.956848

Soliman, Tarek, and Graeme J. Inglis (2018). Forecasting the economic impacts of two biofouling invaders on aquaculture production of green-lipped mussels *Perna canaliculus* in New Zealand. *Aquaculture Environment Interactions*, vol. 10, pp. 1–12.

Srėbalienė, Greta, and others (2019). A comparison of impact and risk assessment methods based on the IMO Guidelines and EU invasive alien species risk assessment frameworks. *PeerJ*, vol. 7, p. e6965.

Stæhr, P.A.U., and others (2023). Trends in New Records of Non-Indigenous Species (NIS) Introduced by Human Activities. In: *OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic*. OSPAR Commission, London. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/indicator-assessments/trends-new-records-nis.

Sundet, Jan H., and Alf Håkon Hoel (2016). The Norwegian management of an introduced species: the Arctic red king crab fishery. *Marine Policy*, vol. *72*, pp. 278–284.

Tait, L. W., and others (2020). Invasive ecosystem engineers threaten benthic nitrogen cycling by altering native infaunal and biofouling communities. *Scientific Reports*, vol. 10, No. 1, p. 1581.

Tait, Leigh W., and others (2021). Loss of giant kelp, *Macrocystis pyrifera*, driven by marine heatwaves and exacerbated by poor water clarity in New Zealand. *Frontiers in Marine Science*, vol. 8, p. 721087.

Tait, Leigh W., and others (2023). Ecosystem function modified by an invasive species: Density and distance dependent changes in sediment characteristics, fluxes, and benthic communities. *Estuarine, Coastal and Shelf Science*, vol. 293, p. 108526.

Tait, Leigh W., and others (2023). Towards remote surveillance of marine pests: A comparison between remote operated vehicles and diver surveys. *Frontiers in Marine Science*, vol. 10, p. 1102506.

Tan, K.S., and Brian Morton (2006). The invasive caribbean bivalve *Mytilopsis sallei* (Dreissenidae) introduced to Singapore and Johor Bahru, Malaysia. *Raffles Bulletin of Zoology*, vol. 54, No. 2, pp. 429–434.

Teixeira, L.M. Pires, and Joel Christopher Creed (2020). A decade on: an updated assessment of the status of marine non-indigenous species in Brazil. *Aquatic Invasions*, vol. 15, No. 1, pp. 30–43.

Therriault, Thomas W., and others (2018). The invasion risk of species associated with Japanese tsunami marine debris in Pacific North America and Hawaii. *Marine Pollution Bulletin,* vol. 132, pp. 82–89.

Therriault, Thomas W., and others (2021). Chapter 22: Invasive Species. In: *Second World Ocean Assessment.* New York: United Nations. https://www.um.edu.mt/library/oar/handle/123456789/77026.

Thomsen, Mads S., and others (2019). Local extinction of bull kelp (*Durvillaea* spp.) due to a marine heatwave. *Frontiers in Marine Science*, vol. 6, p. 84.

Trainer, Vera L., and others (2020). Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful algae*, vol. 91, p. 101591.

Troost, Karin (2010). Causes and effects of a highly successful marine invasion: case-study of the introduced Pacific oyster *Crassostrea gigas* in continental NW European estuaries. *Journal of Sea Research*, vol. *64*, No.3, pp. 145–165.

Tulp, Ingrid, and others (2010). The role of the invasive bivalve *Ensis directus* as food source for fish and birds in the Dutch coastal zone. *Estuarine, Coastal and Shelf Science,* vol. 90, No. 3, pp. 116–128.

Ueki, Yo, and others (2021). Human norovirus disease burden of consuming *Crassostrea gigas* oysters: A case-study from Japan. *Food Control*, vol. 121, 107556.

Ulman, Aylin, and others (2024). Assessment of human health impacts from invasive pufferfish (attacks, poisonings and fatalities) across the Eastern Mediterranean. *Biology*, vol. 13, No. 4, p. 208.

United Nations Environment Programme (UNEP) (2002). COP 6 Decision VI/23. Alien Species That Threaten Ecosystems, Habitats or Species. The Hague, 7–19 April 2002. https://www.cbd.int/decision/cop?id=7197.

Ustups, Didzis, and others (2016). Diet overlap between juvenile flatfish and the invasive round goby in the central Baltic Sea. *Journal of Sea Research*, vol. 107, pp. 121–129.

Verdura, Jana, and others (2019). Biodiversity loss in a Mediterranean ecosystem due to an extreme warming event unveils the role of an engineering gorgonian species. *Scientific reports*, vol. 9, No. 1, p. 5911.

Viola, Sloane M., and others (2018). Anthropogenic disturbance facilitates a non-native species on offshore oil platforms. *Journal of Applied Ecology*, vol. 55, No. 4, pp. 1583–1593.

Watkins, Hannah V., and others (2021). Research biases create overrepresented "poster children" of marine invasion ecology. *Conservation Letters*, vol. 14, No. 3, p. e12802.

Watts, A.M., and others (2015). Characterising biofouling communities on mussel farms along an environmental gradient: a step towards improved risk management. *Aquaculture Environment Interactions*, vol. 8, pp. 15–30.

Wernberg, Thomas (2021). Marine heatwave drives collapse of kelp forests in Western Australia. In *Ecosystem collapse and climate change*, pp. 325–343. Cham: Springer International Publishing, 2021.

Westfall, Kristen Marie, and others (2020). A new approach to molecular biosurveillance of invasive species using DNA metabarcoding. *Global Change Biology*, vol. 26, No. 2, pp. 1012–1022.

Wilcox, Mark A., and others (2024). Identifying higher risk invaders to the Columbia Glaciated Freshwater Ecoregion using a new screening tool: the Non-Indigenous Species Screening Tool (NISST*). Management of Biological Invasions* (in press).

Williamson, Mark (1999). Invasions. *Ecography*, vol. 22, No. 1, pp. 5–12.

Yan, Dong-Chun, and others (2007) White spot syndrome virus (WSSV) transmission from rotifer inoculum to crayfish. *Journal of Invertebrate Pathology*, vol. 94, No. 2, pp. 144–148.

Zaiko, Anastasija, and others (2022). Towards reproducible metabarcoding data: Lessons from an international cross-laboratory experiment. *Molecular Ecology Resources*, vol. 22, No. 2, pp. 519–538.

Zaiko, Anastasija, and others (2024). Structural and functional effects of global invasion pressure on benthic marine communities – patterns, challenges and priorities for a changing world. *Diversity and Distributions* e13838.

Zhan, Aibin, and others (2014). Reproducibility of pyrosequencing data for biodiversity assessment in complex communities. *Methods in Ecology and Evolution*, vol. 5, No. 9, pp. 881–890.

Zhang, Danhua, and others (2017). Introduction and spread of an exotic plant, *Spartina alterniflora*, along coastal marshes of China. *Wetlands*, vol. 37, pp. 1181–1193.

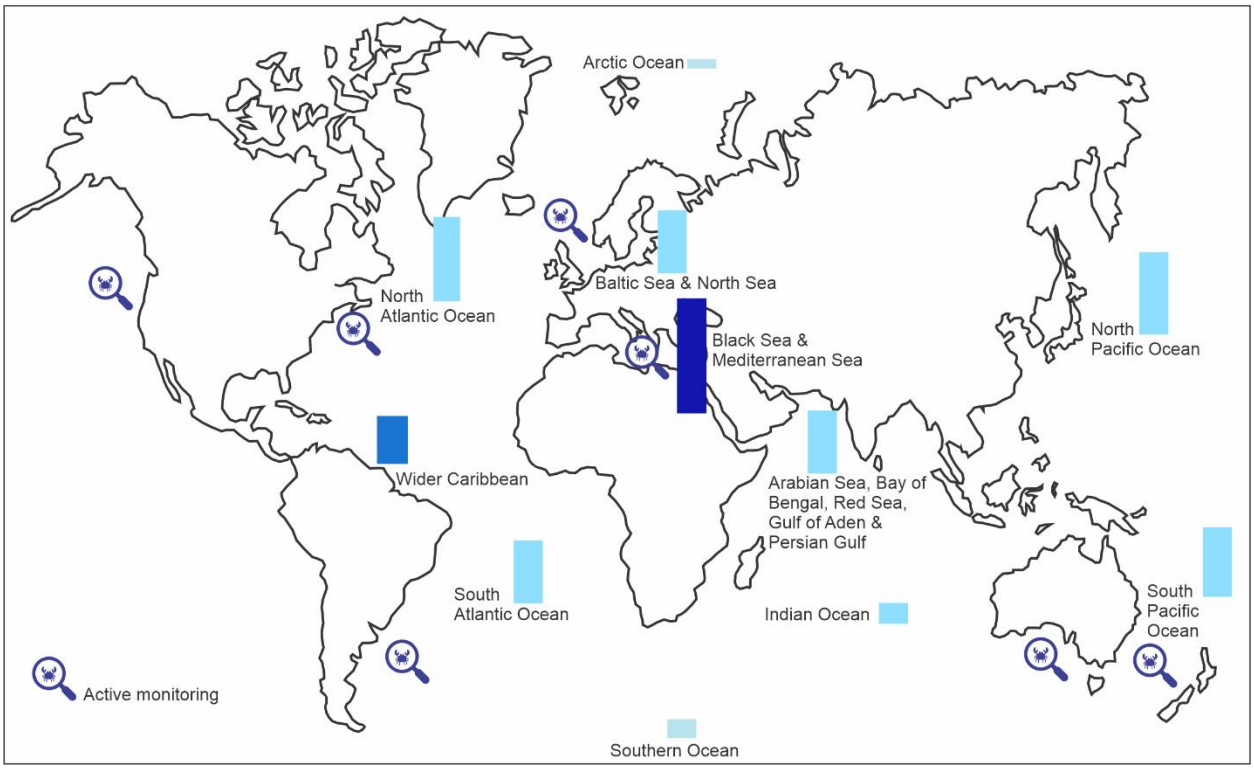


Figure 1 Alien marine species across the various ocean basins. The height of the bars reflects the relative abundance of documented alien taxa, while darker colours indicate a greater increase since WOA II. Regions that have active monitoring programs are indicated.

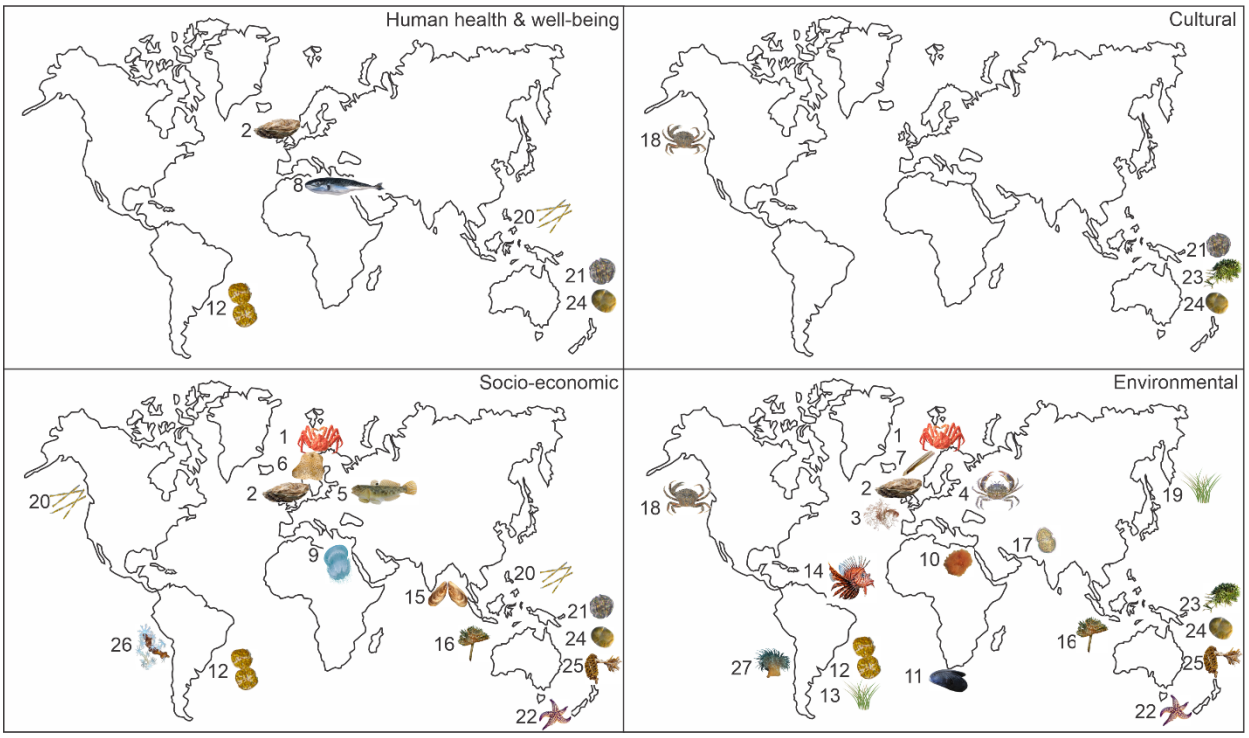


Figure 2 Examples of species that have impacted human health and well-being, socio-economic and cultural assets and the marine environment.

1 Table 1. Examples of NIS that have had demonstrable impacts in the various ocean basins.

#	Species	Impact type	Description	References
Arctic				
1	Red king crab *Paralithodes camtshaticus*	Socio-economic; Environmental	While fished commercially in some areas, causes losses to fisheries in others; reduces biodiversity.	Sundet and Hoel, 2016; Falk-Petersen et al., 2011
North Atlantic Ocean				
2	Pacific oyster *Magallana gigas* (previously known as *Crassostrea gigas*)	Human health & well-being; Socio-economic; Environmental	Carries disease causing viruses; is extensively farmed; alters habitat structure, phytoplankton communities and food webs, reduces biodiversity	Ueki et al., 2021; Des et al., 2022; Troost, 2010
3	Red seaweed *Dasysiphonia japonica*	Environmental	Reduces seaweed diversity	Newton et al., 2013
Baltic Sea				
4	Mud crab *Rhithropanopeus harrisii*	Environmental	Has caused a regime shift through consumption of native species	Kotta et al., 2018
5	Round goby *Neogobius melanostomus*	Socio-economic	Negatively impacts commercial species, but is also fished commercially	Ustups et al., 2016
North Sea				
6	Carpet sea squirt *Didemnum vexillum*	Socio-economic	Threatens shellfish aquaculture	Gittenberger, 2010
7	Atlantic jackknife clam *Ensis directus*	Environmental	Alters food webs as it becomes a dominant food source	Tulp et al., 2010
Mediterranean Sea				
8	Silver-cheeked toadfish *Lagocephalus sceleratus*	Human health & well-being	Causes poisonings and human fatalities	Ulman et al., 2024
9	Nomad jellyfish	Socio-economic	Negatively affects commercial fisheries	Ghermandi et al., 2015

	Rhopilema nomadica			
10	Epiphytic algae *Lophocladia lallemandii*	Environmental	Smothers native seagrasses	El Zrelli et al., 2021
South Atlantic Ocean				
11	Mediterranean mussel *Mytilus galloprovincialis*	Environmental	Changes rocky shore communities and outcompetes native mussels	Sadchatheswaran et al., 2015
12	Dinoflagellate *Alexandrium* sp.	Human health & well-being; socio-economic; Environmental	Consumption causes poisoning, resulting in loss to artisanal fisheries; has even caused the death of whales	Gayoso et al., 2006
13	Smooth cordgrass *Spartina alterniflora*	Environmental	Alters ecosystem functioning	Bortolus et al., 2015
Wider Caribbean				
14	Lion fish *Pterois* spp.	Environmental	Consumes native fish	Côté et al., 2013
Indian Ocean				
15	Black-striped mussel *Mytilopsis sallei*	Socio-economic	Clogs water intakes, fouls ships and maritime infrastructure	Rao et al., 1989; Tan and Morton, 2006
16	Mediterranean fanworm *Sabella spallenzanii*	Socio-economic; environmental	Fouls mussels farms; alters recruitment of native sessile communities	Hewitt, 2003; Halloway and Keough, 2002
Persian Gulf				
17	Dinoflagellate *Heterocapsa circularisquama*	Environmental	Has caused mass mortality of bivalves	Saburova et al., 2022
North Pacific				
18	European green crab *Carcinus maenas*	Environmental; cultural	Eats native species, competes with native crabs and degrades eelgrass habitats.	Howard et al. 2019; Barclay et al., 2024; Fisher et al., 2024
19	Smooth cordgrass *Spartina alterniflora*	Environmental	Alters physical, biological and biochemical processes	Lee et al., 2024

20	Diatoms of the genus *Pseudo-nitzschia*	Human health & well-being; socio-economic	Blooms of these toxic diatoms cause poisoning and fisheries closures	Kim et al., 2018; Perry et al., 2023
South Pacific				
21	Dinoflagellate *Alexandrium catenella*	Human health & well-being; socio-economic; cultural	This microscopic organism causes shellfish poisoning which requires closure of commercial and recreational fisheries	Trainer et al., 2020
22	Northern Pacific seastar *Asterias amurensis*	Socio-economic; environmental	Predates upon native and commercially important species	Ross et al., 2002; 2003
23	Green algae *Caulerpa* spp.	Cultural; environmental	Overgrows benthic habitats and smothers culturally important seagrass	Scott, 2021; Gribben et al., 2013
24	Dinoflagellate *Karenia mikimotoi*	Human health & well-being; socio-economic; cultural; environmental	Causes poisoning and skin irritation in people; kills native species; prevents collection of marine resources by communities and negatively affects fisheries	Li et al., 2019
25	~~Japanese kelp~~Wakame *Undaria pinnatifida*	Socio-economic; Environmental	Fouls aquaculture infrastructure and outcompetes native kelp	Carnell and Keough, 2014; Watts et al., 2015
26	Snowflake coral *Carijoa riisei*	Environmental	Displaces native corals	Sanchez and Ballesteros, 2014
27	Plumose anemone *Metridium senile*	Socio-economic	Overgrows aquaculture infrastructure	Häussermann et al., 2022

Section 4

Chapter 6: Pressures: Erosion and sedimentation

Coordinating Author: Luciana S. Esteves

Writing Team: Bronwyn Goble; Jarbas Bonetti; Mabel Anim; Matthew Eliot; Niki Evelpidou; Trang Minh Duong

1 Keynotes

- Global and regional coastal erosion and sedimentation assessments based on satellite data have proliferated since the mid-2010s, offering ~~providing~~ insights into~~f~~ trends and patterns of change. However, uncertainties and limitations of these methods must be carefully considered.
- The ~~E~~exposure of people, property and economic activities to coastal flooding and erosion is increasing across all latitudes, often associated with climate change impacts.
- The literature ~~covers coastal erosion issues more prominently than changes in sedimentation.~~ focuses more on coastal erosion than on sedimentation changes.
- ~~There is g~~Growing evidence ~~of~~ suggests that coastal erosion ~~intensification~~ in the Arctic is intensifying due to permafrost thaw and increased wave action. This ~~enhanced~~ accelerated erosion is releasing ~~considerable~~ large amounts of nutrients into the Arctic Ocean, with ~~emerging~~ potential implications for carbon sequestration and marine ecosystems.
- "Nature-based solutions, such as the renaturalization of floodplains and intertidal areas, are increasingly being applied to catchments and coastal regions in the Northern Hemisphere. ~~Nature-based approaches, e.g. renaturalisation of floodplains and intertidal areas, are increasingly implemented being applied on catchments and coasts in the Northern Hemisphere to renaturalise floodplains and intertidal areas~~. While these measures~~y~~ can ~~enhance~~ improve long-term resilience ~~in the longer term~~, they may ~~trigger~~ lead to rapid short-term changes ~~in the short-term~~.

2 Introduction

This sub-chapter summarises key findings published in 2018-2023 concerning trends and changes in erosion and sedimentation processes that might affect the world's oceans, highlighting any major changes from previous World Ocean Assessments (WOA). WOAI

described key processes related to erosion and sedimentation in Chapter 26 'Land-Sea Physical Interaction' (Reyna and others, 2016). In WOAII, Chapter 13 'Changes in Erosion and Sedimentation' (Vu and others, 2021) features the topic more prominently, summarising key findings concerning each ocean region in dedicated sub-sections.

~~Both p~~Previous assessments mostly focus on ~~the state of~~ coastal areas~~,~~ rather than erosion and sedimentation changes at sea, ~~more prominently~~with a greater emphasis on erosion due to~~,~~ ~~reflecting~~ a bias in the literature ~~coverage~~. WOAI details anthropogenic pressures, particularly the extent and impacts of land reclamation and catchment disturbances. WOAII ~~highlights~~ emphasises global assessments of shoreline change ~~based on~~using satellite-derived data (Luijendijk and others, 2018).

~~In~~ During the WOAIII period, the number of satellite-derived shoreline change assessments ~~proliferated~~ have expanded (Vos and others, 2023a) at the global to local scales (Konstantinou, and others; 2023; Vos and others, 2023b; Bishop-Taylor and others, 2021; Mao and others, 2021; Konlechner and others, 2020; Mentaschi and others, 2018). Satellites can bridge the gap of data availability in areas of difficult access and cover large areas. However, the methods and algorithms used to extract shoreline positions vary and have intrinsic limitations (see Warrick and others, 2024) that must be fully appreciated before results are used to inform policy or decision-making, particularly at the local level. It is also important to understand that magnitudes and rates of change are specific to time intervals and geographical locations, varying greatly in space and time and according to averaging and aggregation methods.

3 The environmental change since WOAII

Pressures due to human interventions and climate change impacts continue to influence coastal erosion and sedimentation patterns (Cabana and others, 2023). Global warming is projected to exacerbate conditions along coasts due to sea~~-~~-level rise (SLR) and more extreme weather conditions, enhancing storm surges, winds and waves (Ewans and Jonathan, 2023; Narita and others, 2024). These changes are detailed in chapters S4.C3 and S5B.C4. Polar regions, particularly the Arctic, are fast-changing. Sea ice protects high-latitude shorelines and sediment deposited on continental shelves from wave action. In polar regions, coastal erosion results from increased wave exposure caused by reduced sea-ice cover, prolonged ice-free seasons and/or permafrost thaw. These effects have been linked to global warming (Cassidy and others, 2024; Irrgang and others, 2022).

Changes in wind direction and speed influence cross- and long-shore currents and, therefore, sediment transport, affecting coastal erosion and sedimentation (Ibaceta and others, 2023). Coastal erosion is projected to increase in many areas due to SLR and increased wave activity (López-Olmedilla and others, 2022; Ranasinghe and others, 2023; Dong and others, 2024). Potential impacts of coastal erosion include habitat, property and land loss, destruction of cultural and/or geological heritage, migration and other economic losses (Pouye and others, 2024; Solihuddin and others, 2024; Thepsiriamnuay and Pumijumnong, 2024), as detailed in chapter S4.C6. In some coasts, sedimentation may increase (Anderson and others, 2022) due to supply of sediment transported by rivers (Yoon and others, 2023).

Coastal development disrupts or alters local sediment budget, often triggering or worsening coastal erosion (Wang and others, 2022; Saengsupavanich and others, 2024), see S5A.C9. Nature-based solutions have been favoured (Van der Meulen and others, 2023) to mitigate coastal erosion and promote shoreline accretion, including restoration of mangroves (Uddin and others, 2022) and coastal marshes (Fairchild and others, 2021).

3.1 Changes in the overall status

Research continues to unveil the magnitude of anthropogenic disturbances on the sediment cycle and fluxes. Between 1950 and 2010, soil erosion caused by human activities more than quadrupled the mobilisation of fluvial sediment, while supply from land to the coast reduced by 23 per cent, mostly due to retention in dams (Syvitski and others, 2022). Natural variability contributes to a very small proportion of these changes.

Shoreline changes are determined by regional drivers and site-specific factors, including geomorphology and human interferences (Pang and others, 2023). The latter has been identified as a key factor in areas where shoreline changes are largest globally (Luijendijk and others 2018; Mentaschi and others, 2018), while natural cycles (e.g. El Niño Southern Oscillation, Vos and others, 2023b) and major hazards (e.g. cyclones and tsunamis, Bozzeda and others, 2023) can have significant regional and local effects. Although global and regional assessments of shoreline change have been published, the methods differ, preventing comparative analysis of results.

Using satellite data but different methods, Luijendijk and others (2018) assessed sandy beaches worldwide, while Mentaschi and others (2018) covered all coastal typologies (although missing parts of SW Pacific and polar regions). Aggregated results of the former identified overall erosion for Australasia and Africa and mean accretion for other continents, while the latter reported net land loss in all continents/regions (net balance of -14,050 km^2 globally, Fig. 1).

Based on field data of 315 sandy beaches, Bozzeda and others (2023) indicated that 21 per cent were intensely eroding, similar to the findings by Luijendijk and others (2018), but they diverge on the proportion of stable and accreted beaches.

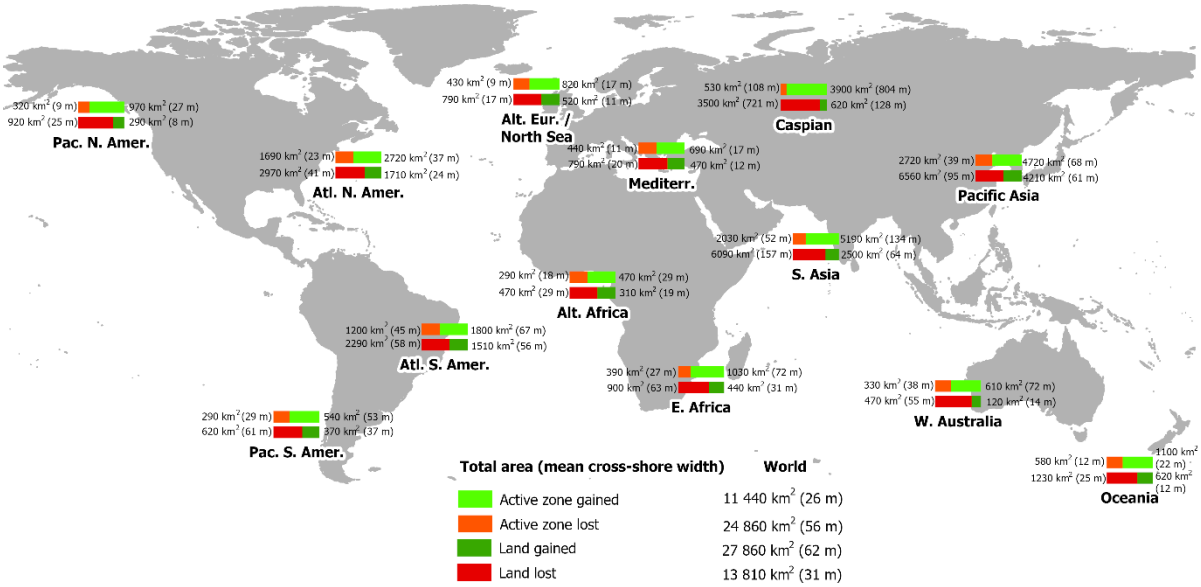


Figure 1. Mean regional losses and gains of coastal (dry) land and active (intermittently wet/intertidal) areas and mean cross-shore width change from 1984-2015 based on satellite data. Adapted from Mentaschi and others (2018).

Globally, there has been a transition from hard engineering solutions towards integrated, sustainable approaches that merge natural, technological, and community-driven inputs. Combined with ecosystem-based management, these approaches are considered to enhance resilience to climate change impacts (Gebrael and others, 2024; van Westen and others, 2024). Arguably, this is one of the most crucial changes in recent years due to the effects on both short and long-term local coastal responses. Growing interest in nature-based solutions stems from a better understanding of the undesired consequences of coastal engineering on natural coastal dynamics.

4 Region-specific changes

4.1 The Arctic Ocean

The Arctic has warmed faster than other regions since the mid-1960s (England and others, 2021), almost four times faster than the global average from 1979-2021 (Rantanen and others, 2022), with sea-ice cover declining over 46 years (Irrgang and others, 2022). It is well-

established that Arctic coastlines are eroding with growing evidence suggesting acceleration. These rapid changes in the Arctic threaten settlements, infrastructure, traditional lifestyles and archaeological sites (Irrgang and others, 2022).

Nutrient and sediment fluxes are changing due to release from melting ice, eroding permafrost and increased wave interactions with the seabed. Predicting the rates and magnitudes of changes is difficult (Irrgang and others, 2022) due to complex air-ice-sea interactions and the enhanced supply from river discharge due to land-ice melt. Emerging research suggests positive feedback between carbon release from melting permafrost and global warming, as higher input of carbon into coastal waters reduces their potential to absorb atmospheric carbon (Manizza, 2024; Nielsen and others, 2022).

4.2 The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Erosion and sedimentation rates on the Baltic coast vary due to isostatic uplifting in the north and subsiding in the south, respectively contributing to accretion and erosion at rates higher than 1 meter/year during 2007-2017 (Weisse and others, 2021). Based on satellite data validated with field measurements, Castelle and others (2024) estimated that sandy European shores on the Atlantic are accreting at a mean rate of 0.21 meters/year during 1984-2021, although the coasts exposed to high wave energy (such as in Portugal and northwest France) are prone to long-term erosion. The Mediterranean coast experiences moderate erosion rates of 0.4–1.0 m/year due to SLR and human activity, particularly along coasts undergoing subsidence (Vecchio and others, 2024). Using satellite data from 1984-2017, Tătui and others (2019) reported 68 per cent of the Black Sea coasts to be stable, with erosion exceeding 1 meter/year along 19 per cent, mostly in Romania, Ukraine, Georgia, and low-lying areas affected by severe storms.

4.3 The South Atlantic Ocean and the Wider Caribbean

Studies on erosion and sedimentation changes in the South Atlantic are site-specific. Its diverse coasts face challenges from catchment changes (Riquetti and others, 2022), limited sediment input from rivers (Oliveira and others, 2023) and beach sand extraction (Pilkey and others, 2022). Storms threaten infrastructure and populations across the region (Serafim and others, 2019; Queiroz and others, 2022; Isla and Cortizo, 2023).

In West Africa, research highlights natural and anthropogenic factors driving coastal changes mostly in Senegal, Nigeria and Ghana (Ankrah and others, 2023). Delta morphology,

sedimentation, fisheries and habitat are affected by changes in river discharge and sediment supply, e.g. in the Volta and Niger (Ideki and Ajoku, 2024), but limited data hinder comprehensive understanding.

Caribbean small island states face coastal erosion and sedimentation issues triggered by hurricanes and SLR, which reduce the natural protection offered by beaches, mangroves and reefs, as observed in Jamaica and the Bahamas (Rangel-Buitrago and others, 2018). The Caribbean Disaster Emergency Management Agency is a key player in regional risk reduction measures, including nature-based solutions (Rhiney and Baptiste, 2019).

4.4 The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

There is limited literature in English covering erosion and sedimentation in this diverse ocean region. Data are mostly available at local level or from global assessments, limiting comparative analysis. Coastal variability due to changing sediment supply from rivers has been identified in India, Sri Lanka, Bangladesh, Malaysia and Indonesia, with an increasing tendency for erosion where downstream sediment transfer is disrupted (Syvitski and others, 2022). Ecological damage to wetlands, particularly mangroves, has been linked to coastal erosion due to disruption ~~of these~~in sediment transfers.

Impacts from human activities on erosion and sedimentation have been reported across the Indian Ocean region. Recent large-scale activities include Mumbai Coastal Road Project in India (Movik and others 2023) and Jakarta Sea Wall in Indonesia, which is an effort to protect against a combination of subsidence and climate change effects (Purnomo and others 2024).

4.5 The North Pacific Ocean

Coastal erosion is a constant threat in the North Pacific, especially on densely populated and economically significant coastlines (Dong and others, 2024; Siringan and others, 2024; Vitousek and others, 2023; Yum and others, 2023; Cai and others, 2022). According to the World Meteorological Organization's "State of the Climate 2023" report, the Pacific Ocean is experiencing SLR rates faster than the global average. SLR can enhance erosion (Siringan and others, 2024; Vitousek and others, 2023), already a critical problem due to artificial sediment retention in many Asian rivers (Binh and others, 2020), which is exacerbated by land subsidence in some locations (Siringan and others, 2024). Studies demonstrate intensification of tropical cyclones in recent decades (Li and others, 2023; Xu and others,

2024) likely due to climate change (Bloemendaal and others, 2022; Wood and others, 2023), often linked to extreme erosion events. Projections indicate a decrease in the mean wave height in the region by the end of the century (Casas-Prat and others, 2024).

Changes in the sea-level along the North Pacific coasts are highly affected by changes in the oceanic circulations and changes in temperature (Cha and others, 2023; Gunnarson and others, 2024). Extreme sea-level events are projected to be more than the global mean (Ran and others, 2023), particularly along the NW Pacific coasts (Fan and Du, 2023).

4.6 The South Pacific Ocean

Systematic assessments of the longer South Pacific coasts have been undertaken (e.g. Thom and others, 2018; Bishop-Taylor and others, 2021; Dickson and others, 2021; Vallarino-Castillo and others, 2024). However, the diverse morphology across the South Pacific islands confounds erosion patterns characterisation (Nunn and others, 2020), except through aggregated assessment (Vos and others, 2023a). There is a strong awareness of erosion and land loss related to SLR in the region, particularly for low-lying atolls, such as Tuvalu (Harun-al-rashid and others, 2023).

El Niño and La Niña have regional effects across the South Pacific (Vos and others, 2023), influencing prevailing winds, storm incidence, sea levels and wave conditions (Vallarino-Castillo and others, 2024). More energetic conditions occur during El Niño phases in the eastern half of the South Pacific, and during La Niña in the western half, affecting the distribution of erosion pressures across the region (Ramsay 2011; Vos and others, 2023b). Recent decades have had greater influence of La Niña phases, and, perhaps coincidentally, have also had exceptional storm events in the western South Pacific, including tropical cyclone Gabrielle impact to New Zealand in 2023 and multiple storms affecting east coast Australia from 2016 to 2024 (Turner and others, 2024).

4.7 The Southern Ocean

In the Southern Ocean, ice-cover changes show high temporal and spatial variability within an overall trend of net increase in 1979-2020 (Reid and Massom, 2022), except on the Amundsen-Bellingshausen seas (West Antarctica), despite an emerging positive trend since 2007 (Parkinson, 2019). Based on sea-ice extent, the maximum length of coastal exposure in Antarctica decreased 30 km per year in 1979-2020 (Reid and Massom, 2022). However, sea-ice cover reached record minima in February 2022, 2023 and 2024 (Riordon, 2024), remaining persistently low in recent years. It is too soon to know whether this is a temporary fluctuation

(Riordon, 2024) or the inception of a new state in the Southern Ocean triggered by long-term global warming (Purich and Doddridge, 2023; Eayrs and others, 2021).

5 Remaining key knowledge and capacity changes and any new gaps

The bias in research coverage and volume persists with large gaps in the Global South, where insufficient generation, transmission and use of reliable in situ data is pervasive, despite emerging or growing research in parts of South America, Africa and Southeast Asia. The increasing popularity of nature-based risk reduction approaches requires deeper understanding of applicability and uncertainties of ecosystem-based management in different geographical contexts (Gracia and others, 2018; Doelle and Puthucherril, 2023). Post-erosion recovery efforts often lack sufficient research, leading to vulnerability to future events (Garzon and others, 2024). ~~Integrating~~ Weaving ~~i~~ndigenous Peoples' knowledge with scientific data must be more widespread to improve understanding of site-specific socioenvironmental systems and promote cooperation among stakeholders (Loch and Riechers, 2021).

References

Anderson, John B., and others. Holocene Evolution of the Western Louisiana–Texas Coast, USA: Response to Sea-Level Rise and Climate Change. Memoir 221. Boulder: Geological Society of America, 2022.

Ankrah, Johnson and others. Shoreline Change and Coastal Erosion in West Africa: A Systematic Review of Research Progress and Policy Recommendation. Geosciences, vol. 13, No. 59, art. 13020059, 2023.

Binh, Doan V., and others. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. Geomorphology, vol. 353, art. 107011, 2020.

Bishop-Taylor, Robbi, and others. Mapping Australia's dynamic coastline at mean sea level using three decades of Landsat imagery. Remote Sensing of Environment, vol. 267, art. 112734, 2021.

Bloemendaal, Nadia, and others. A globally consistent local-scale assessment of future tropical cyclone risk. Science Advances, vol. 8, No. 17, art. eabm8438, 2022.

Bozzeda, Fabio, and others. Global patterns in sandy beach erosion: unraveling the roles of anthropogenic, climatic and morphodynamic factors. Frontiers of Marine Science, vol. 10, art. 1270490.

Cabana, David, and others. Enabling Climate Change Adaptation in Coastal Systems: A Systematic Literature Review. Earth's Future, vol. 11, No. 8, art. e2023EF003713, 2023.

Cai, Feng, and others. Rapid migration of mainland China's coastal erosion vulnerability due to anthropogenic changes. Journal of Environmental Management, vol. 319, art. 115632, 2022.

Casas-Prat, Mercè and others. Wind-wave climate changes and their impacts. Nature Reviews Earth & Environment, vol. 5, No. 1, pp. 23–42, 2024.

Cassidy, Galen, and others. Seasonal coastal erosion rates calculated from PlanetScope Imagery in Arctic Alaska. Remote Sensing, vol. 16, No. 13, art. 2365, 2024.

Castelle, Bruno, and others. Satellite-derived sandy shoreline trends and interannual variability along the Atlantic coast of Europe. Scientific Reports, vol.14, art. 13002, 2024.

Cha, Hyeonsoo, and others. A process-based assessment of the sea-level rise in the northwestern Pacific marginal seas. Communications Earth & Environment, vol. 4, No. 1, art. 300, 2023.

Dickson, Mark, and others. 80 Years of Shoreline Change in Northland, New Zealand. In Proceedings of the Australasian Coasts & Ports 2021, 11-13 April 2022, Christchurch, New Zealand, Deirdre E. Hart and Tom Shand, eds. pp. 373-377, 2022.

Doelle, Meinhard, and Tony George Puthucherril. Nature-based solutions to sea level rise and other climate change impacts on oceanic and coastal environments: a law and policy perspective. Nordic Journal of Botany, vol. 2023, No. 1, e03051, 2023.

Dong, Wan S., and others. The impact of climate change on coastal erosion in Southeast Asia and the compelling need to establish robust adaptation strategies. Heliyon, vol. 10, No. 4, art. e25609, 2024.

Eayrs, Clare, and others. Rapid decline in Antarctic sea ice in recent years hints at future change. Nature Geoscience, vol. 14, pp. 460–464, 2021.

England, Mark R., and others. The recent emergence of Arctic Amplification. Geophysical Research Letters, vol. 48, art. e2021GL094086, 2021.

Ewans, Kevin, and Philip Jonathan. Uncertainties in estimating the effect of climate change on 100-year return value for significant wave height. Ocean Engineering, vol. 272, art. 113840, 2023.

Fairchild, Tom P., and others. Coastal wetlands mitigate storm flooding and associated costs in estuaries. Environmental Research Letters, vol. 16, art. 074034, 2021.

Garzon, Juan L., and others. Development of a Bayesian network-based early warning system for storm-driven coastal erosion. Coastal Engineering, vol. 189, art. 104460, 2024.

Gebrael, Karen, and others. Overview of nature-based solutions for climate resilience in the MENA region. Nature-Based Solutions, vol. 6, art. 100159, 2024.

Gracia, Adriana, and others. Use of ecosystems in coastal erosion management. Ocean & Coastal Management, vol. 156, pp. 277-289, 2018.

Gunnarson, Jaboc L., and others. Drivers of future extratropical sea surface temperature variability changes in the North Pacific. npj Climate and Atmospheric Science, vol. 7, art. 164, 2024.

Harun-al-rashid, Ahmed and Chan-Su Yand. A review on multidecadal coastal changes at Funafuti, Tuvalu from 1897 to 2015. Korean Journal of Remote Sensing, vol. 39, No.1, pp. 23-45, 2023.

Ibaceta, Raimundo, and others. Interannual variability in dominant shoreline behaviour at an embayed beach. Geomorphology, vol. 433, art. 108706, 2023.

Ideki, Oye, and Osinachi Ajoku. Scenario analysis of shorelines, coastal erosion, and land use/land cover changes and their implication for climate migration in East and West Africa. Journal of Marine Science and Engineering, vol. 12, No. 7, art. 1081, 2024.

Irrgang, Anna M., and others. Drivers, dynamics and impacts of changing Arctic coasts. Nature Reviews Earth & Environment, vol. 3, pp. 39–54, 2022.

Isla, Federico I., and Luis C. Cortizo. Coastal erosion in Argentina: The retreating rates of southern South America. Journal of South American Earth Sciences, vol. 126, art. 104342, 2023.

Konlechner, Teresa M., and others. Mapping spatial variability in shoreline change hotspots from satellite data; a case study in southeast Australia. Estuarine, Coastal and Shelf Science, vol. 246, art. 107018, 2020.

Konstantinou, Aikaterini, and others. Satellite-based shoreline detection along high-energy macrotidal coasts and influence of beach state. Marine Geology, vol. 462, art. 107082, 2023.

Li and others, 2023. Recent increase in the potential threat of western North Pacific tropical cyclones. npj Clim Atmos Sci 6, 53. https://doi.org/10.1038/s41612-023-00379-2.

Loch, Theresa K., and Maraja Riechers. Integrating indigenous and local knowledge in management and research on coastal ecosystems in the Global South: A literature review. Ocean & Coastal Management, vol. 212, art. 105821, 2021.

López-Olmedilla, Laura, and others. Effect of alongshore sediment supply gradients on projected shoreline position under sea-level rise (northwestern Portuguese coast). Estuarine, Coastal and Shelf Science, vol. 271, art. 107876, 2022.

Luijendijk, Arjen, and others. The state of the world's beaches. Scientific Reports, vol. 8, art. 6641, 2018.

Manizza, Manfredi. Climate feedbacks from coastal erosion, Nature Climate Change, vol. 14, pp. 899-900, 2024.

Mao, Yongjing, and others. Efficient measurement of large-scale decadal shoreline change with increased accuracy in tide-dominated coastal environments with Google Earth Engine. ISPRS Journal of Photogrammetry and Remote Sensing, vol. 181, pp. 385–399, 2021.

Mentaschi, Lorenzo, and others. Global long-term observations of coastal erosion and accretion. Scientific Reports, vol. 8, art. 12876, 2018.

Movik, Synne, and others. Claiming space: Contested coastal commons in Mumbai. Geoforum, vol. 144, art. 103805, 2023.

Narita, Y., Honda, K., Okamoto, K., Doukai, F., 2024. The Impacts of Future Climate Change on Storm Surges and Wave Heights in Three Major Bays of Japan. In Proceedings of the 34th International Ocean and Polar Engineering Conference, 16–21 June 2024, Rhodes, Greece, p. 2864, 2024.

Nielsen, David M., and others. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change, vol. 12, pp. 263-270, 2022.

Nunn, Patrick D., and others. “Islands in the Pacific: settings, distribution and classification”, in Climate Change and Impacts in the Pacific, pp. 33-170, Lalit Kumar, ed., Springer, 2020.

Oliveira, Emiliano C., and others. Erosion of four Brazilian coastal deltas: how dam construction is changing the natural pattern of coastal sedimentary systems. Anais da Academia Brasileira de Ciências, vol. 95, No. 1, art. e20220576, 2023.

Pang, Tianze, and others. Coastal erosion and climate change: A review on coastal-change process and modelling, Ambio, 52, pp. 2034–2052, 2023.

Parkinson, Claire L. A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. PNAS, vol. 116, No. 29, pp. 14414–14423, 2019.

Pilkey, Orrin H. And others. Vanishing Sands: Losing Beaches to Mining. Durham, London: Duke University Press, 2022.

Pouye, Ibrahima, and others. Evaluation of the Economic Impact of Coastal Erosion in Dakar Region. Journal of Coastal Research, vol. 40, No. 1, pp. 193–209, 2024.

Purich, Ariaan and Edward W. Doddridge. Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment, vol. 4, art. 314, 2023.

Purnomo, Agus H., and others. Revisiting the climate change adaptation strategy of Jakarta’s coastal communities. Ocean & Coastal Management, vol. 253, art. 107112, 2024.

Queiroz, Heithor A.A., and others. Characterising global satellite-based indicators for coastal vulnerability to erosion management as exemplified by a regional level analysis from Northeast Brazil. Science of The Total Environment, vol. 817, art. 152849, 2022.

Ramsay, Doug. Coastal erosion and inundation due to climate change in the Pacific and East Timor. NIWA Technical Report HAM2011-097, 2011.

Ran, Junlin, and others. Quantifying the contribution of temperature, salinity, and climate change to sea level rise in the Pacific Ocean: 2005-2019. Frontiers in Marine Science, vol. 10, art. 1200883, 2023.

Ranasinghe, Roshanka, and others. Assessing coastline recession for adaptation planning: sea level rise versus storm erosion. Scientific Reports, vol. 13, No. 1, art. 8286, 2023.

Rangel-Buitrago, Nelson, and others. Hard protection structures as a principal coastal erosion management strategy along the Caribbean coast of Colombia. A chronicle of pitfalls. Ocean & Coastal Management, vol. 156, pp. 58-75, 2018.

Rantanen, Mika, and others. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, vol. 3, art. 168, 2022.

Reid, Paul. A., and Massom, R.A. Change and variability in Antarctic coastal exposure, 1979–2020. Nature Communications, vol. 13, art. 1164, 2022.

Reyna, Julián, and others. “Chapter 26: Land-Sea Physical Interaction”, in The First World Ocean Assessment, Part V (New York, United Nations, 2016).

Rhiney, Kevon, and Baptiste, April K. Adapting to Climate Change in the Caribbean: Existential Threat or Development Crossroads? Caribbean Studies, vol. 47, No. 2, pp. 59-80, 2019.

Riordon, James. Antarctic sea ice near historic lows: Arctic ice continues decline. NASA, https://phys.org/news/2024-03-antarctic-sea-ice-historic-lows.html, 2024.

Riquetti, Nelva B., and others. Assessment of the soil-erosion-sediment for sustainable development of South America. Journal of Environmental Management, vol. 321, art. 115933, 2022.

Saengsupavanich, Cherdvong, and others. A systematic review of jetty-induced downdrift coastal erosion management. Regional Studies in Marine Science, vol. 74, No. 4, art. 103523, 2024.

Serafim, Mirela B., and others. Coastal vulnerability to wave impacts using a multi-criteria index: Santa Catarina (Brazil). Journal of Environmental Management, vol. 230, pp. 21–32, 2019.

Simões, Rodrigo S. And others. Coastline dynamics in the extreme south of Brazil and their socio-environmental impacts. Ocean & Coastal Management, vol. 230, art. 106373, 2022.

Siringan and others. “Sea Level Rise and Coastal Erosion in the Philippines: Impacts and Adaptation Strategies for Coastal Communities”, in Climate Emergency in the Philippines, Kristoffer B. Berse, and others, eds (Singapore, Springer, 2024).

Solihuddin, Tubagus, and others. The impact of coastal erosion on land cover changes in Muaragembong, Bekasi, Indonesia: a spatial approach to support coastal conservation. Journal of Coastal Conservation, vol. 28, No. 2, art. 43, 2024.

Syvitski, Jaia, and others. Earth's sediment cycle during the Anthropocene. Nature Reviews Earth & Environment, vol. 3, pp. 179–196, 2022.

Tătui, Florin, and others. The Black Sea coastline erosion: Index-based sensitivity assessment and management-related issues. Ocean and Coastal Management, vol. 182, art. 104949, 2019.

Thepsiriamnuay, Hiripong, and Nathsuda Pumijumnong. Sandy beach erosion: impacts and adaptation strategies in Thailand. Environment, Development and Sustainability, 1–24, 2024.

Thom, Bruce G., and others. National sediment compartment framework for Australian coastal management. Ocean & Coastal Management, vol. 154, pp. 103-120, 2018.

Turner, Ian L., and others. A framework for national-scale coastal storm hazards early warning. Coastal Engineering, vol. 192, No.11, art. 104571, 2024.

Uddin, Mohammad M., and others. Ecological development of mangrove plantations in the Bangladesh Delta. Forest Ecology and Management, vol. 517, art. 120269, 2022

Vallarino-Castillo, Ruby, and others. A Systematic Review of Oceanic-Atmospheric Variations and Coastal Erosion in Continental Latin America: Historical Trends, Future Projections, and Management Challenges. Journal of Marine Science and Engineering, vol. 12, No. 7, art. 1077, 2024.

van der Meulen, Frank, and others. Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nordic Journal of Botany, vol. 2023, No. 1, art. e03290, 2023.

van Westen, Bart, and others. Predicting marine and aeolian contributions to the Sand Engine's evolution using coupled modelling. Coastal Engineering, vol. 188, art. 104444, 2024.

Vecchio, Antonio, and others. Sea level rise projections up to 2150 in the northern Mediterranean coasts. Environmental Research Letters, vol. 19, art. 014050, 2024.

Villarroel-Lamb, Deborah. Quantitative risk assessment of coastal erosion in the Caribbean region. Natural Hazards Review, vol. 21, No. 3, art. 04020021, 2020.

Vitousek, Sean, and others. A model integrating satellite-derived shoreline observations for predicting fine-scale shoreline response to waves and sea-level rise across large coastal regions. Journal of Geophysical Research: Earth Surface, vol. 128, No. 7, art. e2022JF006936, 2023.

Vos, Kilian, and others. Benchmarking satellite-derived shoreline mapping algorithms. Communications Earth & Environment, vol. 4, art. 345, 2023a.

Vos, Kilian, and others. Pacific shoreline erosion and accretion patterns controlled by El Niño/Southern Oscillation. Nature Geoscience, vol. 16, No. 2, pp. 140-146, 2023b.

Vu, Ca Thanh, and others. “Chapter 13: Changes in erosion and sedimentation”, in The Second World Ocean Assessment, vol. II, pp. 185-200 (New York, United Nations, 2021).

Wang, Yu-Hai, and others, 2022. Emerging downdrift erosion by twin long-range jetties on an open mesotidal muddy coast, China. Journal of Marine Science and Engineering, vol. 10, No. 5, art. 570.

Warrick, Jonathan A., and others. Coastal shoreline change assessments at global scales. Nature Communications, vol. 15, art. 2316, 2024.

Weisse, Ralf, and others. Sea level dynamics and coastal erosion in the Baltic Sea region. Earth System Dynamics, vol. 12, No. 3, pp. 871-898, 2021.

Wood, Melissa, and others. Climate-induced storminess forces major increases in future storm surge hazard in the South China Sea region, Natural Hazards and Earth System Sciences, vol. 23, No. 7, pp. 2475–2504, 2023.

Yoon, H.H., Lee, J.Y., Kim, J.C., Jun, C.P., Choi, H.W., 2023. Incised-valley filling sedimentation in a small river valley of a wave-dominated, embayed coast in response to Holocene sea level rise, Yeongil Bay, Southeastern Korea. Marine Geology 464, 107127.

Xu, Jing, and others, 2024. Increasing tropical cyclone intensity in the western North Pacific partly driven by warming Tibetan Plateau. Nature Communications, vol. 15, art. 310, 2024.

Yum, Sang-Guk and others. A quantitative analysis of multi-decadal shoreline changes along the East Coast of South Korea. Science of The Total Environment, vol. 876, art. 162756, 2023.

Section 4

Chapter 6: Pressures: Marine infrastructure (outside of coastal areas)

Lead: Vasily Smolyanitsky, Co-Lead: Kwasi Appeaning Addo

Coordinating Author: Constantine Michailides

Writing Team: Paulette Bynoe; Alex Faerman; Senia Febrica; Ellinor Forje; Sérgio Jesus; Eva Loukogeorgaki; Constantine Michailides; Ongezwa Mpisana; Jana Orszaghova; Jorge Ramos; Arshad Rawat; Rodrigo Rojas; Liliana Rusu; Wei Shi; Stefanos Xenarios

1. Keynotes

~~Marine Infrastructure; Marine energy infrastructure;~~Marine noise; ~~Hydrodynamic circulation; Seawater quality; Seabed interaction~~ ~~Shipping and navigation infrastructure; Subsea cables and pipelines; Deep-sea mining; Food technologies; multi-use islands.~~

- Marine infrastructure development outside coastal areas has intensified introducing new pressures on marine ecosystems, including marine noise, sea water quality and changes to hydrodynamic circulation;
- Climate change and adaptation strategies are expected to pose significant risks to marine infrastructure;
- A growing focus is on developing proactive infrastructure strategies to adapt to hazards, including nature-based solutions, buffer zones, physical barriers and systems for early warning and evacuations
- Over the next 10 to 20 years, the future of marine infrastructure presents major challenges, especially concerning climate change, but also offers opportunities for innovation, sustainable growth, enhanced security, and greater resilience.

2. Introduction

The ocean offers immense potential for clean energy, resources~~,~~ exploitation and food production, which have led to a surge in marine infrastructure development beyond traditional coastal areas, leading to a significant increase in their numbers~~traditional coastal areas and to their dramatic rise in numbers~~.

These developments offer opportunities to meet social demands but they pose challenges and pressures such as potential disruptions to marine ecosystems and conflicts with existing maritime activities. The pressures exerted by marine infrastructure~~The compulsion on pressures caused by marine infrastructure~~ (e.g. offshore wind and subsea structures, cables, platforms and pipelines, aquaculture, floating islands etc) during their lifecycle, including installation, operation,

maintenance and decommissioning, "are extensive and widespreadare far and wide (Dannheim et al., 2020; Coolen et al., 2020).

Marine infrastructure development beyond coastal areas has intensified, driven by technological advancements and growing offshore resource demand (Gill et al., 2020). Marine infrastructure places significant pressure on ocean ecosystemsMarine infrastructure exerts unnecessary pressure on the ocean's ecosystems through loss of and disruption to natural habitats and species (Heery et al., 2017), alteration of oceanographic processes and ecological and geomorphic connectivity (Bishop et al., 2017; Firth et al., 2016), noise and vibration generation, decline in marine biodiversitygeneration of noise and vibrations, reduction in the diverse communities of marine life, and the introduction of invasive species (Chapman & Bulleri, 2003; Duarte et al, 2021a; Firth et al., 2016; Airoldi et al., 2015).

Changes in relation to WOA II

- Multiple factors have contributed to changes in open ocean pressures in recent years.Several drivers are responsible for the changes in open ocean pressure over the past few years. While new pressures have emerged, some align with trends previously described in WOA IIEven though there are new pressures, some could be seen as trends already described in WOA II.

Since WOA II, offshore wind farms have expanded notably, while oil and gas infrastructure development continues at an increasing rate (Jouffray et al., 2020). Additionally, substantial developments have occurred in submarine cables and pipelines, with 550 active or planned cables spanning over 1.4 million kilometres worldwide.Moreover, significant changes and developments have occurred in submarine cables and pipelines since 550 active or planned submarine cables spanning over 1.4 million kilometres worldwide are scheduled (The Economist, 2023). Advancements in robotics, material science, and underwater communication have significantly improved the feasibility of deep-sea exploration and resource extraction, in cases previously being out of reach.

At the same time in the past few years, climate change impacts have become more pronounced; the warming seas and ocean acidification continue to negatively affect marine ecosystems, with cascading effects on human communities that rely on ocean resources (OSPAR, 2024; Short et al., 2021). There is growing recognition that these pressures disproportionately affect vulnerable populations, including marine communities in developing countries and small island nations, especially in polar oceans.

3. Mapping tendencies of Marine Infrastructure outside of coastal areas

Based on Bugnot et al. (2021) and global analysis performed of existing and planned marine construction and its impact on the seascape, the spread of marine infrastructure is among the most significant human alterations to global seascapes. Maps illustrating ocean industrialization at a global scale highlight shifts in some of the largest and most economically significant activities at sea (Paolo et al. 2024). Marine infrastructure expansion outside coastal areas

represents a dynamic intersection of technological innovation, economic necessity, and strategic planning.

Efforts are ongoing to develop comprehensive databases that offer information and maps about marine infrastructure. The online maps/databases, covering different disciplinary themes – geology, physics, energy, mineral, biology, seabed habitats, spatial planning and human activities –, whilst also offering data and information on the blue economy operations (EMODnet, 2024; BOEM, 2024; MARCO, 2024; Open Infrastructure Map, 2024; European Maritime Affairs, 2024)

3.1 Marine energy infrastructure

The offshore oil and gas sector has evolved complexly, with some regions shifting towards decommissioning while others expand exploration (Shaffer, 2020). Technological advancements have enabled operations in deeper, more challenging environments (Zou et al., 2021). Oil and gas platforms are usually located on the continental shelf, but technological advances have allowed for deeper water drilling, such as those in the Gulf of Mexico, the North Sea, and off the coast of Brazil (Zou et al., 2021; Dou et al., 2022; Wen et al., 2023). The oil and gas industry has the potential to play a significant role in the sustainable energy transition.

Offshore wind energy has grown remarkably, with larger turbines deployed further offshore. Wind farms are typically located in shallow waters up to 50 meters deep, but their installation moves further offshore to capture stronger and more consistent wind resources. Floating wind farms are also being developed for deeper waters including for example those in the North Sea (Gușatu et al., 2021) and along the U.S. Atlantic coast (Baker et al., 2024; Shields et al., 2023). However, better locations' planning and optimization are required to induce atmospheric dynamics modifications and consequently wind speed reductions (extending as far as more than 40 km downwind from the farm) (Akhtar et al. 2021). The countries with the most consistent environmental and regulatory policies and prone to renewable energy have had the fastest development in implementing these wind turbines (Long, 2014). The production areas with the greatest potential for offshore wind energy are located mainly in Asia (on the coast of the China Sea) and Europe (North Sea, western part of the Baltic Sea and East Atlantic) (Enevoldsen and Jacobson, 2021).

Wave and tidal energy installations are placed in areas with strong tidal currents and significant wave activity, often near the coast but sometimes further out to harness stronger resources (Khojasteh et al., 2023). Tidal energy projects have progressed, with several commercial-scale installations now operational. Wave energy technologies promise future deployment (Neill et al., 2017).

3.2 Shipping and navigation infrastructure

Deepwater ports are located further offshore to accommodate large vessels that cannot navigate closer to shore due to depth constraints. Transoceanic shipping routes have led to the development of infrastructure supporting shipping lanes that traverse open oceans, including emergency response facilities. Seaports, due to their strategic locations and infrastructure, are emerging as pivotal hubs for the production, storage, and distribution of green hydrogen (Notteboom and Haralambides, 2023).

3.3 Subsea cables and pipelines

Subsea communication cables respond to the demand for global connectivity and leads to extensive networks of submarine cables crossing ocean basins. Subsea cable installations have increased significantly, forming a critical part of global communications infrastructure (Submarine Cable Map, 2023). A systematic review of the current security threats of the European Union's subsea data cable network (Bueger et al., 2022) suggests several recommendations on how to improve the resilience of the cable network. Oil and gas pipelines connecting offshore platforms to coastal refineries and distribution networks, usually follow the most direct and safest route along the seabed. Marine renewable infrastructure requires the development of new route power transmission cables to connect offshore renewable energy sources to onshore grids (Cullinane et al., 2022). Recent incidents of cable damage and geopolitical tensions led to a greater emphasis on safeguarding undersea infrastructure. For example, naval exercises have been conducted specifically to protect submarine cables and pipelines (NOAA, 2024).

3.4 Rest technologies (e.g. deep-sea mining, food technologies, multi-use islands)

With advancements in underwater technology, there is increasing interest in mining the deep-sea bed for minerals (e.g. polymetallic nodules, cobalt, and rare earth elements) particularly in the Pacific Ocean's Clarion-Clipperton Zone (Gentry et al., 2017). Also, offshore aquaculture has expanded significantly, with larger fish farms deployed further offshore (Gentry et al., 2017). Combining energy production, food systems, and resource extraction within shared offshore spaces presents a common future pathway globally (Depellegrin et al., 2019). A growing tendency is the utilization of multi-use platforms combining different industries, such as offshore energy production (wind, solar, or tidal) with aquaculture and desalination plants.

4. Interactions and effects on marine ecosystems and human wellbeing

Marine infrastructure interacts with ecosystems on multiple temporal scales. Short-term construction activities cause immediate disturbances, while long-term interactions involve changes to ecosystem structure and function (Dannheim et al., 2020). Infrastructure significantly impacts seabed ecosystems but may also increase habitat heterogeneity (Coolen et al., 2020). Increased underwater noise pollution affects marine life behaviour and physiology (Nowacek et al., 2015). Large-scale infrastructure can alter local hydrodynamics, potentially affecting sediment transport and larval dispersal (van Berkel et al., 2020). Socio-economic impacts include job creation and potential disruption of traditional maritime activities (Hooper et al., 2015). The expansion of marine infrastructure has implications for human health, both positive and potentially negative (Buonocore et al., 2016).

4.1 Marine noise (far field)

Ocean noise perturbs the oceanic environment and impacts marine life to an extent that is still not completely understood (Duarte et al. 2021). Some species are most sensitive to short powerful impulsive bursts, while others are deeply affected by permanent continuous low power disturbances (Merchant et al. 2020). Depending on noise power, frequency and the physical

properties of the ocean, acoustic waves propagate rapidly to long distances (Jensen et al. 1994; Nieukirk et al. 2004). The noise generated by offshore infrastructures is only one component of the overall anthropogenic noise (Sirovic et al. 2021), but important because is persistent.

The accounting of noise generated by offshore infrastructures may be logically split in three phases: installation, operation and decommissioning. Depending on the specific infrastructure, installation may involve bottom fixing (Jiang, 2021) or bottom laying of cables or pipes. Preparatory work generally encompasses careful sounding of the bottom and sub-bottom, often requiring extensive shallow water light seismic surveys (LSS) at the site and on the route to the site (Duarte et al, 2017). Sound sources used in LSS can be very harmful at local or regional level for sensitive species (Duarte et al., 2021; Spadoni et al., 2023). During installation, pile driving and/or dredging are the most common sources of noise (Amaral et al., 2020).

During operation, underwater noise is generated by structural moving parts, turning engines, or other specific sound emitting machinery. Machinery, turbines and other engines above water do transmit vibrations through the submerged supporting structure and/or through the water interface. Although levels are low relative to shipping noise, it can be substantially increased through concentration in wind farms (Tougaard et al., 2020). Offshore infrastructures also generate a significant acoustic particle acceleration signature that is highly disturbing for species leaving at close distance to the ocean bottom, the sea surface or to the supporting infrastructure itself, for wind turbines (Sigray et al., 2011) and marine energy converters (Popper et al, 2023).

4.2 Wave and currents circulation patterns

Hydrocarbon extraction platforms and subsea infrastructure can modify local hydrodynamics by creating physical barriers that affect sediment transport and coastal erosion processes (Erikson et al., 2022). Offshore aquaculture installations similarly affect local water flow and wave patterns, impacting nutrient distribution and sedimentation in the surrounding areas (Wang et al., 2021).

4.3 Seawater quality and marine mammals

Hydrocarbon extraction can lead to water pollution through oil spills, drilling muds, and produced water discharge, which can contain hydrocarbons and heavy metals, affecting seawater quality and impacting the food-chain (Erikson et al., 2022). Marine renewable energy devices generally have less severe impacts, although they can release antifouling agents and other chemicals used to maintain equipment (IEA, 2019). Offshore aquaculture can cause nutrient enrichment and organic matter accumulation, potentially leading to eutrophication and harmful algal blooms, thereby degrading water quality (Wang et al., 2021).

Marine mammals can be affected by offshore activities primarily through noise pollution, physical barriers, and water quality degradation. Noise from hydrocarbons extraction and renewable energy installations can disrupt marine mammal behaviour and communication, (Erikson et al., 2022) (IEA, 2019). Offshore aquaculture poses entanglement risks and disrupts natural foraging patterns and habitats (Wang et al., 2021). Undersea cables, although less impactful, generate electromagnetic fields that can affect marine mammals, especially when high voltages are involved.

4.4 Seabed interaction

Deep-seabed mining posed negative impacts to human health through three possible pathways, including, first, through its impacts on fish stocks and fisheries. Semi-permanent ships, support platforms, and riser pipes transporting mined minerals may interrupt fish migration due to light and noise pollution (Hamley, 2022). Collectively, this impact on global fisheries has repercussions for food security especially for Iindigenous Ppeoples and local communities that are highly dependent on marine ecosystem as their main source of nutrition (Hamley, 2022). Moreover, increased ambient metal concentrations such as copper, lead, zinc, cadmium and rare earth metals on marine ecosystems may accumulate and enter the human food web (Hauton, 2017). There is concern that seabed mining will disturb and resuspend seabed sediments, potentially releasing sequestered carbon (Hamley, 2022).

4.5 ~~Human health~~Health and Wellbeing

Marine infrastructure is vital to advance a country's national economic and security interests. Improving marine infrastructure, such as seaports and shipyards, could improve human well-being by reducing consumer prices, creating new jobs, and assisting local communities in marketing their seafood and farming products to other areas. However, planning and developing marine infrastructure often fails to include Iindigenous Ppeoples and local communities in decision-making processes and to consider the environmental impacts on neighbouring coastal communities and ecosystems (Morgera, 2024; Morgera and Lily, 2022). Environmental Impact Assessments (EIAs) are undertaken on a project-specific basis without considering the dynamic nature of ocean and coastal ecosystems and assessing the cumulative impacts associated with those developments (Sunde, 2023).

5. Summary and Key findings

Marine infrastructure development outside coastal areas has intensified, introducing new pressures on marine ecosystems. While offering economic benefits and potential contributions to sustainable energy and food production, these developments create complex challenges for marine ecosystem health and ocean governance. Primarily, climate change, adaptation strategies, and resilience reflected by rising sea levels and more frequent extreme weather events are expected to pose significant risks to marine infrastructure (Takukder et al., 2022).

The advantages of deploying environmental friendly emerging technologies in the whole life-cycle of a marine infrastructure demonstrated by relevant extensive life-cycle analyses could contribute significantly to the above direction. Furthermore, many governments are adopting more integrated approaches to marine management, considering the interconnections between land and marine use, development, natural hazards, and environmental protection (Eger et al., 2021).

A growing focus is on developing proactive infrastructure strategies to adapt to hazards. These may include nature-based solutions, buffer zones, physical barriers like seawalls, retreat and protect approaches, and systems for early warning and evacuations. While developed nations focus on adaptation and resilience, many developing countries may struggle with basic marine infrastructure needs, potentially widening the global infrastructure gap.

The outlook for marine infrastructure over the next 10-20 years is a significant challenge, particularly from a climate change perspective, but also in terms of opportunities for innovation, sustainable development, security and improved resilience. The success of these efforts will depend on proactive planning, substantial investment, and effective collaboration between governments, industries, and communities at large.

References

Airoldi, L., Turon, X., Perkol-Finkel, S., & Rius, M. (2015). Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. Diversity and Distributions, 21(7), 755-768.

Akhtar, Naveed, and others. Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials. Scientific reports, vol. 11, No. 1, art. 11826, 2021.

Amaral, Jennifer L., and others, Characterization of impact pile driving signals during installation of offshore wind turbine foundations. J. Acoust. Soc. Am., vol. 147, No. 4, 2020.

Baker, Alissa, and others. An Action Plan for Offshore Wind Transmission Development in the U.S. Atlantic Region. U.S. Department of Energy and Bureau of Ocean Energy Management. 2024. https://www.energy.gov/gdo/atlantic-offshore-wind-transmission-action-plan

Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H., ... & Dafforn, K. A. (2017). Effects of ocean sprawl on ecological connectivity: impacts and solutions. Journal of Experimental Marine Biology and Ecology, 492, 7-30.

Bueger, Christian, and others. Security threats to undersea communications cables and infrastructure–consequences for the EU. Report for SEDE Committee of the European Parliament, PE702557, 2022.
https://www.europarl.europa.eu/thinktank/en/document/EXPO_IDA(2022)702557

Bugnot, Ana B., and others. Current and projected global extent of marine built structures. Nature Sustainability, vol. 4, No. 1, pp. 33–41, 2021.

Buonocore, Jonathan J., and others. Health and climate benefits of different energy-efficiency and renewable energy choices. Nature Climate Change, vol. 6, pp. 100-105, 2016.

Bureau of Ocean Energy Management (BOEM), 2024. https://www.boem.gov/

Byomkesh Talukder, Nilanjana Ganguli, Richard Matthew, Gary W. vanLoon, Keith W. Hipel, James Orbinski, Climate change-accelerated ocean biodiversity loss & associated planetary health impacts, The Journal of Climate Change and Health,, Volume 6, 2022, 100114,

Chapman, M. G., & Bulleri, F. (2003). Intertidal seawalls—new features of landscape in intertidal environments. Landscape and urban planning, 62(3), 159-172.

Coolen, Joop W., and others. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. ICES Journal of Marine Science, vol. 77, No. 3, pp. 1250-1265, 2020.

Cullinane, Margaret, and others. Subsea superconductors: The future of offshore renewable energy transmission?. Renewable and Sustainable Energy Reviews, vol. 156, art. 111943, 2022.

Dannheim, Jennifer, and others. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science, vol. 77, No. 3, pp. 1092-1108, 2020.

Depellegrin, D., Venier, C., Kyriazi, Z., Vassilopoulou, V., Castellani, C., Ramieri, E., ... & Barbanti, A. (2019). Exploring Multi-Use potentials in the Euro-Mediterranean sea space. Science of the Total Environment, 653, 612-629.

Dou, Lirong, and others. Analysis of the world oil and gas exploration situation in 2021. Petroleum Exploration and Development, vol. 49, No. 5, pp. 1195-1209, 2022.

Duarte, Carlos M., and others. The soundscape of the Anthropocene ocean. Science, vol. 371, No. 6529, 2021.

Duarte, Henrique, and others. Advanced processing for UHR3D shallow marine seismic surveys. Near Surface Geophysics, vol. 15, No. 4, pp. 347-358, 2017.

Duarte, Ricardo J., and others. Anthropogenic noise predictions for light seismic survey off the SW Portuguese coast. IEEE/MTS Global Oceans'2021, 2021.

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., ... & Juanes, F. (2021a). The soundscape of the Anthropocene ocean. Science, 371(6529), eaba4658.

Eger, S. L., De Loë, R. C., Pittman, J., Epstein, G., & Courtenay, S. C. (2021). A systematic review of integrated coastal and marine management progress reveals core governance characteristics for successful implementation. Marine policy, 132, 104688.

Enevoldsen, P., & Jacobson, M. Z. (2021). Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. Energy for Sustainable Development, 60, 40-51.

Erikson, L.H, Nederhoff, L., Engelstad, A., Kasper, J., Bieniek, P., U.S. Geological Survey (USGS, Pacific Coastal Marine Science Center, Santa Cruz, CA). 2022. Central Beaufort Sea wave and hydrodynamic modeling study. Report 2: Modeled waves, hydrodynamics and sediment transport in Foggy Island Bay. Anchorage (AK): U.S. Department of the Interior, Bureau of Ocean Energy Management.40 p. plus appendices. Report No.: OCS Study BOEM 2022-079. IAA No.: M17PG00046.

European Marine Observation and Data Network (EMODnet), 2024. https://emodnet.ec.europa.eu/

European Maritime Affairs, 2024. https://ec.europa.eu/maritimeaffairs/

Firth, L. B., Knights, A. M., Bridger, D., Evans, A. J., Mieszkowska, N., Moore, P. J., ... & Hawkins, S. J. (2016). Ocean sprawl: and opportunities for biodiversity management in a changing world. Oceanography and Marine Biology: an annual review, 54, 189-262.

Gentry, Rebecca R., and others. Mapping the global potential for marine aquaculture. Nature Ecology & Evolution, vol. 1, No. 9, pp. 1317-1324, 2017.

Gill, Andrew B. and others. Setting the context for offshore wind development effects on fish and fisheries. Oceanography, vol. 33, No. 4, pp. 118-127, 2020

Gușatu, Laura F., and others. Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin. Scientific reports, vol. 11, No. 1, art. 10125, 2021.

Hamley, Graham J.The implications of seabed mining in the Area for the human right to health. Review of European, Comparative & International Environmental Law (RECIEL), vol. 31, No. 3, pp. 389-398, 2022.

Hauton, Chris, and others. Identifying toxic impacts of metals potentially released during deep-sea mining: a synthesis of the challenges to quantifying risk. Frontiers in Marine Science, vol. 4, 2017.

Heery, E. C., Bishop, M. J., Critchley, L. P., Bugnot, A. B., Airoldi, L., Mayer-Pinto, M., ... & Dafforn, K. A. (2017). Identifying the consequences of ocean sprawl for sedimentary habitats. Journal of Experimental Marine Biology and Ecology, 492, 31-48.

Hooper, Tara, and others. Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Marine Policy, vol. 61, pp. 16-22, 2015.

International Telecommunication Union (ITU). International bandwidth usage. 2024. https://datahub.itu.int/data/?e=MLI&i=242

International Energy Agency (2019) Renewables 2019 Analysis and forecast to 2024. https://iea.blob.core.windows.net/assets/a846e5cf-ca7d-4a1f-a81b-ba1499f2cc07/Renewables_2019.pdf

Jensen, Finn B., and others. Computational Ocean Acoustics, AIP Series in Modern Acoustics and Signal Processing. Woodbury, New York: AIP Press, 1994.

Jiang, Zhiyu. Installation of offshore wind turbines: a technical review. Renewable and Sustainable Energy Reviews, vol.139, art. 110576, 2021.

Jouffray, Jean B., and others. The blue acceleration: the trajectory of human expansion into the ocean. One Earth, vol. 2 , No.1, pp. 43-54, 2020.

Khojasteh, Danial, and others. A large-scale review of wave and tidal energy research over the last 20 years. Ocean Engineering, vol. 282, art. 114995, 2023.

Long, Ronan. Harnessing offshore wind energy: legal challenges and policy conundrums in the European Union. The International Journal of Marine and Coastal Law, vol. 29, No.4, pp. 690-715, 2014.

Merchant, Nathan D., and others. Impulsive noise pollution in the Northeast Atlantic: reported activity during 2015–2017. Marine Pollution Bulletin, vol. 152, art. 110951, 2020.

Mid-Atlantic Ocean Data Portal (MARCO), 2024. https://portal.midatlanticocean.org/visualize/

Morgera, Elisa. Participation of Indigenous Peoples in Decision Making Over Deep-Seabed Mining. American Journal of International Law (AJIL) Unbound, vol. 118, pp. 93-97, 2024.

Morgera, Elisa and Hannah Lily. Public participation at the International Seabed Authority: An international human rights law analysis. Review of European, Comparative & International Environmental Law, vol. 31, No. 33, pp. 374-388, 2022.

Morgera, Elisa, and others. Addressing the Ocean-Climate Nexus in the BBNJ Agreement: Strategic Environmental Assessments, Human Rights and Equity in Ocean Science. The International Journal of Marine and Coastal Law, vol. 38, No.3, pp. 1-33, 2023.

National Oceanic and Atmospheric Administration (NOOA). Submarine cables - international framework. 2024. https://www.noaa.gov/general-counsel/gc-international-section/submarine-cables-international-framework

Neill, Simon P., and others. The wave and tidal resource of Scotland. Renewable Energy, vol. 114, pp. 3-17, 2017.

Niner, Holly, and Kirsty McQuaid. Defining the Environmental Impact Assessment process for deep-sea mining. 2021. https://oneoceanhub.org/defining-the-environmental-impact-assessment-process-for-deep-sea-mining/.

Nieukirk, Sharon L., and others. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. J. Acoust. Soc Am., vol. 115, No. 4, 2004.

Notteboom, T., & Haralambides, H. (2023). Seaports as green hydrogen hubs: advances, opportunities and challenges in Europe. Maritime Economics & Logistics, 25(1), 1-27.

Nowacek, Douglas P., and others. Marine seismic surveys and ocean noise: time for coordinated and prudent planning. Frontiers in Ecology and the Environment, vol. 13, No. 7, pp. 378-386, 2015.

One Ocean Hub. Hub research included in UN special rapporteur's report on right to food, fisheries, and climate change. 2024. https://oneoceanhub.org/hub-research-included-in-un-special-rapporteurs-report-on-right-to-food-fisheries-and-climate-change/

Open Infrastructure Map, 2024. https://openinframap.org/

OSPAR Commission. (2024). OSPAR Joint Assessment and Monitoring Programme (JAMP) 2024-2028 OSPAR Agreement 2024-01.

Paolo, Fernando. S., and others. Satellite mapping reveals extensive industrial activity at sea. Nature, vol. 625, pp. 85-91, 2024.

Popper, Arthur, and others. Marine energy converters: Potential acoustic effects on fishes and aquatic vertebrates. J. Acoust. Soc. Am., vol. 154 No. 1, pp. 518-532, 2023.

Shaffer, Brenda. Energy Politics. Pennsylvania: University of Pennsylvania Press, 2020.

Shields, Matt, and others. A Supply Chain Road Map for Offshore Wind Energy in the United States. Golden, CO, National Renewable Energy Laboratory (NREL), NREL/TP-5000-84710. 2023. https://doi.org/10.2172/1922189.

Short, Rebecca E., and others. Review of the evidence for oceans and human health relationships in Europe: a systematic map. Environment International, vol. 146, art. 106275. 2020.

Short, R. E., Cox, D. T., Tan, Y. L., Bethel, A., Eales, J. F., & Garside, R. (2021). Review of the evidence for oceans and human health relationships in Europe: A systematic map. Environment International, 146, 106275.

Sigray, Peter, and Mathias H. Andersson. Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish. J. Acoust. Soc. Am., vol. 130, No, 1, pp. 200-207, 2011.

Sirovic, Ana, and others. "Trends in inputs of anthropogenic noise into the marine environment", in *The Second World Ocean Assessment*, (New York; United Nations, 2021).

Spadoni, Giuliu, and others. Seismic survey risk assessment for the common dolphin population in the south-western coast of Portugal. The Effects of Noise on Aquatic Life, pp. 1923-1937, 2023.

Submarine Cable Map. TeleGeography. 2023. https://www.submarinecablemap.com

Sunde, Jackie and Christian Adams. Inputs for Fisheries Report: The Right to Food and Securing Sustainable Small Scale Fisheries. 2023. https://www.ohchr.org/sites/default/files/documents/issues/food/cfi-food-fisheries/subm-food-securing-sustainable-csos-othe-sunde-j-from-1-ocean-hub-universi-ative.pdf

Sunde, Jackie. Participating in seismic shifts in ocean research and advocacy collaboration in South Africa. 2022. https://oneoceanhub.org/participating-in-seismic-shifts-in-ocean-research-and-advocacy-collaboration-in-south-africa/

The Economist. Big tech and geopolitics are reshaping the internet's plumbing. 2023. https://www.economist.com/business/2023/12/20/big-tech-and-geopolitics-are-reshaping-the-internets-plumbing

Tougaard, Jakob, and others. How loud is the underwater noise from operating offshore wind turbines?. J. Acoust. Soc. Am., vol. 148, No. 5, pp. 2885–2893, 2020.

United Nations. Fisheries and the right to food in the context of climate change. 2024, https://www.ohchr.org/en/documents/thematic-reports/ahrc5549-fisheries-and-right-food-context-climate-change-report-special.

van Berkel, Joshua, and others. The effects of offshore wind farms on hydrodynamics and implications for fishes. Oceanography, vol. 33, No. 4, pp. 108-117, 2020.

Wang, C., Wang, Y., Liu, P., Sun, Y., Song, Z., & Hu, X. (2021). Characteristics of bacterial community structure and function associated with nutrients and heavy metals in coastal aquaculture area. Environmental Pollution, 275, 116639.

Wen, Zhixin, and others. Analysis of the world deepwater oil and gas exploration situation. Petroleum Exploration and Development, vol. 50, No. 5, pp. 1060-1076, 2023.

WindEurope. Wind energy in Europe: 2022 statistics and the outlook for 2023-2027. 2023. https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/

Zou, X. and others. Advances in exploration and development of deep-water oil and gas. Petroleum Exploration and Development, vol. 48 No.1, pp. 1-14, 2021.

Section 4
Chapter 6: Pressures: Cumulative effects

Lead Author: Piers Dunstan

Contributing Authors

Jesper H. Andersen, Sam Dupont, Nohora Galvis, Manuel Hidalgo, Jonne Kotta, Vanessa Stelzenmüller, Kerry Sink, Skip Woolley, Beth Fulton

Key findings

1. There has been continued application of Cumulative Effects Assessment since WOAII
2. These applications are being utilised within national jurisdictions to inform decision making
3. The experiences in application of Cumulative Effects Assessment can guide further development of assessment approaches.

Introduction

Cumulative Effects approaches were reviewed in the Second~~2~~nd World Ocean Assessment. Cumulative effect Assessments (CEA) need to consider ~~the~~ scale and resolution ~~needed~~, the values being assessed, the data available, the uncertainties and the management objective to be met. The chapter identified that expert knowledge and qualitative data were moderately used across assessments, geographic information systems are commonly used, uncertainty is rarely ~~assessed~~ evaluated and integrative techniques remain under~~are still in~~ development.

The chapter identified the key functional steps as

1. Definition of the values of the marine system being assessed
2. Definition of the activities that place pressures on the marine system (stressors)
3. Conceptual linking of pressures and values
4. Assessment of risk and uncertainty
5. Validation

The WOAII chapter highlighted key improvements~~identified that assessments need to~~ needed in assessments:

1. Integrate the ~~incorporate the~~ extent and spatial and temporal variability of~~in~~ data and ~~their~~ associated uncertainty
2. Enhance~~Expand~~ experimental and observational methods for assessing the sensitivity of ecosystem components to stressor impacts~~ experiment-based or observation-based measures of the sensitivity of ecosystem components to the effects of stressors~~,
3. Incorporate repeated temporal studies
4. ~~Improve the linkages between an assessment of cumulative effects and the management measures that may regulate the activities that cause the various pressures~~Strengthen the connections between cumulative effects assessments and management measures designed to regulate pressure-inducing activities.
5. Consider the spatial separation of the activity location and pressure effect
6. ~~explicitly describe the causes and consequences of deleterious effects~~ clearly define the causes and impacts of harmful effects
7. consider approaches that can be applied outside of developed countries.

The Environmental Change since WOAII

Since WOA II an increasing acceptance of Cumulative Effects Assessment (CEA) or Cumulative Impacts Assessment (CIA) as a structured process~~s~~ (Piet et al., 2021), which specifies the functional relationships between human activities, their pressures and ecosystem state (Stelzenmüller et al., 2020) can be observed. The linkages between the ecosystem components assessed in a CEA and their contribution to ecosystem services have only recently been drawn (Ruskule et al., 2023; Simeoni et al., 2023). Particularly in European seas, the need to align CEA boundaries with those where the operational modes of human activities are regulated through Marine Spatial Planning (MSP) processes is increasingly recognised (Hammar et al., 2020; Kirkfeldt and Andersen, 2021). However, future trajectories of human activities and MSP, and how these might influence future CEA outcomes, are rarely explored. (Stelzenmüller et al., 2024). In many regions, CEA are not yet integrated into prevailing management frameworks.

In transboundary settings such as Europe (Mackelworth et al., 2024) or in the Yellow Sea (Ma et al., 2023), socio-economic interests are confined to national boundaries, but ecosystem health and resilience depend on ecosystem processes and exposure to human pressures at multiple spatial and temporal scales (Elliott et al., 2023). National MSP processes require international consultations which increases the complexity in determining effective management responses to mitigate unwanted adverse effects (Cormier et al., 2018).

Mitigating undesirable effects, particularly at multiple spatial scales, requires management responses that are more likely to be reflected in a programme of measures. In practice, this means integrating environmental impact assessments for local projects, such as offshore wind

farms (Oh et al., 2021), with regional environmental assessments of marine spatial plans (Cormier et al., 2022; Kirkfeldt and Andersen, 2021), as well as regional sea assessments. ~~CEA is outside Europe slowly being utilised in several jurisdictions to support decision making~~While there has been extensive utilization of CEA in Europe, applications outside are less common (but see sections on South Africa and Australia).

The integration of CEA into jurisdictional decision making is slowly increasing and moving from scientific studies into policy documents. This update concentrates on where CEA has or is making that transition. Case studies from some jurisdictions showing the different applications of CEA into policy that have occurred since WOA2 are further detailed below.

Region Specific Changes

The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the Persian Gulf

South Africa

Compiling the data and undertaking analys~~e~~is for cumulative impacts and associated assessments of the state of marine ecosystems can be particularly difficult for developing countries where data and capacity are more limited. South Africa is one of the few developing countries that has undertaken cumulative marine pressure mapping as part of the National Biodiversity Assessment (NBA), conducted every 5 -7 years. The most recent NBA mapped 31 pressures on marine biodiversity (Sink et al. 2019) with additional pressure mapping currently underway for the 2025 assessment. The cumulative pressure map is used to develop a national map of ecosystem degradation that is overlaid on an iteratively improving national map of marine ecosystem types to assess ecosystem threat status using an approach aligned with the IUCN ecosystem red-listing standards (Keith et al. 2013). These products are used in policy, spatial planning and systematic conservation planning to support Marine Protected Area expansion (Sink et al. 2023b, SANBI & UNEP-WCMC 2024).

The purpose of the cumulative pressure mapping in South Africa is to produce a map of ecosystem condition to determine the amount and location of natural areas that remain, and their condition in terms of how their composition, structure and function has been

modified from a reference condition of natural. South Africa mapped and evaluated 31 different pressures individually and cumulatively as a surrogate for ecosystem degradation. Both the extent and intensity of pressures were considered together with an expert-derived impact score that accounts for different combinations of pressures and ecosystem type (Sink et al. 2019). An ecosystem condition map was produced with degradation assessed in four categories aligned to the IUCN red-listing criteria for degradation (Criteria C and D).

Building on the NBA, Skein et al. (2022) drew from the cumulative pressure mapping and reports to undertake a scoping exercise for an Integrated Ecosystem Assessment, considering 17 sectors, 17 key pressures, 23 key ecosystem characteristics, and 23 ecosystem services. They noted that fishing, petroleum activities and shipping are widespread sectors resulting in many pressures on multiple ecosystem components and comment on the many interacting pressures cumulatively affecting South African marine ecosystems. Smit et al. (2024) conducted the first ground truthing of marine ecosystem condition in South Africa and showed that pressure mapping is an effective proxy at broad national scales, but that updated and finer scale pressure mapping is needed to improve condition estimates. Planning & management decisions based solely on cumulative impact scores could misrepresent the actual condition of the environment especially at finer scales. Although South Africa has made progress with cumulative pressure mapping, there is a need to increase mapping, modelling and analysis capacity, account for non-linear, synergistic and antagonistic interactions among stressors and ground truth ecosystem condition across multiple ecosystem functional groups. Failure to accurately map pressures and to account for cumulative impacts will mean that potential impacts are missed and poor spatial planning and decisions are likely with negative impacts on people and the environment.

The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Mediterranean Sea

The Mediterranean Sea is the largest and deepest enclosed sea on Earth, known as hotspot of biodiversity. First CEA studies one decade ago already reported a widespread and severe effects in both the western and eastern Mediterranean basins (Coll et al. 2012, Micheli et al. 2013). Pollution and wide spread coastal development were identified as the two primary pressures. This pattern remains consistent nowadays, with the Adriatic Sea

and the western Mediterranean identified as two European areas with the most severe cumulative effects in the coastal and shelf areas due to several anthropogenic pressures, particularly physical loss and disturbance due to intensive fishery, pollution and coastal activities (EEA, 2019). Over the whole basin, long-lasting overexploitation of fish stocks (especially in narrow shelfs), marine litter, the strong warming and heatwaves rates, and the high number of non-indigenous species particularly the Eastern Mediterranean are also generalized patterns (ETC/ICM, 2019).

In terms of species and ecosystems responses to cumulative effects, most of studies over large scales assess the impact on a reduced number of pressures (mainly climate and fishing impacts), with a diversity synergistic or antagonistic responses across species and ecoregions over the whole basin (e.g. Coll et al. 2016, Corrales et al. 2018, Moullec et al. 2023). Many of them have also reported a long-lasting anthropogenic erosion of population and ecosystems resilience, which has triggered and increased sensitivity to natural environmental variability (e.g. Fu et a. 2019, Hidalgo et al. 2011, 2022). Benthic habitats and associated vulnerable species, such as coralligenous species, have been shown to be sensitive to impacts, particularly to local anthropogenic impacts associated to coastal development (Bevilacqua et al. 2018). Mortality events of these marine forest are often associated to heatwaves events in high cumulative impacted areas (Garrabou et al. 2022, Canessa et al. 2024). In the Eastern Mediterranean, cumulative scenarios suggest that the beneficial effects of regulating fishing effort may be dampened by the impact of strong warming and alien species when acting together (Corrales et al. 2018). Spatial erosion of communities due to cumulative impacts is also increasing the heterogeneity of local and sub-regional responses to warming and other impacts, disrupting as well the natural biodiversity gradients (Pennino et al. 2024). Major data gaps in the CEA assessment have been identified in the Mediterranean as well as in the Black Sea, particularly in offshore measurements and open sharing of national indicator threshold values (ETC/ICM, 2019). Strong recent efforts on marine litter monitoring and forecasting tools are rapidly filling the gap of knowledge in this well-established pressure (Galli et al. 2023).

Baltic Sea

As part of the third HELCOM (“Helsinki Commission”) holistic assessment (HOLAS 3; https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2023/), which offered an extensive evaluation of the Baltic Sea's ecosystem health for the period 2016–2021, the HELCOM Spatial Distribution of Pressure and Impact Assessment (SPIA) examined how human activities created pressures on ecosystem components such as

species and habitats. By linking spatial data on ecosystem components with pressures, it identified overlaps and assessed the sensitivity of ecosystems to specific pressures. This approach helped trace which activities drove the impacts and provided insights into the relative impact levels across the region. While SPIA supported holistic Baltic Sea assessments, it did not quantify absolute pressure or impact magnitudes, nor did it function as a status assessment like the Water Framework Directive. Moreover, it was limited to expert knowledge and simplified pressure-response systems, treating cumulative impacts as the sum of individual pressures while overlooking synergistic interactions between them. This limitation biases ecosystem-based management of human activities at sea, threatening the achievement of environmental and socio-economic sustainability goals.

However, a substantial body of scientific literature has accumulated, exploring both the separate and interactive effects of multiple pressures on diverse ecosystem assets and services. This enables shifting the CEA assessment from expert-based to data-driven approaches, allowing for the inclusion of more complex responses to various pressures. The recently developed PlanWise4Blue (PW4B) tool introduces a methodology for CEA by combining scientific evidence with expert judgment, presented through an interactive online tool for environmental managers (Kotta et al., 2020). PW4B's knowledge matrix, based on cause-effect data, quantifies both single and synergistic effects of key human activities on a wide range of nature assets, providing real-world metrics (e.g., species biomass or habitat loss/gain) under different scenarios, rather than arbitrary indices. While some impact coefficients still rely on expert judgment, PW4B will increasingly incorporate empirical data as it becomes available. This free-to-use tool is designed for marine managers and policymakers without scientific backgrounds, offering user-friendly access to the best available data for decision-making.

PW4B has been used in Estonian Maritime Spatial Planning to evaluate environmental sustainability and is fully functional across the Baltic Sea, with plans for expansion to other marine systems (Vaher et al., 2022). Future versions will feature an AI-driven multimodal information retrieval system, capable of extracting and processing impact-related data from scientific publications and integrating it into predictive models.

The South Pacific Ocean

Australia.

Cumulative effects assessment has been identified as an important part of environmental management under the Environmental Protection and Biodiversity Conservation Act (EPBC)(1999). While the EPBC allows for broad regional assessments of cumulative effects, it does not explicitly require ~~include~~ cumulative effects assessments as they are commonly portrayed in the scientific literature (Dales, 2011; Dunstan et al. 2020), such as ~~;~~ Hayes *et al.* 2021, Dunstan *et al.*~~,~~ (~~2020~~2023) and Ostwald *et al.* (2021). Despite the lack of a formal regulatory framework for cumulative effects assessments in Australia, there has been an increasing number of cumulative effect assessments (CEA) in Australia at both local (eg Fulton *et al.* 2017) and regional scales (eg Hayes *et al.* 2021). These CEAs have been developed by the scientific community in collaboration with proponents and government agencies as part of strategic, regional or national assessment.

Notable examples of regional or strategic CEAs are the NSW Marine Estate Management Strategy (MEMA, 2018), Victoria's Marine and Coastal Policy (DELWP, 2020), Spencer Gulf (Gillanders et al., 2016); Gladstone Harbour (Eco Logical Australia, 2019, Fulton et al 2017), the Great Barrier Reef (Dunstan et al, 2020), Gascoyne (Fulton et al., 2015) and Kimberley (Boschetti et al., 2020). These approaches vary from the typical spatial additive assessment frameworks (e.g. Halpern et al. 2008, Stelzenmüller et al. 2018, Hayes et al. 2021, Dunstan et al. 2023) which sum the direct effects on ecosystems, to more strategic quantitative ecosystem-based assessments which explicitly address non-additive and non-linear combinations of effects through the entire ecosystem (e.g. Fulton et al 2015; Fulton et al 2017; Boschetti et al., 2020).

At the national level the Parks Australia's Monitoring Evaluation Reporting and Improvement (MERI) framework (Hayes et al., 2021, Dunstan *et al.* 2023) included a spatial additive assessment of cumulative impacts across Australia's EEZ, based on 39 identified activities~~,~~ that were expected to alter the natural state of Australia's marine ecosystems. The cumulative effects assessment was used to prioritize the locations of monitoring efforts in ~~which~~ Commonwealth Marine reserves to test the effectiveness of management~~for management based on the impact of cumulative effects~~. Recently, an Australia-wide CEA that focused specifically on the effects of commercial, recreational and customary fisheries for at risk species spanning State and Commonwealth jurisdictions was completed (Fulton et al., 2023). This approach used a hierarchical CEA which implements a spatial cumulative additive fishing pressure map based 409 species that commonly interact with Australia's fisheries (Fig. 1). A key aspect of this framework is to move to a quantitative ecosystem model approach in areas where species are identified at higher risk due to spatial cumulative effect hotspots. These regions can then have more specific modelling approaches that deal with ecosystem dynamics between effects and ecosystem values to build a more strategic management framework for high-risk regions.

Finally, the National Climate Risk Assessment has developed cumulative effects on the impact of key climate hazards on Australia's marine ecosystems. This project looked at the trajectories of relative ecosystem risk under different global warming levels to identify which parts of Australia's EEZ are most at risk from near term (global warming level 1.5°C) and long-term (global warming level 3.0°C) climate impacts.

Remaining key knowledge and capacity changes and any new gaps

Future needs and development for cumulative assessment.

There is a need to jointly develop global platform(s) that map human pressures and natural assets, alongside a knowledge base to predict the potential effects of different combinations of human pressures on these assets. These platforms should not only assess the effects of current pressures but also offer the capacity for scenario analyses, helping to prevent unnecessary damage to ecosystems.

Cross-scale responses to CEA footprints

The pressures that are considered as part of CEA assessments vary in spatial footprint.~~different spatial exposure to cumulative impacts is well represented by CEA assessments and similar studies, with~~ Eeffects such as fishing and infrastructure have a clear spatial ~~-~~footprint and act~~ing often~~ at a ~~more~~ local scale, while others related to the climate change such as warming impact~~ing~~ over ~~a~~ regional or larger scales. Thus, different anthropogenic activities and the associated stressors generate distinct footprints. However, system responses are often context-dependent as the same response to a given pressure or combination of pressures do not occur equally elsewhere. Indeed, activities and stressor footprints do not necessarily inform on the populations and ecosystems responses, which often occupy different space and time scales (Low et al. 2023).

Systems responses can be observed at both larger and smaller size than the stressor footprint. Also, changes in ecosystem structure and abundance~~s~~ response can often ~~stretch away from~~be seen away from the activity footprint triggering asynoptic effects on the ecosystems, classically observed in river runoffs or localized pollution sources. Temporal mismatches between stressor addition and ecosystem responses are also generated by legacies and carryover effects (Low et al. 2023). A large response in relation to the stressor can, for instance, occur if the ecosystem response persists for longer than the stressor, or where recovery of ecosystems does not occur after impact cessation (i.e., a

legacy remains), or due to carryover effects of stressors on future life stages (i.e., anadromous or migratory species). Differential spatial and temporal degradation can influence a patchiness in the system responses, as well as natural variation in seascape characteristics may result in some areas being more sensitive to similar effects. It is in these cases, when dispersal and ecological connectivity can contribute to mitigate spatially heterogenous cumulative disturbances (e.g. spatial insurances, Loreau et al. 2023). The way in which the components of ecological systems are spatially and temporally connected and distributed is critical to withstand cumulative combination natural and anthropogenic disturbances, being thus fundamental to resilience. In this sense, marine connectivity plays a pivotal role in supporting resilience (Hilty et al. 2020, Pearson et al. 2021), while how this influence is mediated, and which are the mechanisms of action is still poorly understood.

References

Anthony, K.R.N., Dambacher, J.M., Walshe, T. and Beeden, R. (2013) A framework for understanding cumulative impacts, supporting environmental decisions and informing resilience-based management of the Great Barrier Reef World Heritage Area. Australian Institute of Marine Science, Townsville; CSIRO, Hobart; NERP Decisions Hub, University of Melbourne and Great Barrier Reef Marine Park Authority, Townsville.

Bevilacqua, S., Guarnieri, G., Farella, G. et al. A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. Sci Rep 8, 1757 (2018). https://doi.org/10.1038/s41598-018-20297-1

Boschetti, F., Lozano-Montes, H. and Stelfox, B. (2020) Modelling regional futures at decadal scale: application to the Kimberley region. Scientific Reports 10:849 https://doi.org/10.1038/s41598-019-56646-x

Canessa M, Bertolotto R, Betti F, Bo M, Dagnino A, Enrichetti F, Toma M, Bavestrello G. Variation in the Health Status of the Mediterranean Gorgonian Forests: The Synergistic Effect of Marine Heat Waves and Fishing Activity. Biology. 2024; 13(8):642. https://doi.org/10.3390/biology13080642

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W.W.L., Christensen, V., Karpouzi, V.S., Guilhaumon, F., Mouillot, D., Paleczny, M., Palomares, M.L., Steenbeek, J., Trujillo, P., Watson, R. and Pauly, D. (2012), The Mediterranean Sea under siege: spatial

overlap between marine biodiversity, cumulative threats and marine reserves. Global Ecology and Biogeography, 21: 465-480. https://doi.org/10.1111/j.1466-8238.2011.00697.x

Coll M, Steenbeek J, Sole J, Palomera I, Christensen V (2016) Modelling the cumulative spatial–temporal effects of environmental drivers and fishing in a NW Mediterranean marine ecosystem, Ecological Modelling, 331: 100-114 https://doi.org/10.1016/j.ecolmodel.2016.03.020.

Cormier R., Cormier R., Stelzenmüller V., Creed I. F., Igras J., Rambo H., Callies U., et al. (2018). The Science-Policy Interface of Risk-Based Freshwater and Marine Management Systems: From Concepts to Practical Tools. J. Environ. Manage. 226, 340–346. doi: 10.1016/j.jenvman.2018.08.053

Cormier R., Elliott M., Borja Á. (2022). Managing marine resources sustainably – the 'Management response-footprint pyramid' Covering policy, plans and technical measures. Front. Mar. Sci. 9. doi: 10.3389/fmars.2022.869992

Corrales, X., Coll, M., Ofir, E. et al. Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. Sci Rep 8, 14284 (2018). https://doi.org/10.1038/s41598-018-32666-x

Dales, J.T. (2011). Death by a thousand cuts: incorporating cumulative effects in Australia's Environmental Protection and Biodiversity Conservation Act. Pacific Rim Law and Policy Journal, 20: 149-178.

Department of Environment, Land, Water and Planning 2020 (DELWP) (2020) Marine and Coastal Policy. State Government of Victoria. Available from https://www.marineandcoasts.vic.gov.au/__data/assets/pdf_file/0027/456534/Marine-and-CoastalPolicy_Full.pdf

Dunstan, P.K. , Dambacher, J.M., Thornborough, K., Marshall, N. and Stuart-Smith, R. (2020) Technical Report describing Guidelines for analysis of cumulative impacts and risks to the Great Barrier Reef (Part 1).

Dunstan PK, Woolley SNC, Monk J, Barrett N, Hayes KR, Foster S, Howe SA, Logan D, Samson CR, Francis SO (2023) Designing a targeted monitoring program to support evidence-based management of Australian Marine Parks: National Implementation. Report to the National Environmental Science Program. CSIRO.

Eco Logical Australia (2019). Cumulative Impact Assessment – Gatcombe and Golding Cutting Channel Duplication EIS. Prepared for Aurecon.

EEA, 2019, Marine messages II, EEA Report No 17/2019, European Environment Agency, accessed 02/12/2020

Elliott, M., Borja, Á., and Cormier, R. (2023). Managing marine resources sustainably – ecological, societal and governance connectivity, coherence and equivalence in complex marine transboundary regions. Ocean Coastal Manag. 245, 106875. doi: 10.1016/j.ocecoaman.2023.106875

ETC/ICM, 2019, Multiple pressures and their combined effects in Europe's seas, ETC/ICM Technical Report 4/2019, European Topic Centre for Inland, Coastal and Marine Waters, accessed 02/12/2020.

Fu C, Xu Y, Grüss A, Bundy A, Shannon L, Heymans JJ, Halouani G, Akoglu E, Lynam CP, Coll M, A Fulton EA, Velez L, Shin YJ, (2020) Responses of ecological indicators to fishing pressure under environmental change: exploring non-linearity and thresholds, ICES Journal of Marine Science, Volume 77, Issue 4, Pages 1516–1531, https://doi.org/10.1093/icesjms/fsz182

Fulton, E.A., Boschetti, F., Sporcic, M., Jones, T., Little, L.R., Dambacher, J.M., Gray R., Scott, R. and Gorton, R. (2015) A multi-model approach to engaging stakeholder and modellers in complex environmental problems. Environmental Science & Policy, 48: 44 – 56

Fulton, E.A., Hutton, T., van Putten, I.E., Lozano-Montes, H. and Gorton, R. (2017) Gladstone Atlantis Model – Implementation and Initial Results. Report to the Gladstone Healthy Harbour Partnership. CSIRO, Australia.

Fulton, E.A., Dunstan, P., Treblico, R. (2023), Cumulative impacts across fisheries in Australia's marine environment: Final Report, CSIRO: Hobart, November. CC BY 3.0

Galli M, Baini M, Panti C, Giani D, Caliani I, Campani T, Rosso M, Tepsich M, Levati V, Laface F, Romeo T, Scotti G, Galgani F, Fossi MC, (2023) Oceanographic and anthropogenic variables driving marine litter distribution in Mediterranean protected areas: Extensive field data supported by forecasting modelling, Science of The Total Environment, 903, 166266,https://doi.org/10.1016/j.scitotenv.2023.166266.

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., Bensoussan, N., Turicchia, E., Sini, M., Gerovasileiou, V., Teixido, N., Mirasole, A., Tamburello, L., Cebrian, E., Rilov, G., Ledoux, J.-B., Souissi, J. B., Khamassi, F., Ghanem, R. … Harmelin, J.-G. (2022). Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Global Change Biology, 28, 5708–5725. https://doi.org/10.1111/gcb.16301

Gillanders, B.M., Ward, T.M., Bailleul, F., Cassey, P., Deveney, M.R., Doubleday, Z.A., Goldsworthy, S., Huveneers, C., Jones, A.R., Mackay, A.I., Möller, L., O'Connell, L., Parra, G., Prowse, T.A.A., Robbins, W.D., Scrivens, S. and Wiltshire, K.H. (2016). Spencer Gulf Ecosystem and Development Initiative. Developing Knowledge and Tools to Inform Integrated Management of Spencer Gulf: Case Study on Shipping and Ports. Report for Spencer Gulf Ecosystem and Development Initiative. The University of Adelaide, Adelaide. 110 pp.

Great Barrier Reef Marine Park Authority (GBRMPA)(2014) Great Barrier Reef Region Strategic Assessment: Strategic assessment report. GBRMPA: Townsville.

Keith, D.A., Rodríguez, J.P., Rodríguez-Clark, K.M., Nicholson, E., Aapala, K., Alonso, A., Asmussen, M., Bachman, S., Basset, A., Barrow, E.G., Benson, J.S., Bishop, M.J., Bonifacio, R., Brooks, T.M., Burgman, M.A., Comer, P., Comín, F.A., Essl, F., Faber-Langendoen, D., Fairweather, P.G., Holdaway, R.J., Jennings, M., Kingsford, R.T., Lester, R.E., Nally, R.M., McCarthy, M.A., Moat, J., Oliveira-Miranda, M.A., Pisanu, P., Poulin, B., Regan, T.J., Riecken, U., Spalding, M.D., Zambrano-Martínez, S., 2013. Scientific Foundations for an IUCN Red List of Ecosystems. PLoS ONE 8, e62111.

Halpern, B.S., Walbridge, S., Selkoe, K,A., Carrie V. Kappel, C.V., Micheli, F., Caterina D'Agrosa, C., Bruno, J.F. et al., 2008. A Global Map of Human Impact on Marine Ecosystems. Science 319 (5865): 948–52. https://doi.org/10.1126/science.1149345.

Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., Hume, D., Kågesten, G., Mattsson, D., Törnqvist, O., Zillén, L., Mattsson, M., Bergström, U., Perry, D., Caldow, C., Andersen, J.H., 2020. Cumulative impact assessment for ecosystem-based marine spatial planning. Sci. Total Environ. 734, 139024. https://doi.org/10.1016/j.scitotenv.2020.139024

Hayes, K.R., Dunstan, P., Woolley, S., Barrett, N., Foster, S., Monk, J., Peel, D., Hosack, G.R., Howe, S., Samson, C.R., Bowling, R. and Ryan, M.P. (2021). Monitoring priorities and indicators for Australian Marine Parks in the southeast marine region. Development of the MERI framework and its implementation in the southeast marine region. NESP Marine Biodiversity Hub, Hobart, Australia.

HELCOM (2023): HELCOM Thematic assessment of spatial distribution of pressures and impacts 20162021. Baltic Sea Environment Proceedings No. 189. Available at: https://helcom.fi/post_type_publ/holas3_spa

Hidalgo M, Rouyer T, Molinero JC, Massutí E, Moranta J, Guijarro B, Stenseth NC (2011) Synergistic effects of fishing-induced demographic changes and climate variation on fish population dynamics. Mar Ecol Prog Ser 426:1-12. https://doi.org/10.3354/meps09077

Hidalgo, M., Vasilakopoulos, P., García-Ruiz, C., Esteban, A., López-López, L., & García-Gorriz, E. (2022). Resilience dynamics and productivity-driven shifts in the marine communities of the Western Mediterranean Sea. Journal of Animal Ecology, 91, 470–483. https://doi.org/10.1111/1365-2656.13648

Hilty, J.*, Worboys, G.L., Keeley, A.*, Woodley, S.*, Lausche, B., Locke, H., Carr, M., Pulsford I., Pittock, J., White, J.W., Theobald, D.M., Levine, J., Reuling, M., Watson, J.E.M., Ament, R., and Tabor, G.M.* (2020). Guidelines for conserving connectivity through ecological networks and corridors. Best Practice Protected Area Guidelines Series No. 30. Gland, Switzerland: IUCN.

Hobday, A.J., Smith, A.D.M., Stobutzki, I.C., Bulman, C., Daley, R., Dambacher, J.M., Deng, R.A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon, R., Knuckey, I.A., Ling, S.D., Pitcher, R., Sainsbury, K.J., Sporcic, M. , Smith, T., Turnbull, C., Walker, T.I., Wayte, S.E., Webb, H., Williams, A., Wise, B.S. and Zhou, S. (2011). Ecological risk assessment for the effects of fishing. Fisheries Research, 108:372-384.

Kirkfeldt TS, Andersen JH (2021) Assessment of collective pressure in marine spatial planning: the current approach of EU Member States, Ocean Coast. Manag. 203, https://doi.org/10.1016/j.ocecoaman.2020.105448.

Kotta, J.; Fetissov, M.; Szava-Kovats, R.; Aps, R.; Martin, G. 2020. Online tool to integrate evidence-based knowledge into cumulative effects assessments: Linking human pressures to multiple nature assets. Environmental Advances, 2, 100026.

Korpinen, S., K. Klancik, M. Peterlin, M. Nurmi, L. Laamanen, G. Zupančič, C. Murray, T. Harvey, J.H. Andersen, A. Zenetos, U. Stein, L. Tunesi, K. Abhold, G. Piet, E. Kallenbach, S. Agnesi, B. Bolman, D. Vaughan, J. Reker & E.R. Gelabert (2019): Multiple pressures and their combined effects in Europe's seas. ETC/ICM Technical Report 4/2019. European Topic Centre on Inland, Coastal and Marine waters, 164 pp.

Loreau M, N. Mouquet, A. Gonzalez, Biodiversity as spatial insurance in heterogeneous landscapes, (2023) Proc. Natl. Acad. Sci. U.S.A. 100 (22) 12765-12770,https://doi.org/10.1073/pnas.2235465100

Low JML , Gladstone-Gallagher RV, Hewitt JE, Pilditch CA, Ellis JI, Thrush SF, (2023) Using Ecosystem Response Footprints to Guide Environmental Management Priorities. Ecosyst Health Sustain.;9:0115.DOI:10.34133/ehs.0115

Ma, C., V. Stelzenmüller, J. Rehren, J. Yu, Z. Zhang, H. Zheng, L. Lin, H. C. Yang, and Y. Jin. 2023. “A Risk-Based Approach to Cumulative Effects Assessment for Large Marine Ecosystems to Support Transboundary Marine Spatial Planning: A Case Study of the Yellow Sea.” Journal of Environmental Management 342: 118165.

Mackelworth, P., Fortuna, C. M., Antoninić, M., Holcer, D., Malak, D. A., Attia, K., Bricelj, M., Guerquin, F., Marković, M., Nunes, E., Perez-Valverde, C., Ramieri, E., Stojanović, I., Tunesi, L., & McGowan, J. (2024). Ecologically and Biologically Significant Areas (EBSAs) as an enabling mechanism for transboundary marine spatial planning. Marine Policy, 166, 106231. https://doi.org/10.1016/j.marpol.2024.106231

MEMA (2018). NSW Marine Estate Management Strategy 2018-28. NSW Marine Estate Management Authority, Sydney NSW.

Micheli F, Halpern BS, Walbridge S, Ciriaco S, Ferretti F, et al. (2013) Cumulative Human Impacts on Mediterranean and Black Sea Marine Ecosystems: Assessing Current Pressures and Opportunities. PLOS ONE 8(12): e79889. https://doi.org/10.1371/journal.pone.0079889

Moullec F, Barrier N, Guilhaumon F, Peck MA, Ulses C, Shin YJ (2023) Rebuilding Mediterranean marine resources under climate change. Mar Ecol Prog Ser 708:1-20. https://doi.org/10.3354/meps14269

Ostwald A, Tulloch VJD, Kyne PM, Bax NJ, Dunstan PK, Ferreira LC, Thums M, Upston J, Adams VA (2021) Mapping threats to species: Method matters, Marine Policy 131. https://doi.org/10.1016/j.marpol.2021.104614.

Pearson, R.M., Schlacher, T.A., Jinks, K.I. et al. (2021) Disturbance type determines how connectivity shapes ecosystem resilience. Sci Rep 11, 1188. https://doi.org/10.1038/s41598-021-80987-1

Pennino MG, Zurano JP, Hidalgo M, Esteban A, Veloy C, Bellido JM, Coll M (2024) Spatial patterns of β-diversity under cumulative pressures in the Western Mediterranean Sea, Marine Environmental Research, 195, https://doi.org/10.1016/j.marenvres.2024.106347.

Piet GJ, Tamis JE, Volwater J, de Vries P, van der Wal JT, Jongbloed RH (2021) A roadmap towards quantitative cumulative impact assessments: Every step of the way, comScience of The Total Environment, 784,146847, https://doi.org/10.1016/j.scitotenv.2021.146847.

Rodríguez-Rodríguez D, Sánchez-Espinosa A, Schröder C, Abdul Malak D, Rodríguez J, (2015) Cumulative pressures and low protection: a concerning blend for Mediterranean

MPAs, Marine Pollution Bulletin 101 (1): 288-295, https://doi.org/10.1016/j.marpolbul.2015.09.039.

SANBI & UNEP-WCMC. 2024. Mapping biodiversity priorities: A practical approach to spatial biodiversity assessment and prioritisation to inform national policy, planning, decisions and action. Second edition. South African National Biodiversity Institute, Pretoria.

Simeoni, C, Furlan, E, Pham, HV, Critto, A, de Juan, S, Trégarot, E, Cornet, CC, Meesters, E, Fonseca, C,Botelho, AZ, Krause, T, N'Guetta, A, Cordova, FE, Failler, P, Marcomini, A, (2023) Evaluating the combined effect of climate and anthropogenic stressors on marine coastal ecosystems: Insights from a systematic review of cumulative impact assessment approaches .Science of The Total Environment, 861, 160687, https://doi.org/10.1016/j.scitotenv.2022.160687

Sink, K.J., Van der Bank, M.G., Majiedt, P.A., Harris, L.R., Atkinson, L., Kirkman, S., Karenyi, N. eds., 2019. South African National Biodiversity Assessment 2018 Technical Report Volume 4: Marine Realm. South African National Biodiversity Institute, Pretoria. *http://hdl.handle.net/20.500.12143/6372.*

Sink KJ, Adams LA , Franken M, Harris LR, Currie J, et al. (2023a). Iterative mapping of marine ecosystems for spatial status assessment, prioritization, and decision support. Frontiers in Ecology and Evolution, 11, p.1108118. *https://doi.org/10.3389/fevo.2023.1108118*.

Sink KJ, Lombard, AT, Attwood, CG, Livingstone, TC, Grantham, H, & Holness, SD (2023b.) Integrated systematic planning and adaptive stakeholder process support a 10-fold increase in South Africa's Marine Protected Area estate. Conservation Letters, 16(4), p.e12954. https://doi.org/10.1111/conl.12954.

Skein L, Sink KJ, Majiedt PA, van der Bank MG, Smit KP, Shannon LJ, (2022) Scoping an integrated ecosystem assessment for South Africa, Frontiers in Marine Science, 9, https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2022.975328, DOI=10.3389/fmars.2022.975328

Smit, K.P., Sink, K.J., Shannon, L.J., Bernard, A.T. and Lombard, A.T., 2024. Groundtruthing cumulative impact assessments with biodiversity data: Testing indicators and methods for

marine ecosystem condit bnion assessments in South Africa. Aquatic Conservation: Marine and Freshwater Ecosystems, 34(2), p.e4096. *https://doi.org/10.1002/aqc.4096*

Stelzenmüller, V., Coll, M., Mazaris, A. D., Giakoumi, S., Katsanevakis, S., Portman, M., et al. (2018). A risk-based approach to cumulative effect assessments for marine management. Sci. Tot. Environ. 612, 1132–1140. doi: 10.1016/j.scitotenv.2017.08.289

Stelzenmüller V, Coll M, Cormier R, Mazaris AD, Pascual M et al. (2020) Operationalizing risk-based cumulative effect assessments in the marine environment Science of The Total Environment 724,138118, https://doi.org/10.1016/j.scitotenv.2020.138118.

Stelzenmüller V, Rehren J, Orey S, Lemmen C, Krishna S, Hasenbein M, Püts M, Probst WN, Diekmann R, Scheffran J, Bos OG, Wirtz K (2024) Framing future trajectories of human activities in the German North Sea to inform cumulative effects assessments and marine spatial planning. Journal of Environmental Management 349, 119507, https://doi.org/10.1016/j.jenvman.2023.119507.

Ruskule, A.; Kotta, J.; Arndt, P.; Ustups, D.; Strāķe, S.; Saha, C.R.; Bergström, L. 2023. Testing the concept of green infrastructure at the Baltic Sea scale to support an ecosystem-based approach to management of marine areas. Marine Policy, 147, 105374. https://doi.org/10.1016/j.marpol.2022.105374

Vaher, A.; Kotta, J.; Szava-Kovats, R.; Kaasik, A.; Fetissov, M.; Aps, R.; Kõivupuu, A.2022. Assessing cumulative impacts of human-induced pressures on reef and sandbank habitats and associated biotopes in the northeastern Baltic Sea. Marine Pollution Bulletin,183, 114042. https://doi.org/10.1016/j.marpolbul.2022.114042

Section 4

Chapter 6: Pressures: Pollution

Group of Experts Leads: Maria João Bebianno and Kwasi Appeaning Addo

Co-ordinating Author: Colin Moffat

Topic specialists:

- **Recent Developments in Atmospheric Inputs:** Lars Soneston and Colin Moffat
- **Persistent Organic Pollutants (POPs):** Colin Moffat, Ibrahim Issifu, Benjamin Osei Botwe and Helena Reinardy
- **Pharmaceuticals and personal care products (PPCPs):** Ralf Ebinghaus, Rainer Lohmann and Zhiyong Xie
- **Plastic Pollution:** Francois Galgani, Chinenye Ajanwachuku, Kwang-Sik Choi, Dao Van Hien, Christos Ioakeimidis, Laurent Lebreton, Thomas Maes, Diana Souza Moura, Paula Sobral, Alexander Turra, Stefanie Werner, Shiye Zhao, Vanessa Sarah Salvo, Judith Weiss.
- **Radioisotopes:** Alan Simcock

Keynote Points

- Chemicals and other materials from land-based sources continue to impact ocean ecosystems. ~~Land-based sources of chemicals and other materials continue to impact the ocean.~~
-
- There has been a decline in mercury emissions and precipitation, along with reductions in emissions to air of some organic compounds, in specific regions. ~~There is some evidence for a decline in emissions and precipitation for mercury and some organic compounds in selected areas.~~
-
- The growing demand for non-carbon electricity has increased reliance on nuclear power, likely leading to higher radioactive discharges. ~~The need for non-carbon electricity is increasing the demand for nuclear electricity, and consequently, the related radioactive discharges.~~
-
- Persistent organic pollutants continue to impact all ocean regions including polar regions and ~~and~~ the deep sea, as well as coastal marine ecosystems.
- Toxicity studies indicate significant adverse effects of pharmaceuticals and personal care products on marine organisms, including behavioural changes in fish, invertebrates, and algae. ~~Toxicity studies have shown significant adverse effects on marine organisms of pharmaceuticals and personal care products including behavioural changes in various species such as fish, invertebrates, and algae.~~
-
- Global plastic waste emissions continue to rise, with substantial leakage due to mismanaged waste, microplastic abrasion and loss, littering, and marine activities. ~~Global plastic waste emissions are rising, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering, and marine activities.~~ These plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected.

1. General Introduction

Human activities generate a ~~range~~ multiplicity of pollutants, including pharmaceuticals, heavy metals, organic compounds, radioactive materials, ~~and~~ plastics and its additives, sediments, nutrients, pathogens, energy (heat, light, noise), and numerous other contaminants of emerging concern. The focus of this sub-chapter is pharmaceuticals, personal care products, heavy metals, Persistent Organic Pollutants (POPs), radioactive materials and plastics and its additives. Many of these ~~chemicals~~ compounds and materials ~~they are ultimately deposited~~ultimately reach ~~in~~ the ocean ~~either because of~~through atmospheric transfer and deposition, general land runoff, ~~or via~~ rivers, ~~/~~ storm overflows and sea-based activities. These pollutants~~y~~ may ~~then~~ subsequently be transported more widely by ocean currents. ~~This results in~~As a result, marine biota ~~being~~ are exposed to ~~multiple~~ numerous chemicals, many of which ~~are~~ have physiological~~ly active~~effects. Alongside biodiversity loss and rising concentrations of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, pollutants further intensify the already precarious multiple stressor scenario for marine ecosystems (Figure 1)~~Together with the loss in biodiversity and the consequences of increasing concentrations of greenhouse gases, such as carbon dioxide, methane and nitrous oxide, the presence of pollutants further exacerbates an already precarious multiple stressor situation for marine ecosystems (Figure 1)~~.

This section provides an update on the information provided in World Ocean Assessment II (WOA II) on the concentrations and consequences of ~~persistent organic pollutants~~POPs, plastics and its additives, pharmaceuticals, personal care products and radioisotopes on the ocean and the ~~plants and animals~~marine organisms that live in, on and close to the ocean. This is coupled with recent developments in the understanding of atmospheric inputs to the ocean of a range of chemicals. The materials and chemicals covered in this sub-chapter are similar to those described in ~~World Ocean Assessment~~WOA II. However, there is a greater emphasis on the per-and polyfluoralkyl substances and more in-depth reporting on pharmaceuticals and personal care products.

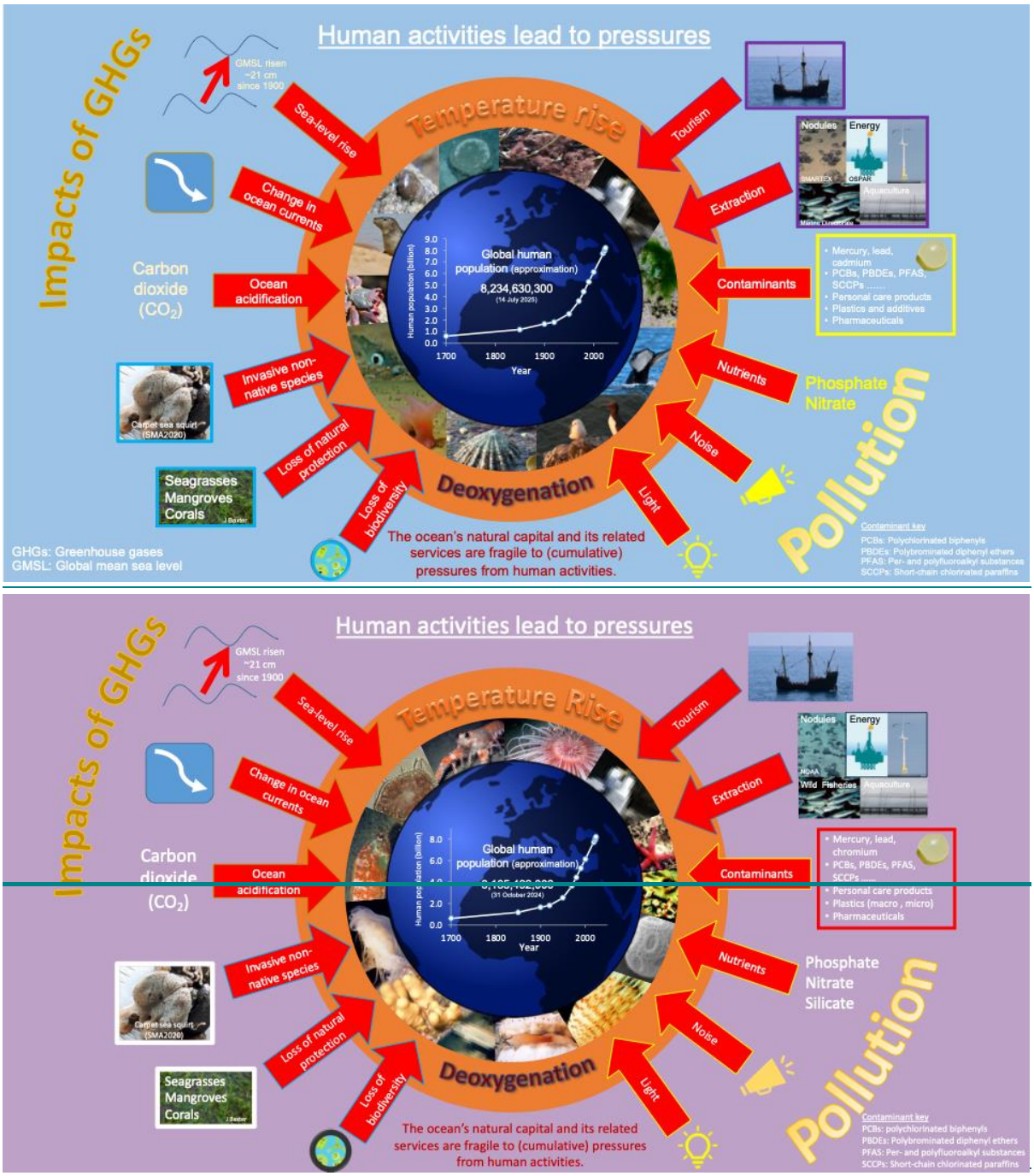


Figure 1: The presence of pollutants further exacerbates an already precarious multiple stressor situation for marine ecosystems. ~~GHGs, Greenhouse gases; GMSL, Global mean sea level; NOAA, National Oceanic and Atmospheric Administration;~~ SMA2020, Scotland's Marine Assessment 2020[26]. World Population from Worldometers[27]. Images of polymetallic nodules and the Barbie Pig are courtesy of The National Oceanography Centre and the Trustees of the UK Natural History Museum with acknowledgement to the NERC SMARTEX project. Images of the sand eel and deep-sea sponge are courtesy of the Scottish Marine Directorate.

[26] Scotland's Marine Assessment 2020, https://marine.gov.scot/sma/
[27] https://www.worldometers.info/world-population/

2. Recent Developments in Atmospheric and Riverine Inputs

Key Message

Both atmospheric deposition and riverine inputs remain important pathways for contaminants, including plastics, to reach the ocean. However, there has~~ve~~ been ~~some recent~~a decline~~s~~ in emissions to the air of heavy metals and some legacy POPs from western Europe~~to the air.~~.

Contaminants continue to be distributed around the globe

Long-range atmospheric transport (LRAT) continues to be a key process by which pollutants move around the planet with the result that pollutants impact ~~animals and plants~~marine organisms a considerable distance from their sources of emission. LRAT is a key reason for pollutants being detected in the polar regions and, together with ocean currents, the deep ocean. This includes the Mariana Trench (Dasgupta and others, 2018). In addition, chlorinated paraffins have been detected in deep-sea cold seep ecosystems where they have been bioaccumulated by~~in~~ deep-sea mussels (Lyu and others, 2023). However, ~~Although~~ the concentrations of~~ Persistent Organic Pollutants (POPs~~some POPs (e.g. PCBs, dicofol)~~)~~ in deep-sea sediments from ~~in some areas, for example, the western Pacific Ocean are relatively low,~~ the western Pacific Ocean were low or the compounds were not detected. In contrast, ~~the predominant sources of~~ polycyclic aromatic hydrocarbons (PAHs) were ~~found~~ detected in the same samples at concentrations between 5.2 ng g^{-1} and 24.5 ng g^{-1}. The predominant sources of the PAHs was determined to be biomass and coal combustion, indicating atmospheric deposition (Ge and others, 2021).

Per- and Polyfluoroalkyl substances (PFASs)

The interest in per-and polyfluoroalkyl substances has grown in recent years. ~~-~~More details about concentrations and impacts can be found in the POPs section~~ on Persistent Organic Pollutants~~. However, determining the source of these compounds is important. Analysis of an ice core from Devon Island, Nunavut, Northern Canada revealed continuous and increasing deposition of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) over the period 1977-2015. North American and Eurasian emission sources, particularly from Continental Asia, were large contributors (Pickard and others, 2018).

There are occasions when riverine inputs remain critical. For example, the riverine input of perfluorooctanesulfonic acid (PFOS) to the Baltic Sea exceeds atmospheric input by a factor of three, whereas for perfluorooctanoic acid (PFOA) and other PFCAs, atmospheric deposition makes a higher contribution to the total inputs to the Baltic Sea (Johansson and Undeman, 2020). Potential sources to the loading of PFOS and other PFASs in the Baltic Sea region rivers are discharges from waste~~-~~water

treatment plants (WWTPs), atmospheric deposition to the catchment areas, and runoff from contaminated sites (HELCOM, 2020). The relative contribution probably varies between different rivers.

Deposition from the atmosphere may be dry or wet. A study (Cousins and others, 2022) investigating four perfluoroalkyl acids (PFOS, PFOA, PFHxS, and perfluorononanoic acid (PFNA)); ~~Abbreviations presented in Table 1 of the Persistent Organic Pollutants Section other than for PFNA, perfluorononanoic acid),~~ concluded that:

- Levels of PFOA and PFOS in rainwater often greatly exceed US Environmental Protection Agency (EPA) Lifetime Drinking Water Health Advisory levels.
- The sum of the four perfluoroalkyl acids in rainwater is often above Danish drinking water limit values.
- Levels of PFOS in rainwater are often above the environmental quality standard (EQS) for Inland European Union (EU) Surface Waters.

~~Furthermore,~~ Cousins and others (2022) further concluded that atmospheric deposition leads to global soils being contaminated.

The large consumption of ~~some~~ specific pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. Septic tanks are also a pathway for emerging contaminants, including different analgesics, antihistamines, antidepressants, betablockers and the antidiabetic drug metformin, to the aquatic environment (Wilschnak and others, 2024).

Case Study – ~~Data from the European Monitoring and Evaluation Programme show~~ declines in emissions and deposition of heavy metals and selected organic contaminants~~deposition~~

Mercury (Hg) in air, precipitation and the emissions to the air from EU countries has decreased in the period 2010-2022 by 1.3%, 3.0%, and 3.2% per year respectively (Travnikov and others, 2024). The declines are higher in the period 2010-2022 compared to the period 2000-2010. European emissions declined faster than the concentrations in air showing the global influence on Hg transport.

In western Europe (European Monitoring and Evaluation Programme (EMEP) Western region) the emissions to air of the metals cadmium (Cd), Hg, and lead (Pb), as well as PCBs, PAHs, HCB, PCDD/F* have declined over the period 2000-2022. In the EMEP Eastern region (~~ECCA countries,~~ Eastern Europe, Caucasus and Central Asia (ECCA) countries) the trends are not completely evident mainly due to incomplete reporting by major emitting countries.

~~A further~~An example of a decrease in deposition was noted for the Baltic Sea where the deposition of Hg, Pb, Cd, and benzo[*a*]pyrene on the Baltic Sea has decreased steadily since 1990 (Gauss and other, 2024).

*Abbreviations presented in Table 1

3. Persistent Organic Pollutants (POPs)

Key Messages

- ~~Persistent organic pollutants (~~POPs~~)~~ remain a global problem due to their persistence, bioaccumulation, and health risks.
- Emerging POPs, such as PFAS and polyhalogenated carbazoles (PHCZs), are gaining increasing attention because of inadequate waste management, climate change remobilization of POPs that have been trapped in water, ice sediments and soil for decades, and inconsistent global enforcement, which continue to exacerbate their environmental and public health impact despite international efforts to eliminate their sources.
- Although POPs are yet another anthropogenic pressure on the ocean, adding to the stress of biological systems, there is some indication that concentrations of some legacy compounds are decreasing.

Introduction

Many chemicals have been produced with the objective of improving the outcomes for humans. These chemicals, ~~, some to treat or prevent disease. These include pharmaceuticals and personal care products (see later) which are part of the complex mixtures to which biota are exposed, especially in coastal environments. Pollution,~~ including ~~from~~ POPs, are discharged and emitted into the environment and continue~~s~~ to be a main stressor on marine ecosystems.

POPs, which are generally halogenated (contain fluorine, chlorine or bromine) hydrocarbons (Guo and others, 2019), may be produced intentionally or unintentionally (Figure 2). They include polychlorinated biphenyls (PCBs; 209 individual congeners), polybrominated diphenyl ethers (PBDEs) and PFAS (Table 1). Although the manufacture of some POPs is now banned, this is only after significant quantities have been manufactured and used. For example, 8,896 kt of HCH were manufactured (Li and others, 2023~~)~~).

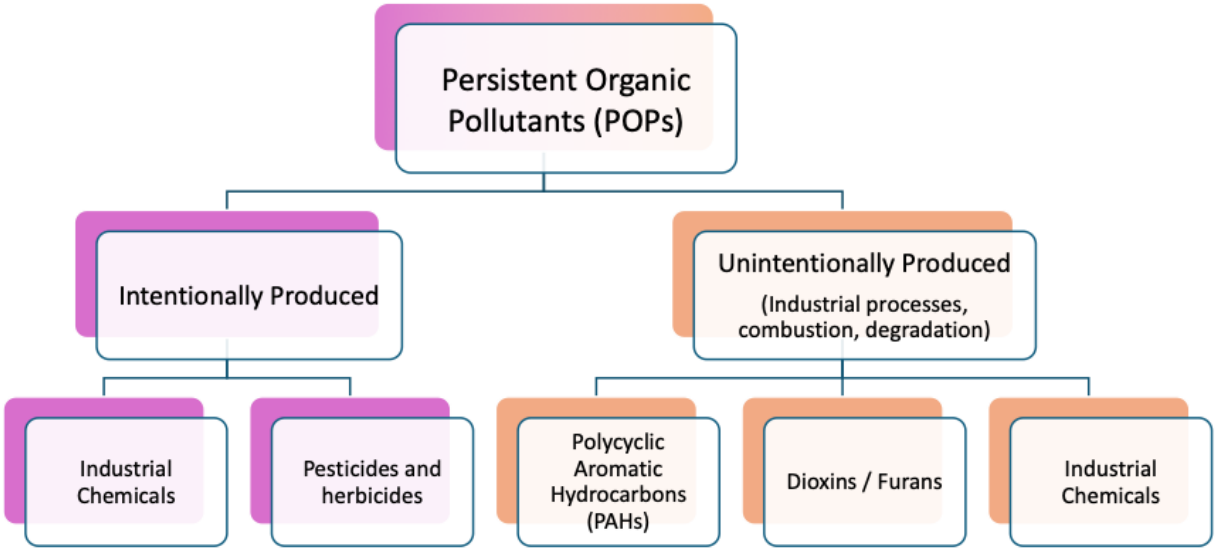


Figure 2: The range of POPs. Industrial chemicals are produced both intentionally and unintentionally. PCBs and PCNs are unintentionally produced during the production of ~~e.g.~~ paints and dyes (Hu and Hornbuckle, 2009; Hannah and others, 2022) and at nonferrous metallurgical facilities (Klimczak and others, 2023) ~~respectively~~. PCDEs are by-products of the synthesis of commercial chlorophenols (Wu and others, 2023). POPs and PAHs may also be produced during combustion. Although PAHs are included in this figure, they are not covered by the Stockholm Convention but are classified as persistent organic pollutants. ~~by organisations including the European Environment Agency[28].~~

POPs continue to be manufactured, with a variety of pathways to the ocean (Figure 3). However, these halogenated compounds persist in the environment and are bioaccumulated, especially in higher trophic levels (Figure 4). This means that as humans introduce new chemicals, further problems arise. In addition, these chemicals are dispersed by ocean currents and atmospheric winds resulting in them being found around the globe (Figure 3).

~~[28] https://www.eea.europa.eu/en/analysis/indicators/persistent-organic-pollutant-emissions-in-europe~~

Chemical Group	Abbreviation	Chemical Group	Abbreviation
Polychlorinated biphenyls	PCBs	Per- and Polyfluoroalkyl substances	PFAS
Polychlorinated diphenyl ethers	PCDEs	Perfluoroalkyl sulfonic acids	PFSAs
Polychlorinated naphthalenes	PCNs	Perfluoroalkyl carboxylic acids	PFCAs
Polybrominated diphenyl ethers	PBDEs	Organochlorinated pesticides	OCPs
Polybrominated biphenyls	PBBs	**Individual Chemical**	**Abbreviation**
Polychlorinated dibenzo-p-dioxins	PCDD	Perfluorooctanesulfonic acid	PFOS
Polychlorinated dibenzofurans	PCDF	Perfluorohexane sulfonic acid	PFHxS
Polyhalogenated carbazoles	PHCZs	Perfluorooctanoic acid	PFOA
Toxaphene	Toxaphene	Perfluoroheptanoic acid	PFHpA
Short-chain chlorinated paraffins	SCCPs	Hexachlorobenzene	HCB
Hexachlorcyclohexane	HCH	Dichlorodiphenyltrichloroethane	DDT

Table 1: POPs and their abbreviations as used in this sub-chapter. -Polychlorinated diphenyl ethers, PHCZs and perfluoroheptanoic acid are not listed in the Stockholm Convention on Persistent Organic Pollutants (POPs). In addition, the Stockholm Convention lists the following groups of PFAS: PFOS, its salts and PFOSF (including all PFOS precursors); PFOA, its salts and PFOA-related compounds (including all PFOA precursors); PFHxS, its salts and PFHxS-related compounds (including all PFHxS precursors); and long-chain PFCAs, their salts and related compounds (including all long-chain PFCAs precursors). This covers many hundreds of related compounds. ~~Neither are PFAS, PFSAs or PFCAs. Rather, the specific chemicals e.g. PFOS (and its salts and perfluorooctane sulfonyl fluoride (PFOSF)) are listed.~~ Organochlorinated pesticide is a global term for a range of pesticides and includes DDT and HCH.

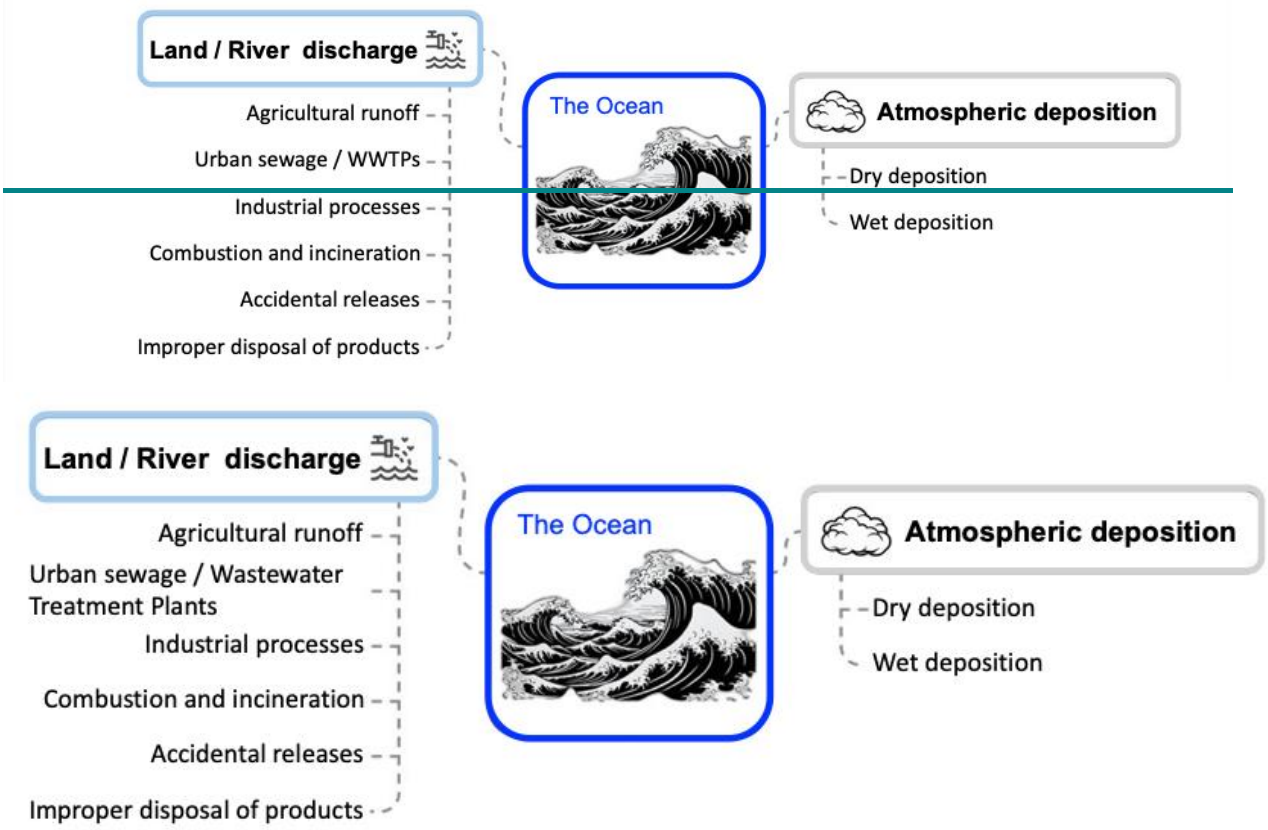


Figure 3: Sources of POPs, as listed in the Stockholm Convention on Persistent Organic Pollutants (POPs). LRAT is primarily responsible for POPs being found in both the Arctic and Antarctic as well as other regions ~~remote~~ distant from the site of discharge. This means that POPs ~~still~~ impact people and wildlife far from where they are released, reinforcing the findings in WOA II that POPs continue to be global contaminants. ~~WWTPs, waste water treatment plants.~~ Processes for removing POPs from wastewater continue to be investigated.~~The urban, domestic and hospital discharges are significant and not removed by most WWTPs.~~

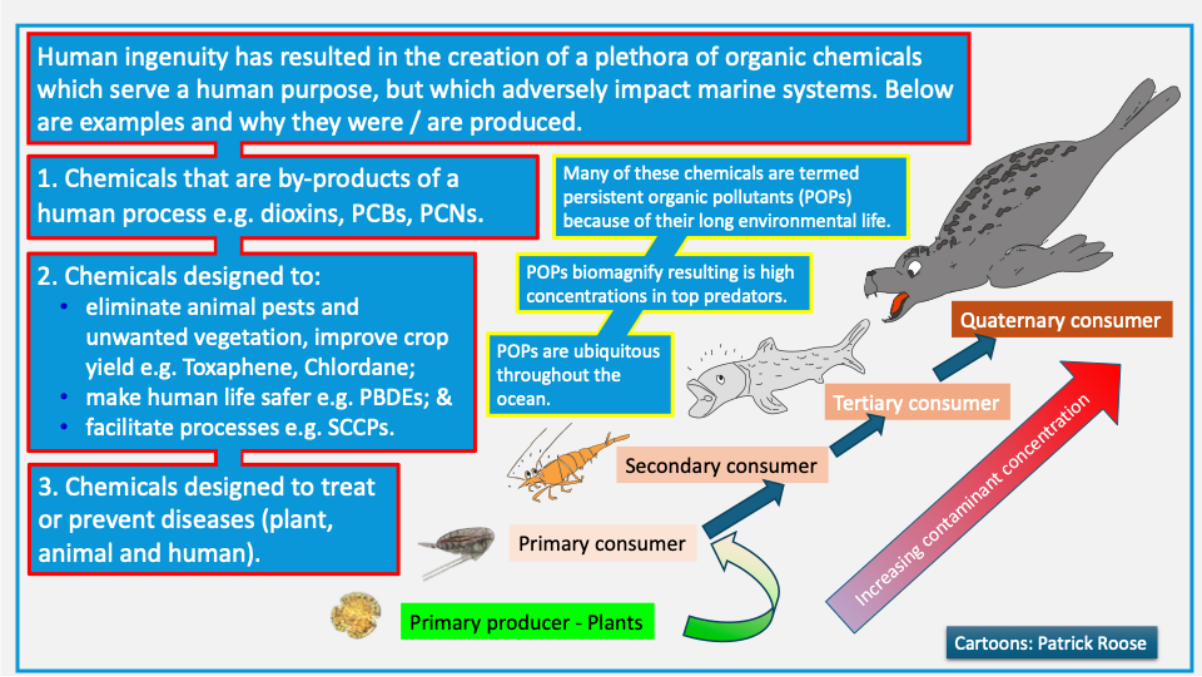
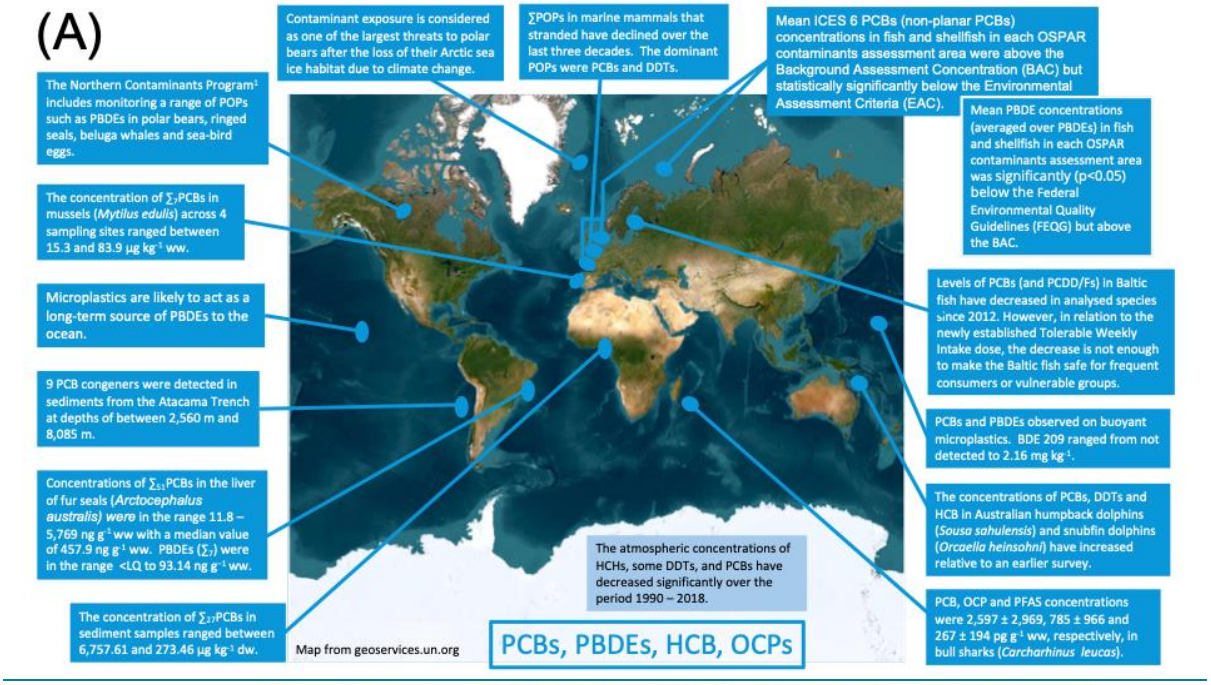


Figure 4: ~~Many chemicals have been produced with the objective of improving the outcomes for humans, some to treat or prevent disease. These include pharmaceuticals and personal care products (see later) which are part of the complex mixtures to which biota are exposed, especially in coastal environments.~~ Persistence and bioaccumulation / biomagnification of POPs mean that apex predators accumulate significant concentrations of POPs. Variation in concentrations can be associated with the prey consumed. Since WOA II, examples include evidence that differences in the concentration of PCBs exists in killer whales (*Orcinus orca*) that had a mixed diet relative to fish specialist killer whales. In addition, male killer whales contained greater concentrations of PCBs than female killer whales regardless of diet (Remili and others, 2021). Cetaceans foraging on pelagic prey species had lower contaminant loads compared to cetaceans that were benthic/coastal feeders (Remili and others, 2024).

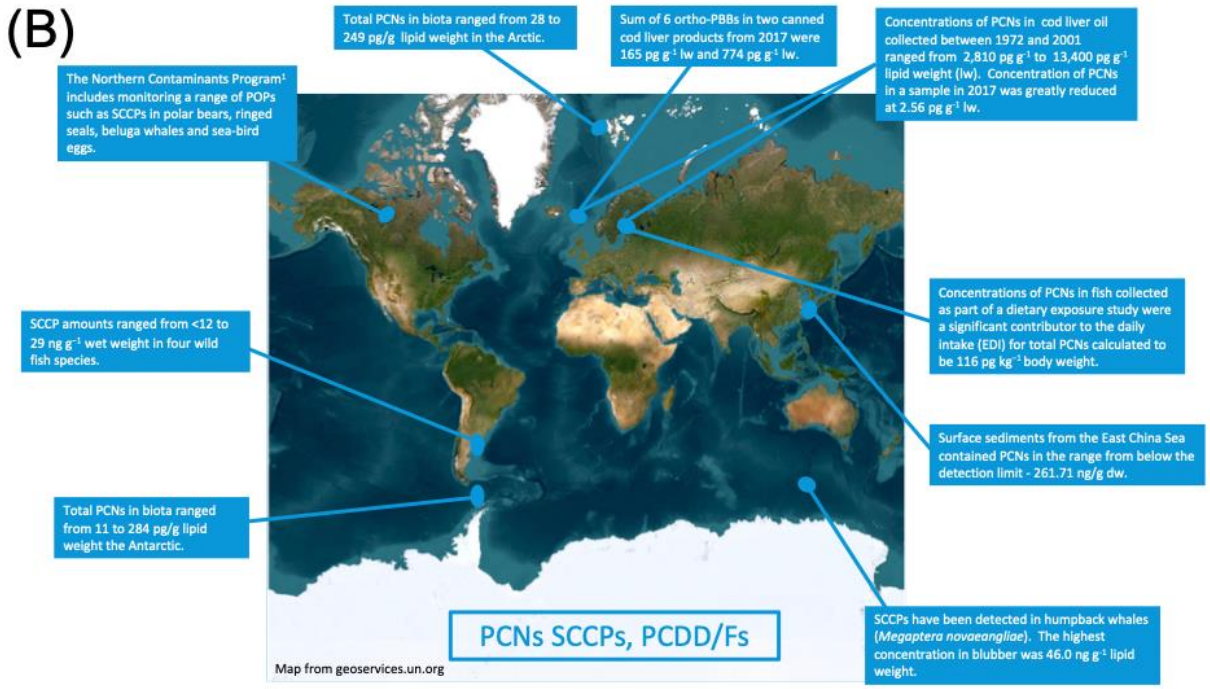
Concentrations of POPs in marine ecosystems

Information on the concentrations of POP~~s~~S in marine ecosystems was published in World Ocean Assessment II. Consequently, the information provided here is based on new data and articles published between 2018 and 2024.

Although the production and use of many POPs have been banned ~~(~~, ~~in~~ the~~some~~ case~~s~~ ~~(e.g.of~~. PCBs~~)~~ at least 30 years ago in terms of ~~ending~~ production~~)~~, POPs continue to be manufactured (Figure 2). Furthermore, replacement chemicals for listed POPs are being detected in the ocean (Langberg and others, 2019). L~~In addition, l~~egacy PCBs are added to by 'contemporary' PCBs which are inadvertently produced during the production of, for example, paints and dyes (Hu and Hornbuckle, 2009) or during electricity production when using coal as the fuel (Montano and others, 2022; Figure 2). Consequently, POPs continue to be present in all oceanic regions ~~(Figure 5A - C)~~ and continue to be transferred to the polar regions through atmospheric transport (Figure 5A- C). With these compounds being detected in marine ecosystems far from their source of production / emission (see Case Study: The Arctic Ocean Region), the basis of any regional assessment tends to be presence. Wherever samples are collected POPs are found, be it water sediment or biota. Sometimes concentrations are very low for legacy POPs, but PFOA and PFOS are found globally in seawater sediments and plankton (Fig 5C). Time series are now of a duration that temporal assessments are possible for some POPs (e.g. Webster and Fryer, 2022).



(A)
Contaminant exposure is considered as one of the largest threats to polar bears after the loss of their Arctic sea ice habitat due to climate change.
∑POPs in marine mammals that stranded have declined over the last three decades. The dominant POPs were PCBs and DDTs.
Mean ICES 6 PCBs (non-planar PCBs) concentrations in fish and shellfish in each OSPAR contaminants assessment area were above the Background Assessment Concentration (BAC) but statistically significantly below
Assessment Criteria (EAC).
The Northern Contaminants Program[1] includes monitoring a range of POPs such as PBDEs in polar bears, ringed seals, beluga whales and sea-bird eggs.
Mean PBDE concentrations (averaged over PBDEs) in fish and shellfish in each OSPAR contaminants assessment area was significantly (p<0.05) below the Federal Environmental Quality Guidelines (FEQG) but above the BAC.
The concentration of ∑7PCBs in mussels (Mytilus edulis) across 4 sampling sites ranged between 15.3 and 83.9 μg kg-1 ww.
Levels of PCBs (and PCDD/Fs) in Baltic fish have decreased in analysed species since 2012. However, in relation to the newly established Tolerable Weekly
to make the Baltic fish safe for frequent consumers or vulnerable groups.
Microplastics are likely to act as a long-term source of PBDEs to the
PCBs and PBDEs observed on buoyant microplastics. BDE 209 ranged from not detected to 2.16 mg kg-1.
9 PCB congeners were detected in sediments from the Atacama Trench at depths of between 2,560 m and 8,085 m.
The concentrations of PCBs, DDTs and HCB in Australian humpback dolphins (Sousa sahulensis) and snubfin dolphins (Orcaella heinsohni) have increased relative to an earlier survey.
Concentrations of ∑6PCBs in the liver of fur seals (Arctocephalus australis) were in the range 11.8 – 5,769 ng g-1 ww with a median value of 457.9 ng g-1 ww. PBDEs (∑7) were in the range <LQ to 93.14 ng g-1 ww.
The atmospheric concentrations of HCHs, some DDTs, and PCBs have decreased significantly over the period 1990 – 2018.
PCB, OCP and PFAS concentrations were 2,597 ± 2,969, 785 ± 966 and 267 ± 194 pg g-1 ww, respectively, in bull sharks (Carcharhinus leucas).
The concentration of ∑27PCBs in sediment samples ranged between 6,757.61 and 273.46 μg kg-1 dw.
Map from geoservices.un.org
PCBs, PBDEs, HCB, OCPs



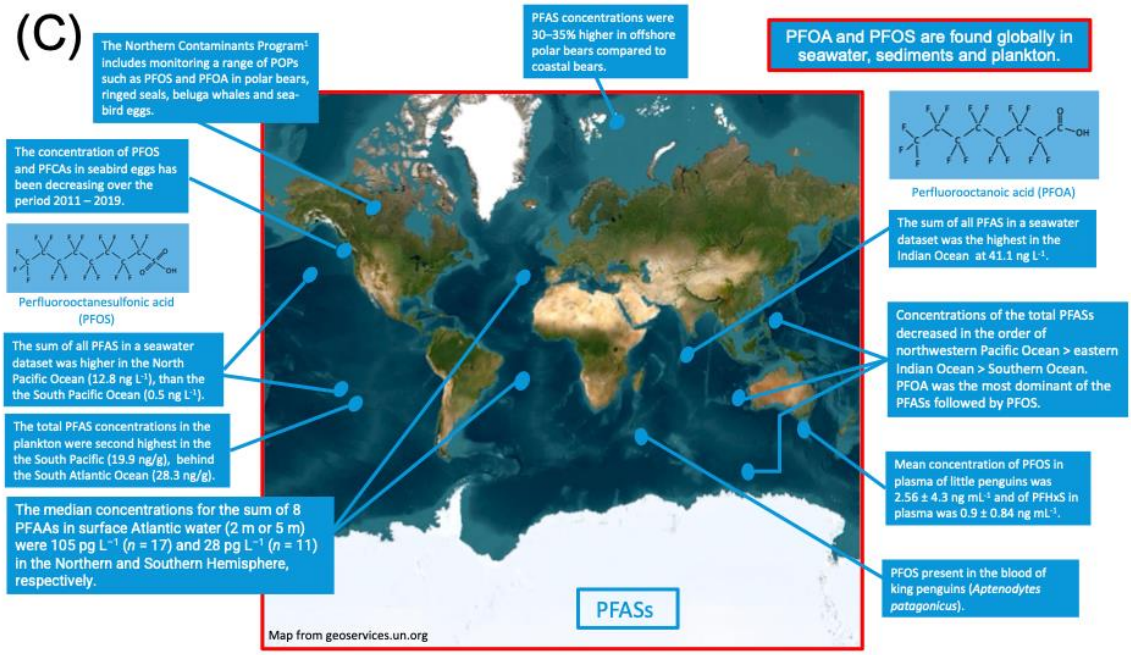


Figure 5: Concentrations of (A) PCBs, PBDEs and HCB; (B) PCNs, SCCPs and PCDDs/Fs; (C) PFASs in various matrices (seawater, sediments and biota) across the ocean, encompassing all the WOA III Regions. Abbreviations as in Table 1 or earlier in sub-chapter.[29]

[29] References for Figure 5 [anticlockwise from bottom right except Northern Contaminants Program]: (A) Chynel and others, 2021; Cagnazzi and others, 2020; Yeo and others, 2020; Mikolaczyk and others, 2021; Webster and Fryer, 2022; Williams and others, 2023; Routti and others, 2019; Esteves and others, 2024; Sobek and others, 2023; Turner, 2022; Pereira and others, 2024; Unyimadu and Benson, 2023; Luarte and others, 2023 (B) Casa and others, 2019; Liu and others, 2018; Zacs and others, 2021; Falandysz and Fernandes, 2020; Falandysz and others, 2020; Dong and others, 2023; Girones and others, 2023; Dong and

[1]Northern Contaminants Programme https://science.gc.ca/site/science/en/northern-contaminants-program

~~References [anticlockwise from bottom right except Northern Contaminants Program] (A) Chynel and others, 2021; Cagnazzi and others, 2020; Yeo and others, 2020; Mikolaczyk and others, 2021; Webster and Fryer, 2022; Williams and others, 2023; Routti and others, 2019; Esteves and others, 2024; Sobek and others, 2023; Turner, 2022; Pereira and others, 2024; Unyimadu and Benson, 2023; Luarte and others, 2023 (B) Casa and others, 2019; Liu and others, 2018; Zacs and others, 2021; Falandysz and Fernandes, 2020; Falandysz and others, 2020; Dong and others, 2023; Girones and others, 2023; Dong and others, 2023 (C) Mollier and others, 2024; Wells and others, 2024; Shan and others, 2021; Khan and others, 2024; Muir and others, 2019; Kesic and others, 2023; Khan and others, 2024; Khan and others, 2024, Savvidou and others, 2023.~~

~~[1]Northern Contaminants Programme https://science.gc.ca/site/science/en/northern-contaminants-program~~

~~collected POPs are found, be it water sediment or biota. Sometimes concentrations are very low for legacy POPs, but PFOA and PFOS are found globally in seawater sediments and plankton (Fig 5C). Time series are now of a duration that make temporal assessments of POP contamination possible for some POPs (e.g. Webster and Fryer, 2022) and this will improve with time.~~

Case Study: The Arctic Ocean Region

Overview of Changes in POPs in the Arctic Ocean Region

POPs pose a significant environmental and health threat to the ocean due to their long-term persistence, potential for bioaccumulation, and ability to travel long distances (AMAP, 2021). Among the most affected regions is the Arctic Ocean, which acts as a primary sink for POPs transported from industrial regions through atmospheric and oceanic pathways. The cold temperatures in the Arctic slow the degradation of these chemicals, allowing them to persist in the environment for extended periods.

Changes in the Overall Status

Since the WOA II, there has been a general decrease in the concentrations of many legacy POPs, such as PCBs, DDT and HCHs in the Arctic region. However, this positive trend is not without exceptions. Emerging contaminants, particularly PFASs, have been increasingly detected in the Arctic. These substances, which were not previously recognized as significant threats, are now considered a growing concern due to their persistence, potential for long-range transport, and bioaccumulative properties (UNEP, 2019).

Factors Contributing to the Change Observed

The decline of legacy POPs in the Arctic is primarily driven by international regulations including the Stockholm Convention, regional initiatives (OSPAR Convention, the Arctic Monitoring and Assessment

---

others, 2023 (C) Mollier and others, 2024; Wells and others, 2024; Shan and others, 2021; Khan and others, 2024; Muir and others, 2019; Kesic and others, 2023; Khan and others, 2024; Khan and others, 2024, Savvidou and others, 2023.)

Programme (AMAP)), and a global shift in industrial practices. Reduced emissions and changes in atmospheric transport have lowered the influx of POPs to the Arctic, while environmental degradation processes and sequestration have further diminished their concentrations. These combined efforts have significantly reduced POP levels, contributing to the protection of Arctic ecosystems and human health.

Impacts of the Change on and Interactions with Other Components of the Marine System

The changes in POP concentrations have significant implications for the Arctic marine ecosystem. POPs are known to be bioaccumulated in the Arctic food web, leading to high concentrations in top predators such as polar bears, seals as well as there being detectable concentrations in ~~,~~ fish and plankton (AMAP, 2021). This bioaccumulation disrupts the natural balance of the ecosystem, affecting the health and reproductive success of wildlife. Moreover, the re-mobilization of POPs due to climate change increases the risk of contamination in previously pristine areas, exacerbating the stress on already vulnerable species (Borgå and others, 2012). Figure CS1 visualizes the bioaccumulation of POPs in different Arctic marine species, with a focus on top predators. The data highlights particularly high concentrations of POPs in polar bears and seals, posing significant health risks to these species and the ecosystems they inhabit.

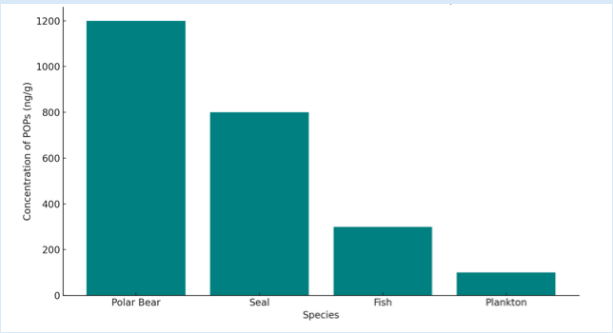


Figure CS1: Bioaccumulation of POPs in different Arctic marine species. Data sources from AMAP (2021) and Johansen and others (2017).

Social, Economic, and Cultural Aspects Associated with the Change

The socio-economic and cultural implications of POP contamination in the Arctic are profound, particularly for Indigenous Peoples~~communities~~. These communities rely heavily on marine resources for subsistence, cultural practices, and economic activities. The contamination of key food sources, such as seals and fish, poses serious health risks, including increased cancer rates, endocrine disruption, and reproductive issues (WHO, 2018). Furthermore, the loss of biodiversity and the degradation of the marine environment threatens the cultural identity and traditional practices of Indigenous peoples, who have coexisted with the Arctic environment for millennia (Downie and Fenge, 2003). Economically, the impacts are significant, as the degradation of marine resources can affect the livelihoods of those dependent on fisheries and

ecotourism. The long-term sustainability of these economic activities is at risk if POP contamination continues to undermine the health of the marine ecosystem.

Implications for Achieving the Targets of ~~the~~ SDG14

The observed decline in POPs in the Arctic supports the attainment of several SDGs, particularly those related to environmental health, clean water, and the protection of life below water and on land. Continued monitoring and policy enforcement are essential to maintain and further these gains, ensuring a safer and healthier environment for both human and ecological communities in the Arctic. However, emerging contaminants (PFAS and HCB) are becoming increasingly prevalent and might pose a major challenge to protecting the Arctic's marine biodiversity. Climate change further complicates these efforts by altering the dynamics of POP distribution, transport pathways, sources and sinks, and increasing the risk of contamination in previously unaffected areas (UNEP, 2019).

Achieving SDG14 requires a multifaceted approach, including strengthening international cooperation, enhancing regulatory frameworks, and implementing targeted strategies to mitigate the impacts of POPs in the Arctic. T~~It is also essential to integrate t~~he knowledge and perspectives of Indigenous ~~communities~~ Peoples must be ~~integrated~~woven into these efforts, ensuring that their cultural and socio-economic needs are addressed in the pursuit of sustainable development.

Cetaceans contain significant concentrations of POPs. These include PCBs, the isomers of dichlorodiphenyltrichloroethane (DDTs), PBDEs, HCHs, HCB and dieldrin (Figure 6A – C; Williams et al 2023). However, this data from cetacean strandings around Great Britain, as well as showing significant spatial and taxonomic heterogeneity, also revealed that the summed concentration of POPs, which was dominated by PCBs and DDTs, declined for all species over the last 30 years. However, pollutants remain a threat to biodiversity in several species and regions covered by the study.

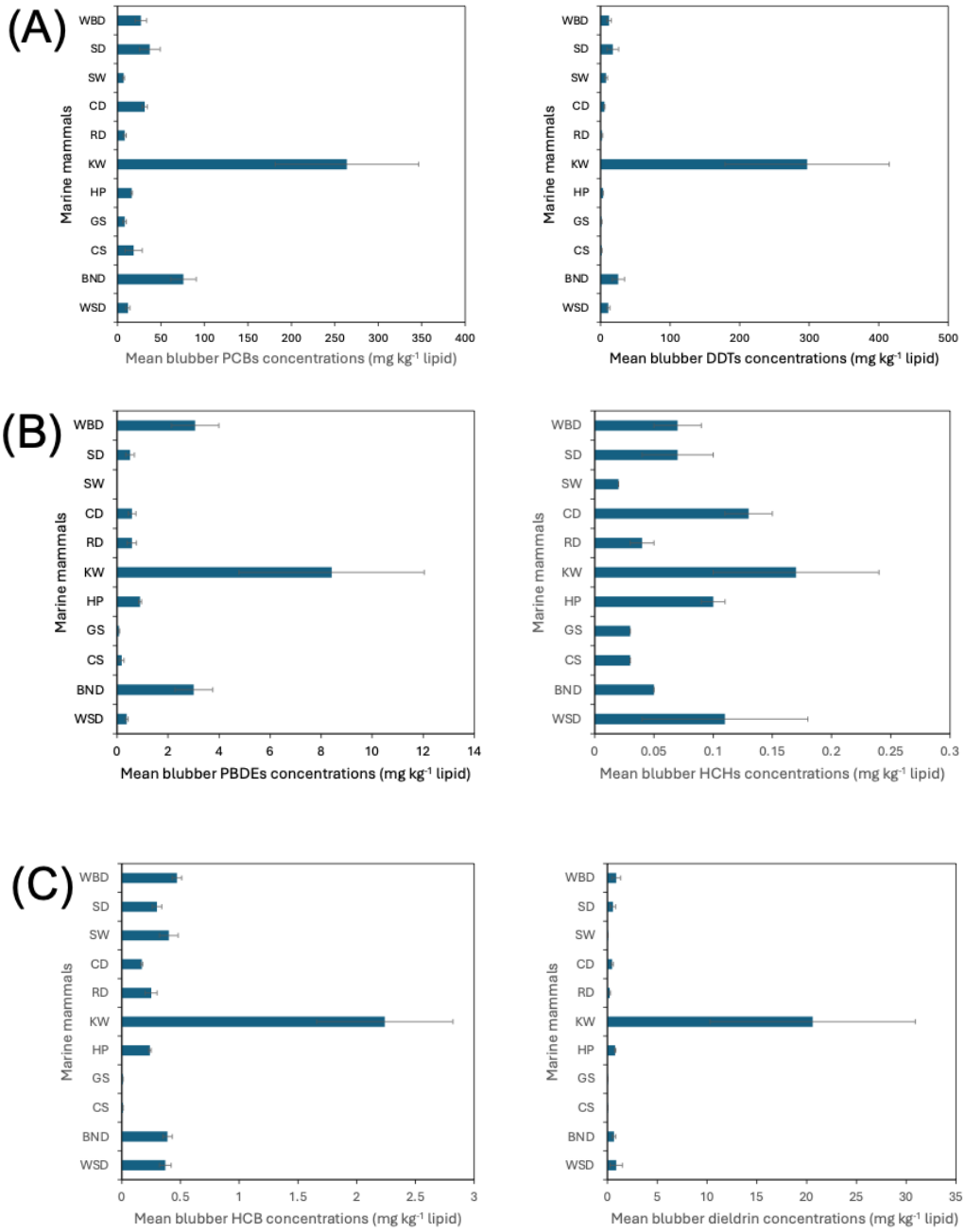
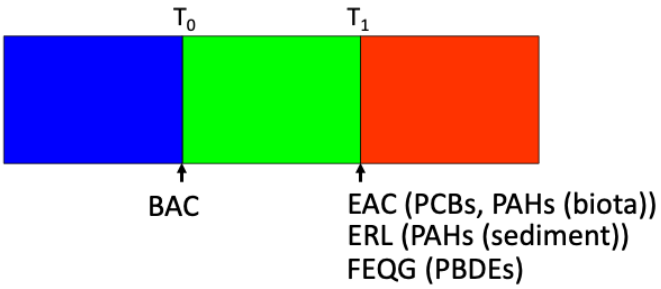


Figure 6: Mean concentration of (A) PCBs and isomers of dichlorodiphenyltrichloroethane (DDTs); (B) PBDEs and HCHs; (C) HCB and dieldrin in the blubber of eleven species of cetacean that had stranded on the coast of Great Britain over the period 1990 – 2018 with a decomposition code of less than 4. ~~This gave a sample size of 1,070 individuals.~~ Individual species sample size ranged from 6 for sperm whales to 731 for harbour porpoises.

Key: WSD - Atlantic white-sided dolphin (*Lagenorhynchus acutus*); BND - Bottlenose dolphin (*Tursiops truncatus*); CS – Common Seal (*Phoca vitulina*); GS - Gray seal (*Halichoerus grypus*); HP – Harbour porpoise (*Phocoena Phocoena*); KW – Killer whale (*Orcinus orca*); RD - Risso's dolphin; (*Grampus griseus*) CD - Short-beaked common dolphin (*Delphinus delphis*); SW – Sperm whale (*Physeter macrocephalus*); SD – Striped dolphin (*Stenella coeruleoalba*); WBD – White-beaked dolphin (*Lagenorhynchus albirostris*). Error bars are Standard Errors. (Figure produced from data presented in Williams and others, 2023)

In recent years, greater attention has been paid to using assessment criteria to determine the status of marine waters with respect to the concentration of hazardous substances. This is exemplified by the recent hazardous substances assessment in the North-East Atlantic (OSPAR, 2023[30]). In this case, measured concentrations were assessed as either being near natural background levels for naturally occurring substances and close to zero for man-made substances, at or above the Background Assessment Concentration (BAC) but statistically significantly below the Environmental Assessment Criteria (EAC), or some other criterion depending on the contaminant, or statistically significantly above the EAC (or alternative assessment criteria) (Figure 7). These results give a clear indication of status, showing that in the OSPAR contaminants assessment areas, although the concentrations of non-planar PCBs in fish and shellfish were all below the EAC, CB118 (a dioxin-like PCB) concentrations in biota were above the EAC in seven of the thirteen assessment areas indicating possible adverse effects on marine life in these areas (Figure 8).



T: Transition point
BAC: Background Assessment Concentration (OSPAR / ICES. Testing whether measured concentrations are near natural background levels for naturally occurring substances and close to zero for man-made substances)
EAC, Environmental Assessment Criteria (OSPAR. Concentrations below EACs are considered to present no significant risk to the environment)
ERL, Effects Range – Low (US Environmental Protection Agency. Concentration of a chemical in sediment below which toxic effects are rarely observed among sensitive species)
FEQG, Federal Environmental Quality Guideline (Developed under the Canadian Environmental Protection Act from 1999. Concentrations below the FEQGs should not cause any chronic effects on marine organisms)

Figure 7: A ~~There continue to be a~~ range of assessment criteria, as exemplified by those used by the OSPAR Convention, are used to assess the impacts of pollutants including POPs. In this example, the status is 'blue' if the concentration of the contaminant is significantly below the BAC. This point is signified by the transition point T_0. T_1 is the transition point between the concentration of a contaminant being at or above the BAC but statistically significantly below the EAC and the concentration being statistically significantly above the EAC.

[30] https://www.ospar.org/work-areas/cross-cutting-issues/qsr2023

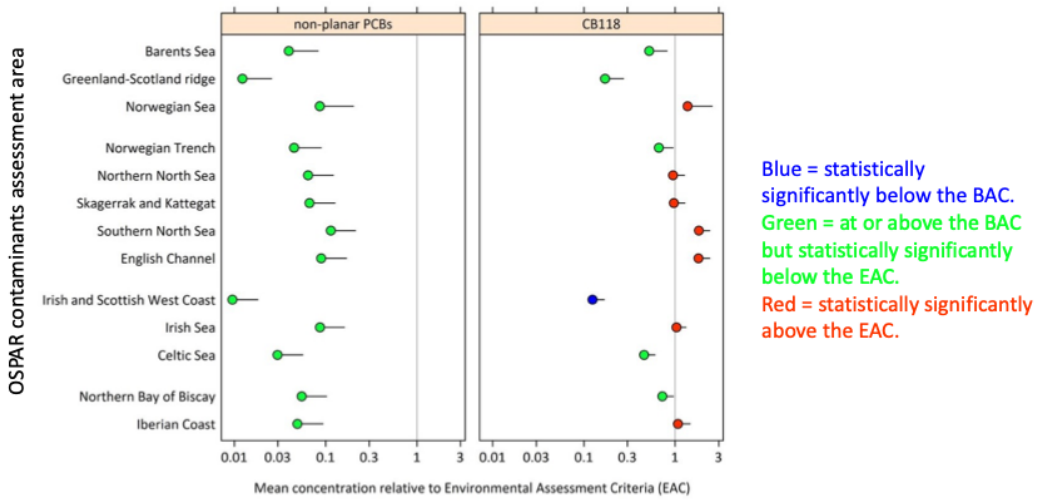


Figure 8: An assessment of PCBs in fish and shellfish by OSPAR contaminants assessment area. This is based on the mean PCB (ICES 6 PCBs (non-planar PCBs) and CB118) concentrations in fish and shellfish in each OSPAR contaminants assessment area, relative to the EAC (with 95% upper confidence limits) where the EAC value is 1. Concentrations are significantly below the EAC if the upper confidence limit is below 1. The concentrations of the non-planar PCBs were all below the EAC. CB118 (a dioxin-like PCB) concentrations in biota were above the EAC in seven of the thirteen assessment areas indicating possible adverse effects on marine life in these areas. Only in Irish and Scottish West Coast biota were mean concentrations for CB118 below the BAC. (Source: OSPAR Commission, 2023[31]; Webster and Fryer, 2022)~~.~~

Influencing f~~F~~actors resulting in an overall decrease in the concentration of some POPs

Listing under the Stockholm Convention on POPs continues. This means that society is responding to the continuing problem of POPs and their impact on the environment. Part of the reason for this, and ultimately for concentrations in some instances showing a decline, is a combination of social, cultural and economic factors (Figure 9). For example, there is an increased public awareness of the impacts of pollution, not only on the ocean, but for human health. There is also a growing recognition that the ocean is vitally important as part of the living system of the Earth and is central to building both a healthy economy and vibrant society. This change, together with the implementation of the SDGs (see next section), has helped increase awareness of the impacts of pollution and engendering a response from communities. Integrating the traditional practices and knowledge of Indigenous peoples has also impacted on the desire to reduce pollution. Finally, changes in industrial, agricultural and waste management practices, partly as a result of legislation, but also because of the public demand for sustainable products, has further helped.

[31] https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/indicator-assessments/pcb-biota-sediment/

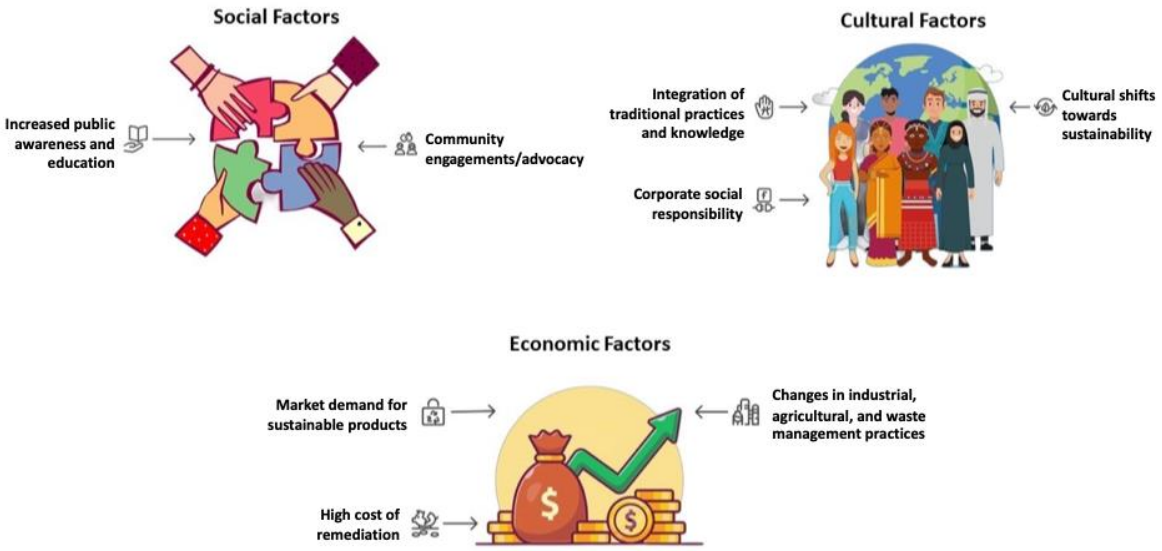
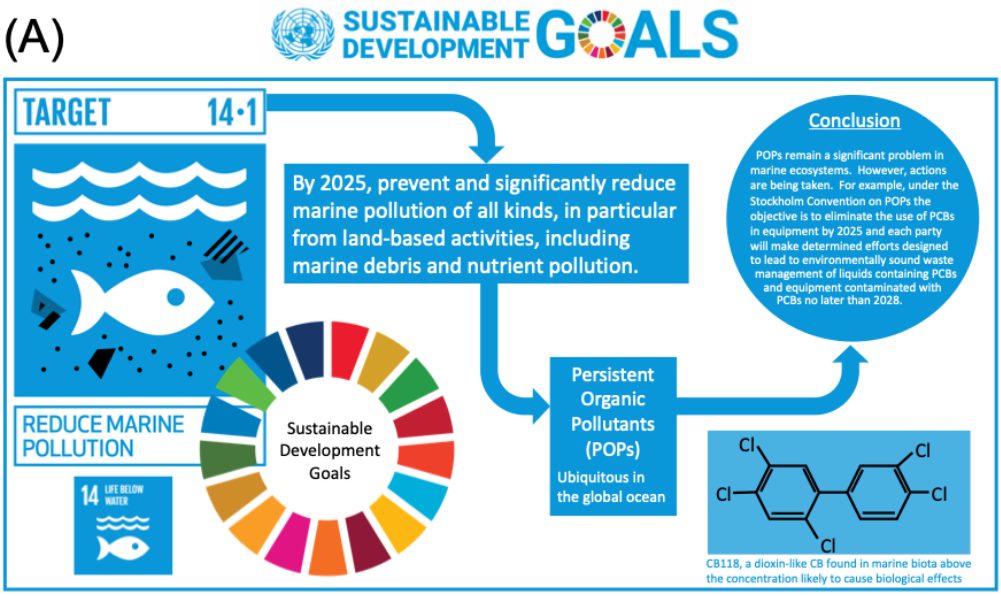


Figure 9: There is evidence that for at least some POPs there is an overall decrease in concentration. ~~ in some species.~~ The potential reasons are multifactorial and include social, cultural and economic factors.

Consequences for delivering the SDGs

POPs ~~continue to be~~are ubiquitous contaminants. The significant number of compounds and varying half-lives mean that concentrations of specific POPs in 2025, the date set for SDG Target 14.1 (Figure 10A) will likely be greater than ~~those~~ the POP concentrations that are expected to cause biological effects. However, what is more relevant is the impact on biota of the ~~cocktail~~ multitude of POPs to which they are ~~being~~ exposed. This remains difficult to assess. In addition, POPs continue to be of concern from the perspective of human health which has a consequence for Target 3.9 (Figure 10B) as well as impacting the delivery of other SDGs (Figure 10C – E).

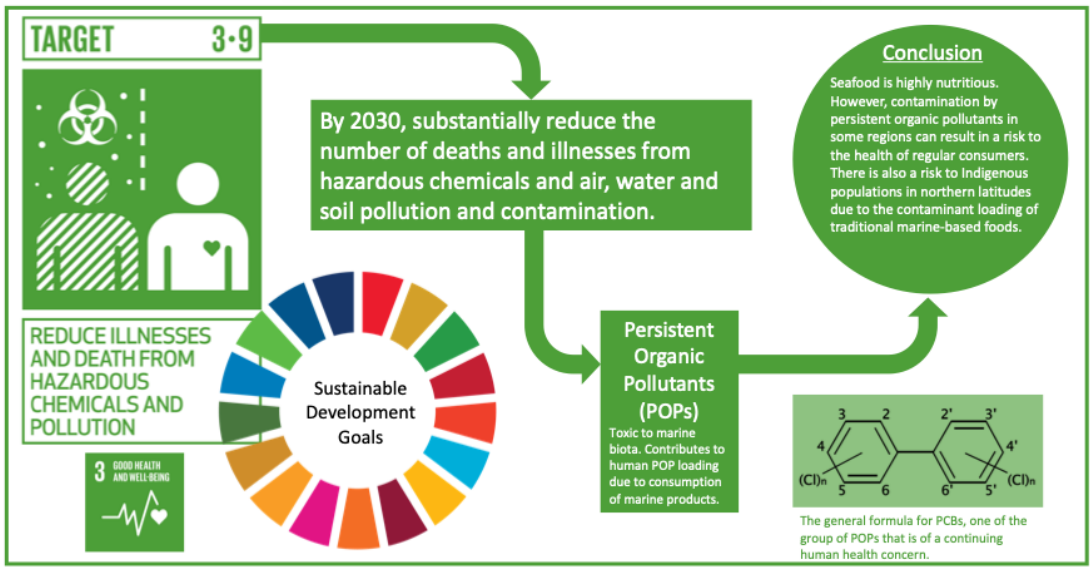
(A)


SUSTAINABLE DEVELOPMENT GOALS
TARGET 14·1
By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.
Conclusion
POPs remain a significant problem in marine ecosystems. However, actions are being taken. For example, under the Stockholm Convention on POPs the objective is to eliminate the use of PCBs in equipment by 2025 and each party will make determined efforts designed to lead to environmentally sound waste management of liquids containing PCBs and equipment contaminated with PCBs no later than 2028.
REDUCE MARINE POLLUTION
Sustainable Development Goals
Persistent Organic Pollutants (POPs)
Ubiquitous in the global ocean
Cl
Cl
Cl
Cl
CB118, a dioxin-like CB found in marine biota above the concentration likely to cause biological effects

1

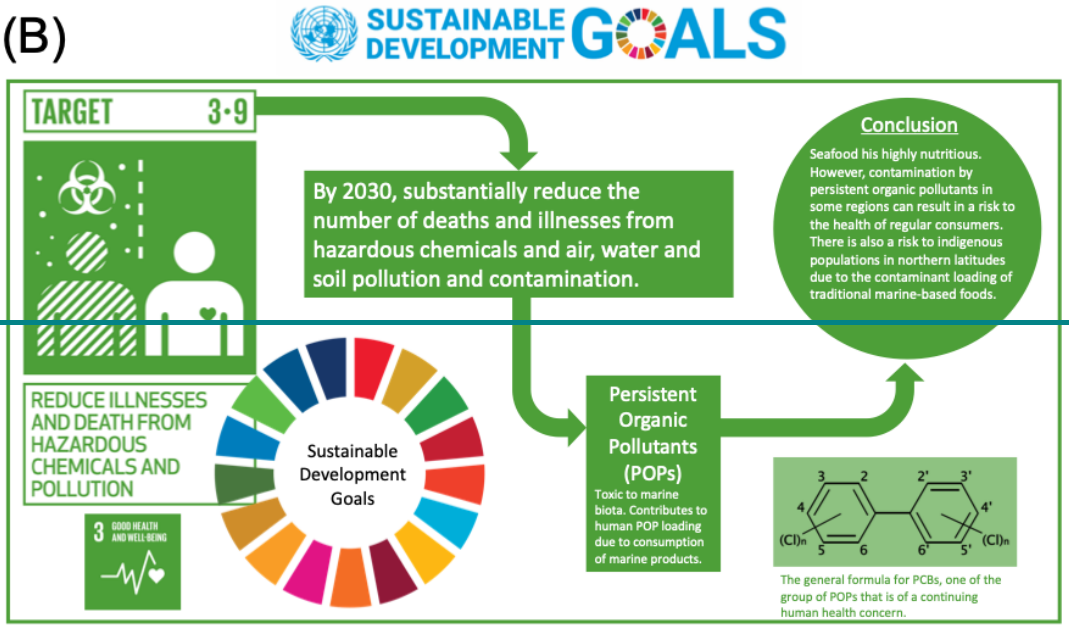
2

(B)


SUSTAINABLE DEVELOPMENT GOALS
TARGET 3.9
By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.
Conclusion
Seafood is highly nutritious. However, contamination by persistent organic pollutants in some regions can result in a risk to the health of regular consumers. There is also a risk to Indigenous populations in northern latitudes due to the contaminant loading of traditional marine-based foods.
REDUCE ILLNESSES AND DEATH FROM HAZARDOUS CHEMICALS AND POLLUTION
3 GOOD HEALTH AND WELL-BEING
Sustainable Development Goals
Persistent Organic Pollutants (POPs)
Toxic to marine biota. Contributes to human POP loading due to consumption of marine products.
The general formula for PCBs, one of the group of POPs that is of a continuing human health concern.

1

(B)


SUSTAINABLE DEVELOPMENT GOALS
TARGET 3.9
By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.
Conclusion
Seafood his highly nutritious. However, contamination by persistent organic pollutants in some regions can result in a risk to the health of regular consumers. There is also a risk to indigenous populations in northern latitudes due to the contaminant loading of traditional marine-based foods.
REDUCE ILLNESSES AND DEATH FROM HAZARDOUS CHEMICALS AND POLLUTION
3 GOOD HEALTH AND WELL-BEING
Sustainable Development Goals
Persistent Organic Pollutants (POPs)
Toxic to marine biota. Contributes to human POP loading due to consumption of marine products.
The general formula for PCBs, one of the group of POPs that is of a continuing human health concern.

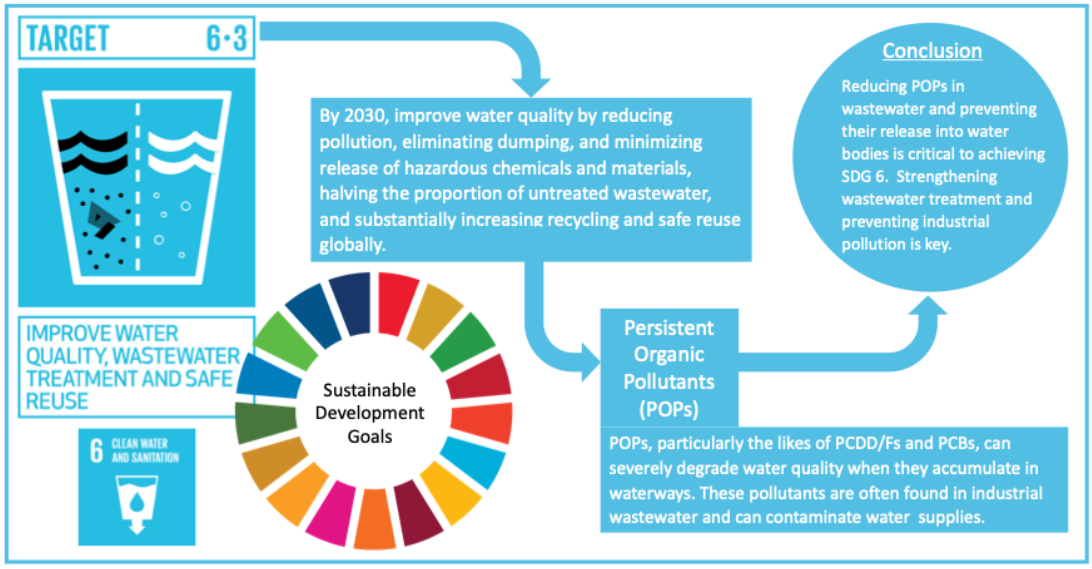
2

3

4

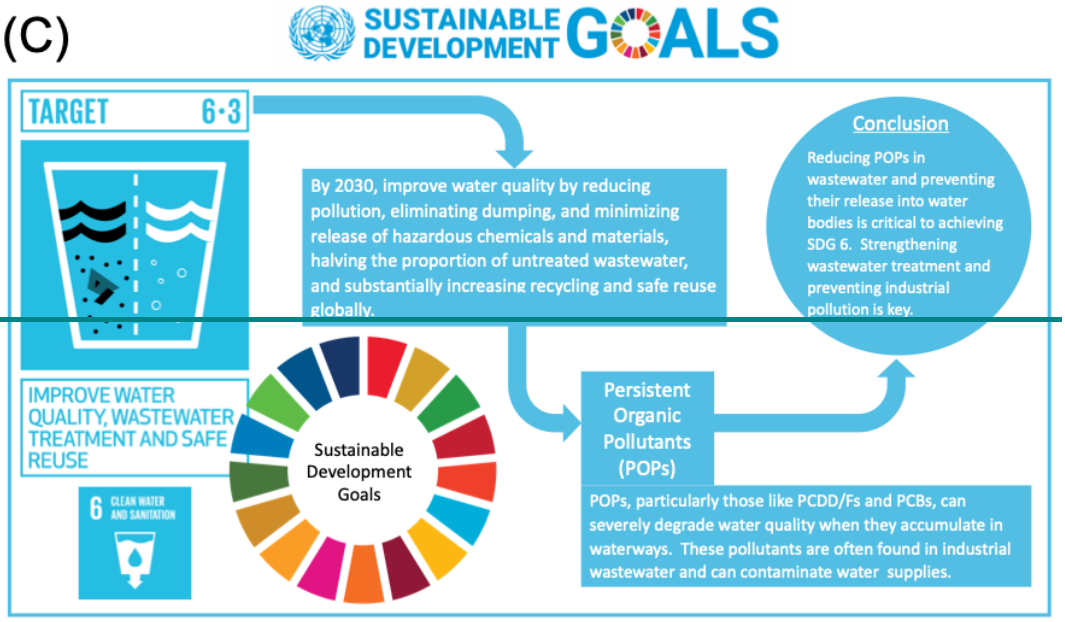
5

(C)


SUSTAINABLE DEVELOPMENT GOALS
TARGET 6·3
By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.
Conclusion
Reducing POPs in wastewater and preventing their release into water bodies is critical to achieving SDG 6. Strengthening wastewater treatment and preventing industrial pollution is key.
IMPROVE WATER QUALITY, WASTEWATER TREATMENT AND SAFE REUSE
Sustainable Development Goals
Persistent Organic Pollutants (POPs)
POPs, particularly the likes of PCDD/Fs and PCBs, can severely degrade water quality when they accumulate in waterways. These pollutants are often found in industrial wastewater and can contaminate water supplies.
6 CLEAN WATER AND SANITATION

1

(C)


SUSTAINABLE DEVELOPMENT GOALS
TARGET 6·3
By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.
Conclusion
Reducing POPs in wastewater and preventing their release into water bodies is critical to achieving SDG 6. Strengthening wastewater treatment and preventing industrial pollution is key.
IMPROVE WATER QUALITY, WASTEWATER TREATMENT AND SAFE REUSE
Sustainable Development Goals
Persistent Organic Pollutants (POPs)
POPs, particularly those like PCDD/Fs and PCBs, can severely degrade water quality when they accumulate in waterways. These pollutants are often found in industrial wastewater and can contaminate water supplies.
6 CLEAN WATER AND SANITATION

2

3

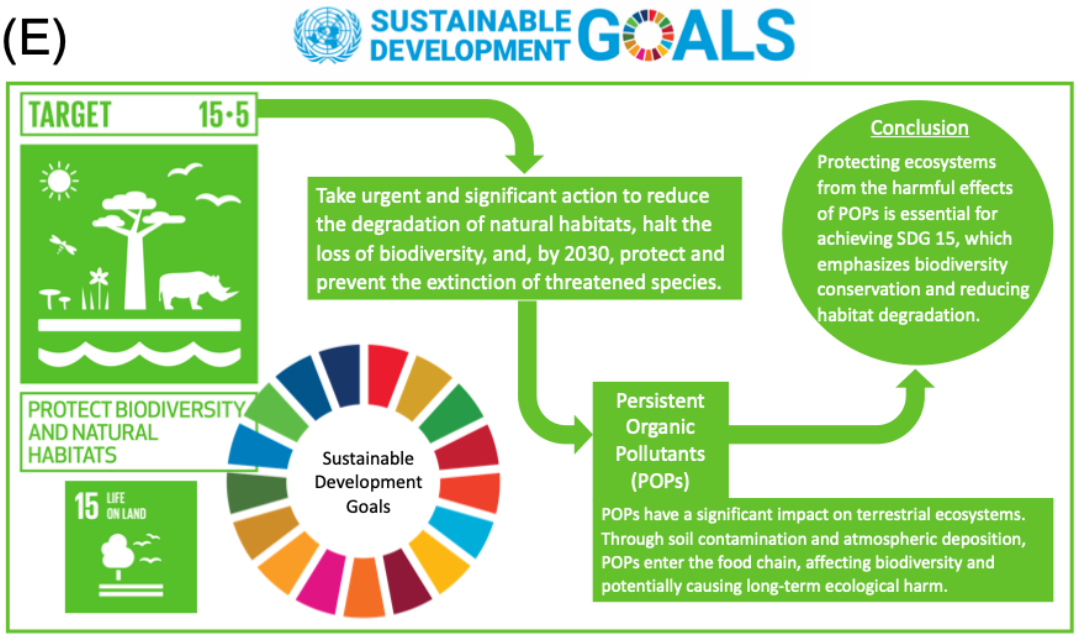


Figure 10: Consequences for a ~~range~~ number of Sustainable Development Goal Targets. (A) Target 14.1, Reduce Marine Pollution; (B) Target 3.9 Reduce illness and death from hazardous substances and pollution; (C) Target 6.3, Improve water quality, wastewater treatment and safe reuse; (D) Target 12.4, Responsible management of chemicals and waste; (E) Target 15.5, Protect biodiversity and natural habitats.

Ecotoxicology

When assessing ~~Often in the assessment of~~ the impacts of POPs on marine ecosystems, the results are often presented based on individual congeners ~~(e.g. CB118 which is a dioxin-like PCB)~~ or as a grouping of congeners. For example, when assessing the impacts of PCBs the assessment might focus on a dioxin-like PCB (e.g., CB118) or ~~(e.g.~~ the ICES 6 non-planar PCBs~~;~~ (Webster and Fryer, 2022). ~~-~~However, biota are exposed not just to ~~CB-118~~a single congener or indeed a group of congeners. ~~the ICES 6 non-planar PCBs.~~ Rather, they are exposed to all the bioavailable pollutants in their geography. ~~-~~This is why ecotoxicological assessments are vital since some of these tests more correctly assess the impact of all anthropogenic chemicals in their environment rather than of a single compound or group of compounds.

Understanding concentration ~~level~~s and impacts of POPs in the marine environment lags behind our understanding of freshwater systems due to fewer marine-based ecotoxicity testing models and systems. Testing programs focus on bioaccumulative compounds within high trophic species destined for human consumption (e.g. chemical monitoring programs such as ~~the~~ undertaken by the UK Food Standards Agency), therefore data on other compounds, mixtures, and congeners is limited for the marine environment (Hutchinson, 2017; Tlili and Mouneyrac, 2021). Of increasing concern is the impact of mixtures of chemical compounds and the combined toxicity of environmentally realistic co-occurring contaminants with a dynamic exposure complexity which is hard to replicate in laboratory toxicity testing (Burgeot and others, 2023). Chemical contaminants can interact in multiple ways, and 7% of pesticides have been estimated to act in synergy (Cedergreen, 2014). Synergistic impacts are particularly concerning due to the potential for extreme impacts not predictable by single compound regulated toxicity testing (Orr and others, 2024; Pirotta and others, 2022). There is an urgent need to combine toxicity estimations of mixtures, in addition to climate change altering profiles of physical stressor conditions in the marine environment, to truly estimate POPs contributions to marine multi-stressor environments.

Developments in legislation continue to bring change

As has been highlighted, The Stockholm Convention on Persistent Organic Pollutants (POPs) is the global basis for the regulation of POPs. Developments continue in respect of listed chemicals. In addition, the target dates ~~for~~ leading to the improved management of PCBs are rapidly approaching (Table 2).

Year	Decision / Change	Source
2019	The Conference of the Parties listed PFOA, its salts and PFOA-related compounds and dicofol in Annex A to the Stockholm Convention (decision SC-9/12). The Conference of the Parties also amended Annex B to eliminate many of the exemptions for PFOS, its salts and PFOSF.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2021	The regulation was revised to include stricter limits on certain POPs, such as Perfluorohexane sulfonic acid (PFHxS), which is widely used in industrial processes and can cause significant environmental harm.	European Union (2019). Regulation (EU) 2019/1021 of the European Parliament and of the Council on Persistent Organic Pollutants.
2022	The Basel Convention's COP adopted new guidelines that address the management of waste containing newly listed POPs, such as certain brominated flame retardants, and improve waste disposal practices to minimize environmental contamination.	Basel Convention Secretariat (2022). Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. United Nations Environment Programme.
2022	The Conference of the Parties listed PFHxS, its salts and PFHxS-related compounds in Annex A to the Stockholm Convention (decision SC-10/13).	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2023	The Conference of the Parties listed Dechlorane Plus and UV-328 and methoxychlor in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	Eliminate the use of PCBs in existing equipment.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	The Conference of the Parties listed MCCPs, long-chain PFCAs, their salts and related compounds, and chlorpyrifos in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2028	Ensure environmentally sound waste management of PCBs.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2030	Exemptions for recycling of articles containing commercial pentaBDE and commercial octaBDE expire.	The Stockholm Convention on Persistent Organic Pollutants (POPs).

Year	Decision / Change	Source
2019	The Conference of the Parties listed PFOA, its salts and PFOA-related compounds in Annex A to the Stockholm Convention (decision SC-9/12).	The Stockholm Convention on Persistent Organic Pollutants (POPs)
2021	The regulation was revised to include stricter limits on certain POPs, such as Perfluorohexane sulfonic acid (PFHxS), which is widely used in industrial processes and can cause significant environmental harm.	European Union (2019). Regulation (EU) 2019/1021 of the European Parliament and of the Council on Persistent Organic Pollutants.
2022	The Basel Convention's COP adopted new guidelines that address the management of waste containing newly listed POPs, such as certain brominated flame retardants, and improve waste disposal practices to minimize environmental contamination.	Basel Convention Secretariat (2022). Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. United Nations Environment Programme.
2022	The Conference of the Parties listed PFHxS, its salts and PFHxS-related compounds in Annex A to the Stockholm Convention (decision SC-10/13).	The Stockholm Convention on Persistent Organic Pollutants (POPs)
2023	Dechlorane Plus and UV-328 were added to the list of POPs at the 11th Conference of the Parties (COP-11), with obligations to eliminate their production and use.	United Nations Environment Programme (2023). Stockholm Convention on Persistent Organic Pollutants. United Nations Environment Programme.
2025	Eliminate the use of PCBs in existing equipment.	The Stockholm Convention on Persistent Organic Pollutants (POPs)
2028	Ensure environmentally sound waste management PCBs.	The Stockholm Convention on Persistent Organic Pollutants (POPs)
2030	Exemptions relating to polybrominated diphenyl ethers expires.	The Stockholm Convention on Persistent Organic Pollutants (POPs)

Table 2: Recent developments in legislation and selected future targets. MCCPs, medium-chain chlorinated paraffins.

Remaining key knowledge, capacity changes and new gaps

A key gap is the continuing challenge of determining the impact of the chemical mixtures to which marine organisms ~~the plants and animals in the ocean~~ are exposed. This is exacerbated by the consequences of other forms of pollution (including synergistic interactions with nanoplastics (e.g. Kamalakannen and others, 2024)) and the changing temperatures, water oxygen concentration and acidity because of increasing concentrations of greenhouse gases. Furthermore, the analytical challenges are significant due to the complexity of the POP mixtures coupled with the analytical methods required for quantification of POPs in the ocean. Finally, human ingenuity continues to result in emerging contaminants and POP replacements including polyhalogenated carbazoles (PHCZs; Gao and others, 2024)). They have been detected in marine sediments, seawater, zooplankton, bivalves, fish, harbour seals and cormorant eggs (Wu and others, 2017; Hu and others, 2021; Hu and others, 2024). 6:2 F~~f~~luorotelomer sulfonate (6:2 FTS; Grimberg and others, 2024) has been used as an alternative for legacy PFAS and has recently been shown to be potentially immunotoxic (Bohannon and others, 2023). These alternatives are often not benign and add further complexity to understanding the full impact and consequences of POPs in the ocean.

4. Pharmaceuticals and personal care products (PPCPs)

Key Messages

The first and second World Ocean Assessments provide a foundational understanding of the occurrences and impacts of PPCPs on the global ocean. Key findings in the past 5 years are:

- Advances in analytical techniques have significantly enhanced the identification and quantification of PPCPs in marine environments, leading to more comprehensive data collection.
- Expanded monitoring programs have increased our understanding of PPCP prevalence in various oceanic regions, particularly in the North Pacific and North Atlantic.
- Studies have identified certain "hot spots" in coastal seas where PPCPs accumulate, and have elucidated their effects on marine organisms, including issues such as bioaccumulation and toxicity to phytoplankton, fish and benthic species.
- Improvements in wastewater treatment technologies are necessary to reduce PPCP levels in effluents, thereby alleviating the pressure on coastal marine environments.

Action plans and priorities have been developed on how to decrease the presence and potential impacts of pharmaceuticals in the environment. These include reducing demand and use of pharmaceuticals as well as better disposal and end of pipe emission reduction. The ultimate and most expensive option is advanced wastewater treatment to remove active pharmaceutical ingredients (APIs) before their wider ~~spread~~ distribution in the environment (Caban and Stepnowski, 2021).

Introduction

Pharmaceuticals and personal care products (PPCPs) comprise a diverse array of substances, including prescription and therapeutic drugs, veterinary medications, fragrances, sunscreen agents, and diagnostic compounds. Currently, around 4,000 pharmaceutically active substances are available globally, with an annual consumption of approximately 100,000 tons (Pawłowska and Biczak, 2024). P~~C~~PCPs have increasingly become of significant environmental concern due to their persistence, bioaccumulative properties, toxic potential, and often high mobility (Chakraborty and others, 2023). Over the past few decades, many research and monitoring initiatives have employed advanced sampling and analytical techniques, such as Liquid Chromatography – Mass Spectroscopy (MS)/MS (LC-MS/MS), Gas Chromatography (GC)-MS, and non-targeted high-resolution mass spectrometry, to detect various PPCPs in the global ocean (Guo and others, 2023). Commonly detected compounds include antibiotics, hormones, and UV filters with varying concentrations of these substances across different regions.

The COVID-19 pandemic has further exacerbated this issue by significantly increasing the use of specific medications and treatments, notably antivirals, antimicrobials, and antidepressants (Li and others, 2023). The large consumption of some of these pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. PPCPs are now pervasive in both the open ocean~~s~~ and coastal areas, with particularly high concentrations found near densely populated or industrial zones, wastewater discharge points, harbours and around mariculture (Lin and others,

2023). These pollutants can be transported through river outflows, ocean currents, and atmospheric deposition, often accumulating in marine organisms and sediments, especially in marginal seas (Maghsodian and others, 2022).

The ecological impacts of PPCPs are profound and concerning. Toxicity studies have shown harmful effects on marine organisms, including endocrine disruption, the development of antibiotic resistance, and behavioural changes in various ~~species~~ marine biota ~~such as~~including fish, invertebrates, and algae (Yang and others, 2020, Mezzelani and Regoli, 2022)). The widespread presence of PPCPs poses a threat to marine biodiversity and ecosystem health. Moreover, human exposure to PPCPs, though less direct, remains a critical issue. This exposure primarily occurs through the consumption of seafood and during leisure time activities in contaminated waters (National Academies of Science, Engineering and Medicine, 2024). Such exposure raises serious concerns about chronic health risks, including hormonal disruptions and the proliferation of antibiotic-resistant bacteria.

In World Ocean Assessment II, PPCPs were included in chapter 11 **Changes in Liquid and Atmospheric Inputs to the Marine Environment from Land (including through Groundwater), Ships and Offshore Installations,** section 6 Pharmaceuticals and personal care products (United Nations, 2020), which summarized the data of PPCPs in global ocean up to 2017. Therefore, the assessment of PPCPs in this work is focused on the new data and articles reported in the time-period from 2018 to 2024~~3~~.

Description of environmental change since the second World Ocean Assessment

Recently, scientists have turned their attention to emerging chemical contaminants present in low concentrations, such as PPCPs, which pose significant threats to coastal and ocean environments through bioaccumulation and metabolism. Research and monitoring of the occurrences of PPCPs in marine waters is important, but the inclusion of metabolites is particularly needed as these compounds often go undetected and can be as persistent and hazardous as their parent substances. As illustrated in Table 3, the global concentrations of frequently detected PPCPs such as antibiotics, β-blockers, antiulcer agents, antiepileptics, antiasthma drugs, antihistamines, calcium channel blockers, lipid-regulating agent, and hormones in coastal water across the world are reported.

Location	Antibiotics									
	Erythromycin		Clarithromycin		Roxithromycin		Sulfamethoxazole		Sulfamethazine	
	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII
Baltic Sea	n.d.-0.14	n.a.	0.03-14	n.a.	n.d.-0.48	n.a.	0.74-21	n.a.	n.d.	n.a.
North Sea	0.13-0.94	n.a.	0.4-1.66	n.a.	n.d-2.86	n.a.	1.78-13.0	n.a.	n.d.	n.a.
Aegean Sea	n.d.	n.a.	16	n.a.	n.a.	n.a.	45507	n.a.	n.a.	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.02 - 1.02	n.a.	n.a.	n.a.
Mediterranean	9	n.d. - 2.3	5	n.d. - 441.4	n.a.	n.d.-1.3	14	n.d.-99	n.a.	n.d.-9.1
Pearl River Delta, China	n.d.-126	n.a.	n.a.	n.a.	n.d.-12.0	n.a.	n.d.-40.6	n.a.	n.a.	n.a.

Bohai Sea	n.a.	0-150	n.a.	0.82-37	n.a.	0-630	n.a.	0-140	n.a.	0-130
Yellow Sea	n.a.	0-121.2	n.a.	0-6.55	n.a.	0-11.8	n.a.	0-1.92	n.a.	0-250.66
East China Sea	n.a.	0-57.07	n.a.	0-6.38	n.a.	0.33-34.81	n.a.	0.81-16.65	n.a.	0-2.03
South China Sea	n.a.	0-1900	n.a.	0.06-1.5	n.a.	0-47	n.a.	0-17.5	n.a.	0-16.4
Boulder Basin, USA	<1.0	n.a.	n.a.	n.a.	n.a.	n.a.	5.4 ± 11	n.a.	n.a.	n.a.

1

2

3

4

Location	**ICM X-ray (ng L^{-1})**				**NSAIDs (ng L^{-1})**				**Antiepileptic (ng L^{-1})**	
	Iomeprol		**Iopromide**		**Diclofenac**		**Ibuprofen**		**Carbamazepine**	
	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII	WOAII	WOAIII
Arctic, Longyearbyen	n.a.	n.a.	n.a.	n.a.	1-4	n.a.	0.4-1	n.a.	n.a.	n.a.
Arctic, Tromsø	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.d. - 52	n.a.	n.a.	n.a.
Baltic Sea	1.05-34.5	n.a.	0.42-3.34	n.a.	n.d.-48	n.d.-27.1	n.a.	n.d.-1219.7	1.98-10.6	0.6-12.2
North Sea	7.66-207	n.a.	7.27-34.1	n.a.	n.d.-4.82	<MQL-35.35	n.a.	47.12-209.6	4.78-29.7	<MQL-78.9
Himmerfjärden	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	45759	n.a.
Aegean Sea	83	n.a.	109	n.a.	45447	n.a.	n.a.	n.a.	45537	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.11-0.36	n.a.
Sea of Marmara, Turkey	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL-1300	n.a.	<MDL-2130	n.a.	<MDL-1840
Mediterranean, Spain	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-31.9	n.a.	n.a.	n.a.	n.d.-31.1
Mediterranean, Tunesia	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-23	n.a.	n.d.	n.a.	n.d.-0.5
Mediterranean, Italy	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-441	n.a.	n.d.-2550	n.a.	n.d.-123
Gran Canaria, Med	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-344	n.a.	n.a.	n.a.	n.a.
Tejo Estuary, Portugal	n.a.	n.a.	n.a.	n.a.	n.a.	1.6-51.8	n.a.	<LOQ	n.a.	n.d.
Santos Bay	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	326.1-2094	n.a.	n.a.	n.a.
Guaruja, Brazil	n.a.	n.a.	n.a.	n.a.	n.a.	85.7	n.a.	n.a.	n.a.	0.1
Sao Paulo coast, Brazil	n.a.	n.a.	n.a.	n.a.	n.a.	9.9	n.a.	n.a.	n.a.	0.5
Santa Catarina, Brazil	n.a.	n.a.	n.a.	n.a.	n.a.	7.9	n.a.	n.a.	n.a.	0.3
Red Sea	n.a.	n.a.	n.a.	n.a.	14020	n.d.-26.9	508	n.a.	110	n.a.
Klang river estuary, Malaysia	n.a.	n.a.	n.a.	n.a.	n.a.	0.47-10.8	n.a.	n.a.	n.a.	n.a.
Durban, South Africa	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	170	n.a.	n.a.
Bohai&Yellow Sea	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL-1.53	<MDL-5.11	<MDL-5.11	n.a.	n.d--38.26
Boulder Basin, USA	n.a.	n.a.	n.a.	n.a.	<1.0	n.a.	n.a.	n.a.	3.9±5	n.a.

Sydney Estuary, Australia	n.a.	n.a.	3-12.5	<0.1-94.3	n.a.	n.a.	n.a.	<0.5	n.d-2.7	<0.1-106.4

Location	Lipid regulation (ng L^{-1})	ß-Blocker (ng L^{-1})			Antidepressants (ng L^{-1})	
	Bezafibrate	Atenolol	Metoprolol	Propanpolol	Fluoxetine	Citalopram
Baltic Sea	n.d.-0.64	n.a.	0.1-0.8	n.a.	n.a.	n.a.
North Sea	n.d-2.06	<MQL-30.8	<MQL-23.5	<MQL-35.2	<MQL	<MQL-23.3
Aegean Sea	45415	n.a.	n.a.	n.a.	n.a.	n.a.
Adriatic Sea	0.02-0.14	n.a.	n.a.	n.a.	n.a.	n.a.
Mediterranean, Spain	n.d.-0.5	0.4-138.9	n.d.-5.1	n.d.-5.9	n.d.-0.6	n.a.
Mediterranean, Tunesia	n.d.	n.d.	n.d.	n.d.	n.d.-41	n.a.
Mediterranean, Italy	n.d.	0.1-451	n.a.	n.a.	n.a.	n.a.
Tejo Estuary, Portugal	0.84-13.4	0.49	n.a.	0.02-1.89	1.09-16.2	n.a.
Atlantic, Spain (Rías Baixas)	n.a.	n.a.	n.a.	n.a.	n.d.-10.6	n.d.-92.5
Guaruja, Brazil	n.a.	0.3	n.a.	n.a.	n.a.	n.a.
Sao Paulo coast, Brazil	n.a.	13.2	n.a.	n.a.	n.a.	n.a.
Santa Catarina, Brazil	n.a.	3.2	n.a.	n.a.	n.a.	n.a.
Bohai&Yellow Sea	n.d.-3.55	n.d.-4.35	n.d.-0.46	n.d.-1.43	n.a.	n.a.
Puget Sounds, USA	n.a.	n.a.	1.5	n.a.	n.a.	n.a.
Sydney Bay, Australia	n.a.	n.a.	<0.05-7.7	n.a.	<0.1-36	<0.1-2.6

ICM, Iodinated contrast medium; NSAIDs, Non-steroidal anti-inflammatory drugs

Table 3: PPCPs measured in coastal waters (ng L^{-1}), comparison between WOAII and WOAIII.

Variability of PPCP distribution can be seen in the example of the global distribution of six antibiotics in oceanic waters (Figure 11). Higher concentrations (up to 10,000 ng l^{-1}) are observed near densely populated or industrial regions, such as Western Europe, East Asia, and the African coast. Lower levels are evident in more remote regions, ~~like~~ like the Southern hemisphere and polar areas. Regions such as the Mediterranean and Southeast Asian coasts appear to be hotspots for antibiotic contamination (Maghsodian and others, 2022)

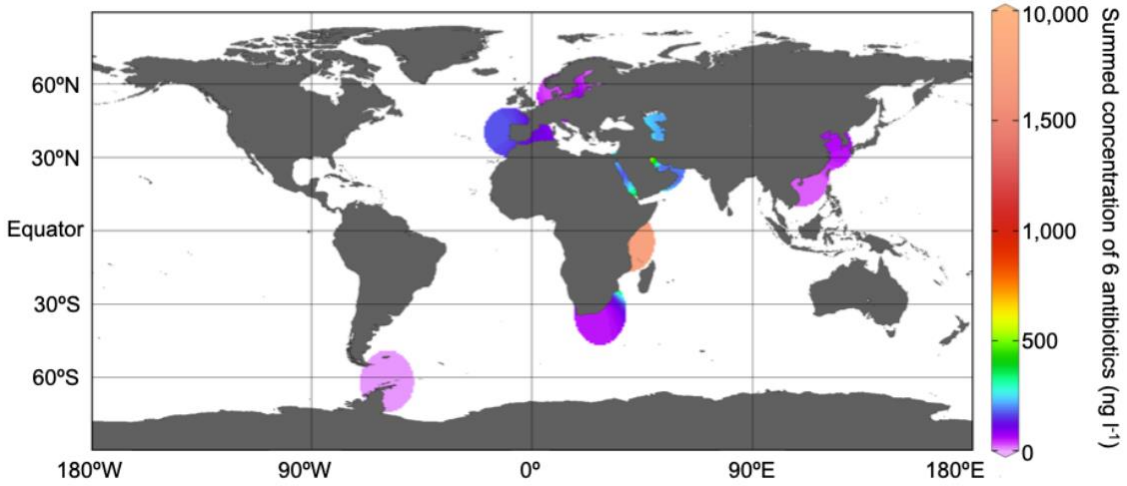


Figure 11.

Geographical distribution of the antibiotics azithromycin, enrofloxacin, florfenicol, ofloxacin, sulfamethoxazole and trimethoprim in the world's oceans. (Image created by Zhiyong Xie, writing team member, using Ocean Data View)

A global monitoring study of pharmaceuticals was published, with data on 67 catchments highlighting the potential delivery of these compounds to the world's seas and oceans. The most contaminated samples were reported for African and Asian rivers. Up to 53 active pharmaceutical ingredients (APIs) were detected, with four compounds being present in all tested waters: caffeine, nicotine, acetaminophen/ paracetamol and cotinine (Wilkinson and others, 2022).

Region-specific changes

The Arctic Ocean

PPCP residues have been detected in various environmental compartments, from coastal seawater to high-level biota in the Arctic. The primary sources of these pollutants are local, domestic and municipal wastes, along with sewage. The lack of modern wastewater treatment plants (WWTPs) in larger Arctic settlements results in higher PPCP release rates into the Arctic aquatic environment. Up until 2018, 110 PPCP-related substances have been found in the Arctic with detectable residue concentrations. In the European Arctic, eleven pharmaceutical substances were measured in seawater and plankton samples collected in the Arctic fjord at Ny-Ålesund in 2019 (Korkmaz and others, 2022). 17α-ethynylestradiol and fenoprofen were the most frequently detected pharmaceuticals, ranging from 340–850 ng l^{-1} and 230–600 ng l^{-1}, respectively. These levels were higher than those of estrone (<43–420 ng l^{-1}) and 17β-estradiol (<29–140 ng l^{-1}), with estrone likely being the primary degradation product of 17β-estradiol. Diclofenac, ibuprofen, and naproxen concentrations determined in this study were also higher than those found in other Arctic studies. Choi and others (2020) measured PPCPs in effluent and seawater collected at Ny-Ålesund using the targeted, coupled with suspect and non-target screening methods in effluent samples. PPCPs such as caffeine, paraxanthine/theophylline, acetaminophen, cetirizine, diethyl toluamide (DEET), and icaridin were detected in all samples, with concentrations ranging from 4–280,000 ng l^{-1} in the effluent and 2–98 ng l^{-1} in the seawater. In the Canadian Arctic, organic diffusive gradients in thin film (o-DGT) passive samplers were deployed in Iqaluit and Cambridge Bay to monitor

PPCPs in Nunavut. Seven active pharmaceutical ingredients (APIs), including atenolol, carbamazepine, metoprolol, naproxen, sulfapyridine, sulfamethoxazole, and trimethoprim, were found at least once, with concentrations varying from non-detectable to 5,200 ng l^{-1}. Due to the cold climate, these pharmaceuticals degrade slowly, resulting in prolonged presence. Consequently, the toxicological impact of PPCP release in the Arctic differs from that in temperate regions, posing exposure risks to local populations through contaminated fish and resistant microbes.

The North Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean and the North Sea

Adenaya and others (2024) analyzed 62 APIs and one UV filter from the surface microlayer to the corresponding underlying water (0 cm, 20 cm, 50 cm, 100 cm, and 150 cm) at four stations in the southern North Sea. Eleven APIs (caffeine, carbamazepine, gemfibrozil, ibuprofen, metoprolol, salicylic acid, clarithromycin, novobiocin, clindamycin, trimethoprim~~,~~ and tylosin) were detected in >95%, and benzophenone-4, a UV-filter, in 83% of all seawater samples.

Following the recommendations from the Helsinki Commission (HELCOM), several studies have been carried out since 2020 for the investigation of the occurrence, transport, sedimentation and bioaccumulation in the riverine run-off and the estuaries of the Baltic Sea. In the Eastern Gulf of Finland, seven APIs were identified in seawater samples, including caffeine (81%), carbamazepine (81%), ketoprofen (60%), diclofenac (23%), ciprofloxacin, trimethoprim, and clarithromycin, with concentrations varying from 0.1 to 4,500 ng l^{-1}. Antibiotics were found in trace amounts. In sediment samples, six APIs were detected with concentrations ranging from 0.1 to 66 ng g^{-1} (Chernova and others, 2021). Kucharski and others (2022) have investigated 130 APIs in sediments collected from the Odra River estuary (south west Baltic Sea). Among them, 48 out of 130 APIs were detected at concentrations above the limit of quantification (LOQ) with detection frequence higher than 10%; carbamazepine, sulpiride, fexofenadine, clindamycin, tramadol, bisoprolol, and lidocaine were found to be the predominant compounds in the sediment. Most of the APIs measured recently in the seawater and sediment of the Baltic Sea were in line with those found in the effluent water surrounding the Baltic Sea (Zandaryaa and Frank-Kamenetsky, 2021; Undeman and others, 2022; Jucyte-Cicine and others, 2024). Ninety-eight (98) multi-class APIs, including cardiovascular drugs, antidepressants, antibiotics, and sulfonamides, were screened in the muscle tissue of fish caught in the Baltic Sea (Bobrowska-Korczak and others, 2021). Eleven pharmaceuticals (bisoprolol, carbamazepine, clarithromycin, erythromycin, fluoxetine, metronidazole, ofloxacin, promazine, sulfadimethoxine, thiabendazole and tianeptine) were detected in fish muscle, while none of them were found in bream and crucian.

Alygizakis and others (2016) measured PPCPs in seawater from the northwestern part of the Black Sea using non-target screening and deep learning convolutional neural networks (Chitescu et al., 2021). Thirty-five PPCPs were tentatively identified by library spectrum match. The River Danube ~~river~~ is an important ~~input~~ source of PPCPs entering the Black Sea and the Mediterranean. PPCPs have been measured in seawater ~~of~~ from the Mediterranean since 2016 (Alygizakis and others, 2016). ~~-~~Thirty-eight (38) out of the 158 target APIs were detected, and 15 of them with frequencies of detection equal to or higher than 50%. Amoxicillin, caffeine and salicylic acid were the predominant compounds with concentrations in the range of <5.0–130 ng l^{-1}, 5.2–78 ng l^{-1} and <0.4–53 ng l^{-1}, respectively. UV filters and

musk fragrances were screened in ~~the~~ Western Mediterranean coastal areas, e.g. Mar Menor Lagoon (south east Spain) and Ebro Delta (north east Spain). The musks, galaxolide (HHCB), hexylcinamal and the UV filters~~,~~ homosalate, ethylhexyl salicylate, octocrylene and dibutyl adipate were all detected in summer with concentrations varying from a few ng l^{-1} to 1000s ng l^{-1} (García-Pimentel and others, 2023). In Augusta Bay, southern Italy, APIs were studied simultaneously in untreated wastewater (2400–67,000 ng l^{-1}), marine receiving water (550–28,000 ng l^{-1}) and~~,~~ seawater (12–280 ng l^{-1}), which showed clear decreasing trends from the land sources to the sea (Feo and others, 2020). The substances with the most significant concentrations in seawater included ciprofloxacin, ofloxacin, atenolol, irbesartan, losartan, valsartan, and carbamazepine. Valsartan showed the highest concentration across all samples, ranging from 209-1057 ng l^{-1}.

The South Atlantic Ocean and the Wider Caribbean

PPCPs were measured in seawater, sediment and biota in Camps Bay, off the South Atlantic coast of South Africa and diclofenac, acetaminophen, and carbamazepine present in sewage were able to enter the Bay although they were diluted quickly by the upwelling current (Ojemaye and others, 2020). The concentrations of caffeine, diclofenac and carbamazepine in the single ng l^{-1} range were similar to other marine regions, while triclosan and acetaminophen were much lower than other studies. PPCPs, such as UV filters, were found in seawater and lionfish collected in Grenada, West Indies. Oxybenzone was the predominant compound, with concentrations varying from not detected ~~n.d.~~to ~~–~~120 ng l^{-1} in seawater and 0.12–2.9 μ~~n~~g kg~~l~~$^{-1}$ ww in muscle of lionfish (Horricks and others, 2019).

The Indian Ocean, the Arabian Sea, the Bay of Bengal, the Red Sea, the Gulf of Aden and the ~~Persian~~ Gulf

In the Indian Ocean, APIs were investigated in water and sediment in the Southeast coast of South Africa (Ohoro and others, 2021). Carbamazepine and trimethoprim were found in most sediment samples with an average of 8.75 ± 1.45 ng g^{-1} and 0.62 ± 0.83 ng g^{-1}. They were not detectable in seawater across all the seasons. Due to the low water exchange with the open sea, relatively high concentrations of PPCPs were detected in the lagoon located at the Saudi Arabian coastal waters of the Red Sea, which were in the range of 7– >3000 ng l^{-1} (metformin), <LOQ – 2400 ng l^{-1} (acetaminophen) and 62– >3000 ng l^{-1} (caffeine) (Ali and others, 2017). Two Antibiotics, amoxicillin and azithromycin, were detected in urban wastewater discharged into the coast of the ~~Persian~~ Gulf with concentrations up to 335,000 ± 105,000 and 288,000 ± 38,000 ng l^{-1}, showing a concerning volume of antibiotics being released into the northern ~~Persian~~ Gulf (Daliri and others, 2022). A study of azithromycin in seawater (7 ng l^{-1}) and sediment (5-10 ng g^{-1}) in the ~~Persian~~ Gulf in 2020 showed the concentration increased 3-4 fold relative to pre-COVID19 levels (Mirzaie and others, 2022).

The South and North Pacific Ocean

Pharmaceuticals have been screened in the coastal waters of Fiji's main island in the South Pacific. Seventy-two of 80 APIs were quantified at least once with average concentrations ranging between 0.04 ng l^{-1} for diltiazem and 19 ng l^{-1} for ketoconazole (Dehm and others, 2021). In the North Pacific, most studies were carried out in the marginal seas of China, the Republic of Korea and Japan. Near-shore

areas exhibit higher PPCP levels due to direct discharge from urban wastewater and riverine inputs, with concentrations ranging from a few ng to low µg per litre. Commonly detected PPCPs include antibiotics, anti-oxidants, analgesic/anti-inflammatory drugs, caffeine and synthetic musk fragrances. In contrast, offshore waters show significantly lower concentrations, typically in the low ng per litre range, due to oceanic current dilution and degradation processes (Lu and others, 2023; Guo and others, 2023a)~~A large screening survey for 30 PPCPs from Jiaozhou Bay watershed, Yellow Sea and the East China Sea presented clear transport trends from the rivers (average: 680 ng l^{-1}) to the Bay (170 ng l^{-1}) and to coastal seas (100 ng l^{-1}) (Lu and others, 2023). Fifty-six PPCPs were identified in Yantai Bay of the Yellow Sea, with concentrations ranging from 28-180 ng/L, with 1 H-benzotriazole (a multi-use compound including in pharmaceuticals) accounting for ~ 58.0% of the total. The highest PPCP concentrations were found in winter and spring. During winter, the levels of antioxidants, analgesic/anti-inflammatory drugs, and human-used antibiotics were notably higher, whereas in summer, aquaculture-used antibiotics and UV filters showed significantly elevated concentrations, which is in line with their respective usage patterns (Guo and others, 2023)~~. In the Bohai Sea (Guo and others, 2023b), PPCPs were widely detected in seawater, sediments, and benthic organisms, with the antioxidant 1H-benzotriazole emerging as the most prevalent of the PPCPs. Along the coastal line of the Bohai and Yellow seas, the total concentrations of thirty PPCPs in Chinese coastal waters ranged from 0.88 to ~~-~~1200 ng l^{-1}, varying significantly and generally being higher when compared to the concentrations in Korean coastal waters, which ranged from 9.9 to ~~-~~440 ng l^{-1}.

The Southern Ocean

Data for PPCPs are rare in the Southern Ocean due to its remoteness from the continents where the PPCPs are used. However, relatively high concentrations of PPCPs were measured in the glacial river and the coastal seawaters near research stations. Antarctic PPCP concentrations were influenced more by the type of treatment systems employed at research stations. The primary issue is the absence of tertiary treatment in most research stations, leading to higher PPCP ~~levels~~ concnetrations in their effluents. Wastewaters from Antarctic research stations have been found to contain 56 different PPCPs, while 23 PPCPs have been detected in the nearby coastal waters and sea ice (Balakrishna and others, 2023). The concentrations in the wastewaters ~~reach~~ are at concentrations of ~~1000s of~~ µ~~n~~g l^{-1} for substances such as UV filters and antibiotics. In contrast, due to dilution and degradation, the concentrations in the coastal waters and sea ice are two orders of magnitude lower (Emnet and others, 2015; Perfetti-Bolaño and others, 2022).

Remaining gaps

The following important research gaps remain:

- PPCPs are predominantly studied in coastal areas that receive discharges from sewage, wastewater treatment plants, and river runoff. Future research needs to focus more on PPCPs in the open ocean and their long-range transport via ocean currents. Additionally, there is limited knowledge about the long-term ecological impacts of chronic high~~low~~-level PPCP exposure on marine organisms.
- Comprehensive data on global PPCP distribution is also lacking, especially in under-studied regions such as the South Atlantic, the Caribbean Sea, South Pacific, and Indian Ocean. The lack

of standardized methods for sampling, analysis, and reporting further reduce efficient comparability for assessment and modelling.

- The full extent of PPCPs present in the global ocean is limited by non-~~standardized~~ validated methods and target analyte lists. Agreeing on a few PPCPs for baseline monitoring would help fill in important data gaps.

Addressing these gaps is essential for effective PPCP impact mitigation in the global ocean. This includes improved wastewater treatment technologies, stricter regulations on the disposal and management of pharmaceuticals, and enhanced public awareness about the environmental impact of PPCPs. The potential for long-term health effects necessitates further research and comprehensive risk assessments to better understand and mitigate these risks. Continued research and international collaboration are essential to develop effective strategies to reduce the presence and impact of PPCPs, thereby protecting marine ecosystems and public health.

5. Plastic Pollution

Key Messages

- Global plastic waste emissions are rising, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering, and marine activities.
- Plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected. In some regions, significant impacts are debated.
- Plastic pollution costs billions of US dollars annually. Addressing this issue requires reducing production, ~~advancing material science innovations,~~ promoting reuse, rethinking product design, advancing material science innovations in recycling~~recycling~~, controlling the full plastic life cycle and finding alternatives to single-use plastics in support of legal bans to help lessen the scale of the problem.
- A legally binding treaty against plastic pollution (UNEA Resolution 5/14[32]) is currently being negotiated to address the full lifecycle of plastic products and additives~~, including reducing primary plastic production and legacy plastics~~, aligning with several SDGs and regional action plans around the globe.

Plastic pollution

Plastic pollution is driven by the rise in production since the 1950s and its persistence in the environment (Geyer, 2020). Plastic waste emissions are estimated at 52.1 million metric tonnes per year, with littering being the largest source in the Global North and uncollected waste dominating the Global South (Cottom and others, 2024).

[32] The fifth session of the Intergovernmental Negotiating Committee to develop an international legally binding instrument on plastic pollution, including in the marine environment (INC-5), took place from 25 November to 1 December 2024 in the Republic of Korea.

**Changes sSince ~~the Second World Ocean Assessment II (~~WOA II~~)~~

1. Changes in the Overall Status

Plastics, especially microplastics, impact all marine ecosystems (Suaria and others, 2020, Bergmann and others, 2022, Pierdomenico and others, 2023; Figure 12). Single-use plastics make up 40% of global litter, while fishing contributes 15% (Morales-Caselles and others, 2021), variations exist between high and low-income countries.

2. Factors Contributing to the Change

Understanding marine plastic pollution has advanced recently, based on new methods for detecting microplastics, nanoplastics, and satellite-based detection, providing more precise data (Huang and others, 2023; Cózar and others, 2024). In addition, there has been ~~as well as~~the development of predictive tools (Rieger and others, 2024) and regional assessments with new common indicators agreed and monitored by Regional Seas Conventions (e.g. OSPAR QSR2023, UNEP/MAP 2023 MED QSR and HELCOM HOLAS 3 2023). Rivers and stormwater overflows, due to extreme weather events, are major contributors of riverine litter (Lebreton and others, 2017; Meijer and others, 2021, Cózar and others, 2024, Nyberg and others, 2023, Zhang and others, 2023, Kaandorp and others, 2023).

Floating and beach macro- and microplastics, account for 3-4% of total ocean plastic (Isobe and Iwasaki, 2022), with estimates at 24.4 trillion microplastic pieces in the world's upper oceans (Isobe and others, 2021). Plastics in deep-sea and coral reef ecosystems, are also well-documented (Corinaldesi and others, 2021, Galgani and others, 2022; Nakajima and other, 2021; Pinheirho and others, 2023), with increasing concentrations in remote areas and the deep sea (Galgani and others 2021).

Studies also revealed infiltration of microplastics from every ocean layer to hadal trenches (Egger and others, 2020, Zhao and others, 2022, ~~and~~ 2023 and 2025, Peng and others, 2018), with recent estimates suggesting substantial microplastic concentrations in the water column (Sonke and others, 2022, Harris and others, 2023), which are gradually exported to the deep ocean (Harris and others, 2023).

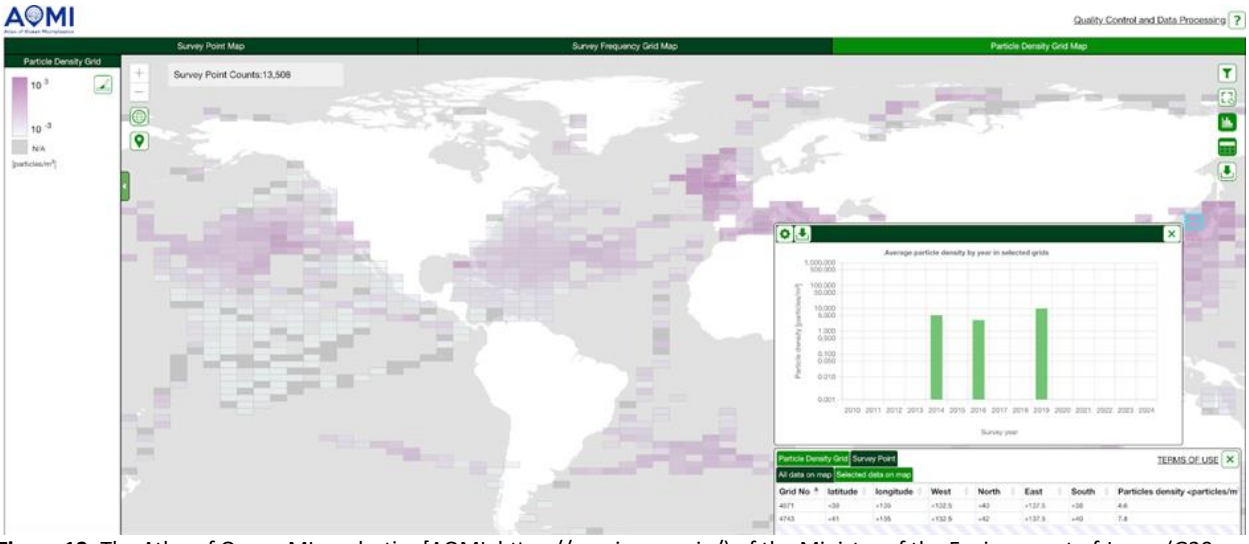


Figure 12: The Atlas of Ocean MIcroplastics [AOMI, https://aomi.env.go.jp/) of the Ministry of the Environment of Japan (G20 related) supports long term monitoring].

3. Interactions with Other Components of the Marine System.

Plastic pollution poses a significant threat to marine habitats (Figure 13) and natural processes, reducing ecosystem resilience, human livelihoods, food security, and harm to biota (see also Section 5A-Chapters 1A, 1B and 1D on fisheries and aquaculture, chapter 4 on tourism and chapter 6 on shipping). Four thousand and seventy-six (4,076) marine species have been reported to be affected by litter (HYPERLINK "https://litterbase.awi.de/interaction.graph"LITTERBASE: Online Portal for Marine Litter (awi.de)).

~~**Figure 13:** Ocean plastic pollution effects and interactions including toxic effects of microplastics across trophic levels (Figures: Paula Sobral)~~

Microplastics arise from multiple sources including tyres, textiles, cosmetics, paint and the fragmentation of larger items (Weis and others, 2022; Thompson and others, 2024), with documented impacts to the environment (Tamis and others, 2021; Leistenschneider and others, 2023). While sewage and wastewater treatment plants may remove some of these particles (Liu and others, 2021), millions still enter water bodies, most containing toxic or hormonal disruptive additives (e.g. phthalates, dyes, etc.).

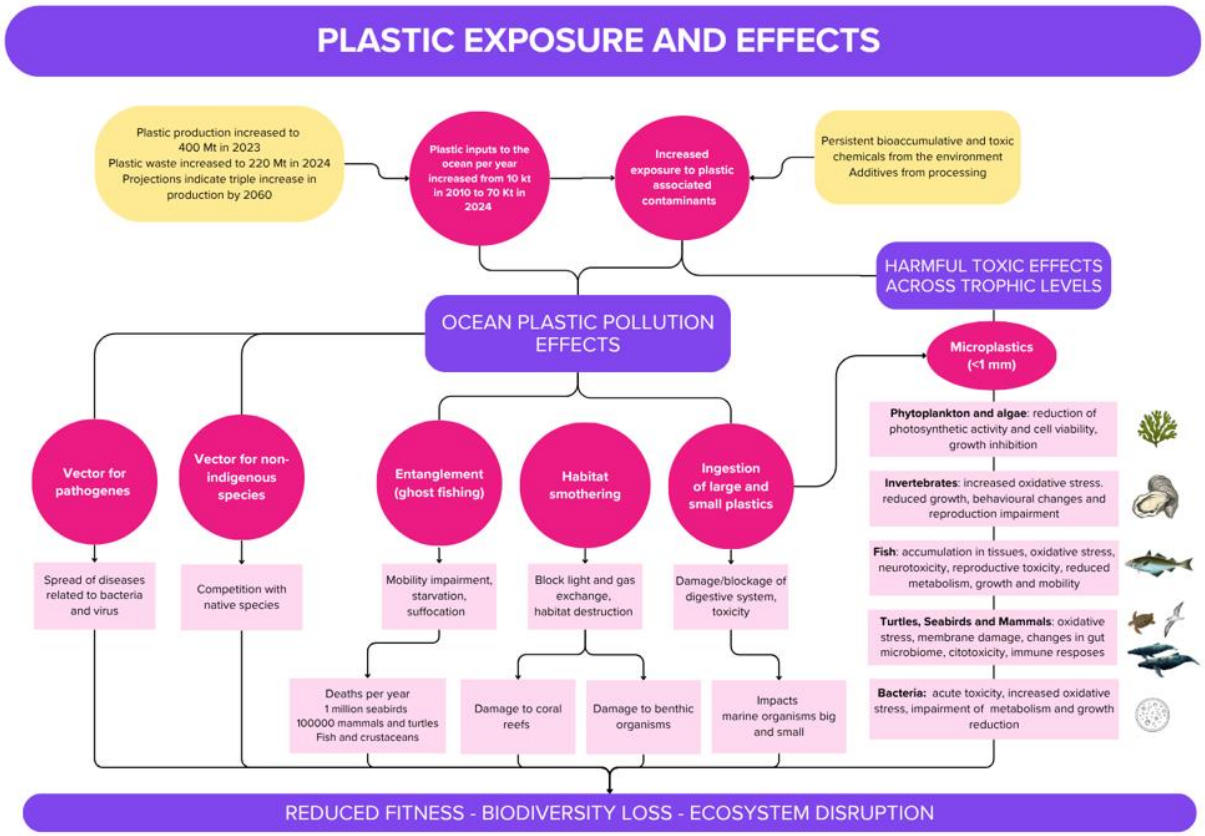


Figure 13: Ocean plastic pollution effects and interactions including toxic effects of microplastics across trophic levels (Figure: Paula Sobral, member of the writing team)

4. The Social, Economic, and Cultural Aspects Associated with Any Change

The social and economic costs of plastic pollution are significant, with tourism, fishing, and shipping sectors losing billions of US dollars annually due to reduced revenue and cleanup activities (UNEP, 2021). While efforts to collect and recycle valuable plastics exist, solutions must prioritise innovation in material science, eco-design, reuse, ~~recycling,~~ and durable alternatives to single-use plastics and modification in fishing gear configuration with recycling as the final option in the waste hierarchy. Challenges remain with "bioplastics," (Paul-Pont and others, 2023), which can release microplastics, oligomers and toxic chemicals with largely unknown health risks (Zimmerman and others, 2020). Improved waste management technologies, like AI and robotics, and public engagement in recycling and sustainable practices are essential steps forward (Fang and others, 2023).

Policies

There are a number of~~Among~~ global initiatives being considered at various forums including the ~~(G7, G20, UN Conventions, Ocean Decade),~~ negotiations on an international legally binding ~~treaty against~~instrument on plastic pollution, including in the marine environment ~~have started~~ (UNEA

Resolution 5/14). These represent~~ing~~ a crucial step towards economic and social transformation (CIEL, 2022; Lampitt and others, 2023; Maes and others, 2023; Syberg and others, 2024). Beside essential provisions on downstream measures such as advancements in waste management, the treaty ideally will apply a comprehensive plastic life cycle approach and also emphasise prevention, ~~by planning to set binding targets for reducing plastic production, enhancing recycling and supporting Extended Producer Responsibility schemes~~ aligning with SDGs 3, 6, 11, 14, and 15 and complementing existing governance structures (Maes and others, 2023). The UNEP Regional Seas Programme also addresses ocean degradation, fostering collaboration among 143 Member States~~countries~~ through 18 Regional Seas Conventions, 14 of which have in place regional plans to combat marine litter, some of them legally binding. These efforts are complemented by national and local action plans, and active NGO involvement.

Region-specific changes

There is a range in understanding of various factors across the different ocean basins (Table 4). Most scientific studies in recent years have shown no significant changes in the amounts of marine litter worldwide with many areas being classified as non-Good Environmental Status (United Nations Environment Programme, 2024), except in remote areas (Galgani et al., 2021). However, the implementation of management, reduction and prevention measures and good practices has demonstrated that certain components of plastic pollution have been decreasing in recent years (e.g., microplastics in the North Sea, Kuhn et al., 2023). More recently, bans on priority single-use plastics adopted in some regions have led to significant reductions in beach pollution, with decreases of up to 30% in areas such as Europe, Mediterranean and the USA (MSFD, 2024; United Nations Environment Programme, 2024; Papp et al., 2025).

Ocean	Sources/ distribution	Importance	Circulation	Impacts
Arctic Ocean	+++	+++	+++	++
North Atlantic, Baltic Sea and North Sea	++	++	+	+
Mediterranean Sea and Black Sea	+	+	+	+
South Atlantic Ocean	+++	++	++	+++
Indian Ocean	++	+++	++	+++
North Pacific	++	+	+	+
South Pacific	++	++	++	+++
Southern Ocean	++	++	++	++

Quantities of Plastic		Limted		moderate
		significant		important

Uncertainties/ Knowledge gaps	low	significant	critical
	+	++	+++

Table 4: Overview of the state of knowledge of marine litter in the different basins of the world ocean. (expert judgment, WOA3 Plastic pollution writing team). Atlantic Ocean includes the Caribbean Sea.

Knowledge and capacity changes

UNEP (2021), GESAMP (2019, 2021 & 2024), G7 and G20 (MoEFCC, 2023) support a comprehensive approach to assessing plastic pollution, focusing on monitoring, modelling, remote sensing, and socio-economic impacts. This includes developing global mass balance models (Borelle and others, 2020; Harris and others, 2023), conducting advanced life cycle impact analyses (Casagrande and others, 2024) which also takes ~~into~~ account of the economic and ecological costs of emissions and releases into environmental compartments, and exploring blockchain technology (Gong and others, 2022). Key components include standardizing methodologies, improving plastic flow tracking, and defining indicators from source to sea, as well as assessing the impact of marine litte~~r~~r' ~~s impact~~ on wildlife and socio-economic ~~effect~~s. Innovative approaches like monitoring ~~species~~ the biota on plastic, ingested microplastics, water-column micro- and ~~,~~ nano-plastics (Moon and others, 2024) and seafloor imagery are also crucial (Sandra and others, 2023), while GESAMP (2021) highlights data gaps on sea-based sources of marine litter and dumped plastics.

6. Radioisotopes

Key Message

- In the North--East Atlantic, discharges from nuclear power stations were assessed to have continued to decrease since 2015. Comparable statistics for other regions are not compiled.
-
- The growing demand for non-carbon electricity has increased reliance on nuclear power, likely leading to higher radioactive discharges.~~A key change is that the need for non-carbon electricity is increasing the demand for nuclear electricity, and consequently the related radioactive discharges.~~
-

Context

Radioisotopes in the ocean arise from both natural processes and anthropogenic inputs. Naturally occurring radioisotopes were examined in World Ocean Assessment I, and no new global assessment is available.

Developments since WOA II

Six main routes have led to anthropogenic inputs to the ocean of radioisotopes. ~~:~~

1. Inputs from nuclear weapons testing~~:~~
   These are purely historic. However, the consequences of nuclear weapons testing on the physical

and mental health of Pacific Islanders remains evident (Patel, 2024; Pineda and others, 2023).

~~3.~~

2. Inputs from nuclear disasters

~~:~~The most recent nuclear disaster was that at Tokyo Electric Power Company (TEPCO)'s Fukushima Daiichi Nuclear Power Station~~Fukushima~~ (March 2011). The preventive and multi-layered measures against contaminated water in the station were implemented based on three principles:

- Removing contamination sources.
- Redirecting ground water from contamination source.
- Preventing leakage of contaminated water.

Measures to prevent leakage of contaminated water include the installation of a sea-side impermeable wall and a groundwater drainage system. This was installed to stop groundwater from flowing into the port area and to pump it. These measures lead to the protection of the marine environment against pollution.

Japan has been analyzing all water prior to its discharge into the sea to ensure that all radionuclides, other than tritium, are removed using an Advanced Liquid Processing System (ALPS) and other systems, bringing concentrations below the regulatory standards. In addition, ALPS treated water has been discharged into the sea after being sufficiently diluted with seawater, while confirming that the concentration of tritium is below the regulatory standards. The IAEA concluded in its Comprehensive Report of July 2023 that the discharge of ALPS treated water into the sea is consistent with relevant international safety standards, and that the discharge will have a negligible radiological impact on people and the environment. (IAEA 2023a).~~This is continuing to lead to inputs of radioisotopes (mainly tritium) into the ocean, as water used for cooling the damaged plant and groundwater seeping into the site is treated and released. Such releases began in March 2024, in accordance with a plan evaluated by the International Atomic Energy Agency (IAEA) as consistent with relevant international safety standards and having a negligible radiological impact on people and the environment. Such discharges are likely to continue for 30 years (IAEA, 2023a; IAEA 2024a).~~

3. Inputs from nuclear power plants~~:~~

At the end of 2023, there were 413 nuclear power stations in operation worldwide, with a net electrical capacity of 373.7 gigawatts, compared with 450 with a capacity of 395 gigawatts at the end of 2018 (IAEA, 2024~~b~~). In the North~~-~~East Atlantic, discharges from nuclear power stations were assessed to have continued to decrease since 2015 (OSPAR 2023, OSPAR, 2024). Comparable statistics for other regions are not compiled.

Discharges of tritium in cooling water are generally a significant component of radioisotope discharges from nuclear power stations, although they have relatively low radiological impact

(Eyrolle and others, 2018). Industrial-scale abatement of tritium in such discharges is currently assessed as not technically feasible (OSPAR, 2023).

Substantial increases in nuclear electricity generation are forecast over the next decades, as a response to the need to reduce reliance on electricity from fossil fuels. The IAEA foresees a likely increase in worldwide nuclear electricity generating capacity from 371 gigawatts in 2022 to between 458 and 890 gigawatts in 2050 (IAEA, 2023b). Because tritium discharges from nuclear power plants are generally related to the level of activity, corresponding increases in tritium discharges are likely.

4. Inputs from nuclear fuel re-processing~~:~~

Where statistics are available, these remain substantially more significant than discharges from nuclear power plants (OSPAR, 2023). Six of the eight nuclear fuel reprocessing plants mentioned in WOA I and II remain in operation. The plants at Tokai (Japan) and Sellafield (United Kingdom) have ceased operation (JAEA, 2023, Sellafield 2022). The plant at Rokkasho~~a~~ (Japan) is planned to commence operations in 2026 (JNFL, 2024).

5. ~~Naturally Occurring Radioactive Material :~~ Inputs from ~~NORM~~Naturally Occurring Radioactive Material (NORM) industrial activities~~:~~

There is no evidence of any significant global change since 2018.

6. Nuclear medicine

~~:~~ There is no evidence of any significant global change since 2018. However, the medicinal radionuclide and radiopharmaceutical market, as well as the theranostics market, are expected to grow. Furthermore, an outpatient policy will mean an increased and uncontrolled excretion of radionuclides and their decay products into the environment (Pichler and others, 2025).

Changes in environmental conditions~~:~~

C~~c~~limate change impacts, and ocean acidification, will very likely have many effects on the impacts of radionuclides to the ecology of the marine environment. Sea-level rise, which exacerbates the impacts of cyclones and storm surges, will likely impact some nuclear power plants (NPPs), although to date most NPPs have continued to operate during storm ~~n~~events (Gwynn and others, 2024).

7. End Note

Although some positive changes have been documented because of the impact of regulation on emissions and discharges of all forms, it is apparent that the ocean contains a complex array of chemicals and materials ~~as a consequence~~due to ~~of~~ human activities on land and at sea. Despite concentrations of some legacy chemicals decreasing, those legacy chemicals remaining have been ‘added to’ by the new,

emerging contaminants ~~chemicals~~. This ~~enlarges the cocktail~~means that the ocean contains an increasing number of chemical types.

The mobile nature of the ocean and atmosphere mean that chemicals and materials are found far from their source. ~~This means that~~As a consequence, every geographical location on the planet is impacted to some extent by chemical contaminants.

Ultimately marine ~~plants and animals~~biota continue to be impacted by a vast array of chemicals, some carried on plastics as well as some that leach from plastics. Although our understanding of the impact of chemicals, including plastics, is improving, it remains extremely limited. However, there is a growing body of evidence that pollution has many adverse impacts that combine with other pressures on exposed marine ~~plants and animals~~biota. The cumulative effects of multiple types of pollution and other external pressures are resulting in significant changes to marine systems.

8. References

Adeleye, Xue, and others. Abundance, fate, and effects of pharmaceuticals and personal care products in aquatic environments. Journal of Hazardous Materials, vol. 424, art. 127284, 2022.

Adenaya, Quintero, and other. Vertical distribution and risk assessment of pharmaceuticals and other micropollutants in the southern North Sea coastla waters. Marine Pollution Bulletin, vol. 200, art. 116099, 2024.

Ali, Ronning, and others. Occurrence of pharmaceuticals and personal care products in effluent-dominated Saudi Arabian coastal waters of the Red Sea. Chemosphere, vol. 175, pp. 505-513, 2017.

Alygizakis, Gago-Ferrero, and others. Occurrence and spatial distribution of 158 pharmaceuticals,of abuse and related metabolites in offshore seawater. Science of the Total Environment, vol. 541, pp. 1097-1105, 2016.

AMAP (2021). The Impact of POPs in the Arctic. Arctic Monitoring and Assessment Programme

AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of climate change. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 2021.

Balakrishna, Praveenkumarreddy, and others. Occurrences of UV filters, endocrine disruptive chemicals, alkyl phenolic compounds, fragrances, and hormones in the wastewater and coastal waters of the Antarctica. Environmental Research, vol. 222, art. 115327, 2023.

Bergmann, Collard, and others. (2022): Plastic pollution in the Arctic , Nature Reviews Earth & Environment, vol. 3, pp. 323-337, 2022 .

Bobrowska-Korczak, Stawarska, and others. Determination of Pharmaceuticals, Heavy Metals, and Oxysterols in Fish Muscle. Molecules, vol. 26, No. 5, art. 1229, 2021.

Bohannon, Narizzano, and others. Next-generation PFAS 6:2 fluorotelomer sulfonate reduces plaque formation in exposed white-footed mice. Toxicological Sciences, vol. 192, No. 1, pp. 97 – 105, 2023.

Borgå, Gabrielsen, and others. Biomagnification of organochlorines along a Barents Sea food chain. Environmental Pollution, vol. 113, No. 2, pp. 187-198, 2001.

Borrelle, Ringma, and others. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science, vol. 369, No. 6510 pp. 1515–1518, 2020.

Burgeot, Mauffret, and others. Integrated biological effects and chemical contaminants approach: a case study. In: OSPAR 2023: The 2023 Quality Status Report for the North-East Atlantic, OSPAR Commission, London, 2023.

Caban, Magda and Piotr Stepnowski. How to decrease pharmaceuticals in the environment? A review. Environmental Chemistry Letters, vol. 19, pp 3115 – 3138, 2021.

Cagnazzi, Harrison, and others. Geographic and temporal variation in persistent pollutants in Australian humpback and snubfin dolphins. Ecological Indicators, vol. 111, art.105990, 2020.

Casa, van Mourik, and others. First detection of short-chain chlorinated paraffins (SCCPs) in humpback whales (*Megaptera novaeangliae*) foraging in Antarctic waters. Environmental Pollution, vol. 250, pp. 953 – 959, 2019.

Casagrande, Silva, and others. Ecotoxicity effect factors for plastic additives on the aquatic environment: a new approach for life cycle impact assessment. Environmental Pollution, vol. 341,122935, 2024.

Cedergreen, N. Quantifying synergy: A systematic review of mixture toxicity studies within environmental toxicology. PLoS One, vol. 9, No. 5, art. 96580, 2014.

Chakraborty, Adhikary, and others. Pharmaceuticals and Personal Care Products as Emerging Environmental Contaminants: Prevalence, Toxicity, and Remedial Approaches. ACS Chemical Health & Safety, vol. 30, pp. 362-388, 2023.

Chen, Chen, and others. Pharmaceuticals and personal care products in the seawater around a typical subtropical tourist city of China and associated ecological risk. Environmental Science and Pollution Research, vol. 28, pp. 22716-22728, 2021.

Chernova, Zhakovskaya, and others. Occurrence of pharmaceuticals in the Eastern Gulf of Finland (Russia). Environmental Science and Pollution Research vol. 28, 68871-68884, 2021.

Chitescu, Ene, and others. Emerging and Persistent Pollutants in the Aquatic Ecosystems of the Lower Danube Basin and North West Black Sea Region-A Review. Applied Sciences, vol. 11, No. 20, art. 9721, 2021.

Choi, Kim, and others. Ny-Alesund-oriented organic pollutants in sewage effluent and receiving seawater in the Arctic region of Kongsfjorden. Environmental Pollution, vol. 258, art. 113792, 2020.

Chynel, Munschy, and others. Legacy and emerging organic contaminants in two sympatric shark species from Reunion Island (Southwest Indian Ocean): Levels, profiles and maternal transfer. Science of the Total Environment, vol. 751, art. 141807, 2021.

CIEL. Towards a Global Treaty to End Plastic Pollution: Ensuring Meaningful and Effective Stakeholder Involvement in the Intergovernmental Environmental Negotiations. CIEL. Washington, DC, 2022.

Corinaldesi, Canensi, and others. Multiple impacts of microplastics can threaten marine habitat-forming species. Communications Biology, vol. 4, art. 431, 2021.

Cottom, Cook, and others. A local-to-global emissions inventory of macroplastic pollution. Nature, vol. 633, pp. 101–108, 2024.

Cousins, Johansson, and others. Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). Environmental Science and Technology, vol. 56, No. 16, pp. 11172 – 11179, 2022.

Cózar, Arias, and others. Proof of concept for a new sensor to monitor marine litter from space. Nature Communications, vol. 15, art. 4637, 2024.

Daliri, Martinez-Morcillo, and others. Occurrence and ecological risk assessment of antibiotic residues in urban wastewater discharged into the coastal environment of the Persian Gulf (the case of Bandar Abbas). Environmental Monitoring and Assessment, vol. 194, No. 12, art. 905, 2022.

Dasgupta, Peng, and others. Toxic anthropogenic pollutants reach the deepest ocean on Earth. Geochemical Perspectives Letters, vol. 7, art. 1814, 2018.

Dehm, Singh, and others. Screening of pharmaceuticals in coastal waters of the southern coast of Viti Levu in Fiji, South Pacific. Chemosphere, vol. 276, art. 130161, 2021.

Dietz, R. Contaminants in Marine Mammals in Greenland – with linkages to trophic levels, effects, diseases and distribution. Doctor's dissertation (DSc). National Environmental Research Institute, University of Aarhus, Denmark, 2008.

Dong, Zhang, and others. Occurrence and trophic transfer of polychlorinated naphthalenes (PCNs) in the Arctic and Antarctic benthic marine food web. Environmental Science and Technology, vol. 57, No. 44, pp. 17076 – 17086, 2023.

Downie, D. L., and T. Fenge. Northern lights against POPs: Combatting toxic threats in the Arctic. McGill-Queen's University Press, 2003.

Egger, Sulu-Gambari, and others. First evidence of plastic fallout from the North Pacific Garbage Patch. Scientific Reports, vol. 10, art. 7495, 2020.

Emnet, Gaw, and others. Personal care products and steroid hormones in the Antarctic coastal environment associated with two Antarctic research stations, McMurdo Station and Scott Base. Environmental Research, vol. 136, 331-342, 2015.

Environmental Working Group. PFAS contamination in U.S. drinking water. Retrieved from [EWG Website], 2022.

Esteves, Alves, and others. PCBs contamination in water and *Mytilus edulis* along the north Portuguese Atlantic Ocean coastline and analysis of potential carcinogenic risk to human health. Marine Pollution Bulletin, vol. 27, art. 116823, 2024.

Eyrolle, Ducros, and others. An updated review on tritium in the environment. Journal of Environmental Radioactivity, vol. 181, 128 – 137, 2018.

Falandysz, Jerzy and Alwyn R. Fernandes. Compositional profiles, persistency and toxicity of polychlorinated naphthalene (PCN) congeners in edible cod liver products from 1972 to 2017. Environmental Pollution, vol. 260, art. 114035, 2020.

Falandysz, Smith, and others. Dioxin-like polybrominated biphenyls (PBBs) and ortho-substituted PBBs in edible cod (*Gadus morhua*) liver oils and canned cod livers. Chemosphere, vol. 248, art. 126109, 2020.

Fang, Yu and others. Artificial Intelligence for waste management in smart cities: a review. Environmental Chemistry Letters, vol. 21, pp. 1959-1989, 2023.

Feo, Bagnati, and others. Pharmaceuticals and other contaminants in waters and sediments from Augusta Bay (southern Italy). Science of the Total Environment, vol. 739, art. 138927, 2020.

Galgani, Brien, and others. Are litter, plastic and microplastic quantities increasing in the ocean? Microplastics and Nanoplastics, vol. 1 art. 2, 2021.

Galgani, Angiolillo, and others. Marine Litter, Plastic, and Microplastics on the Seafloor. In Plastics and the Ocean: Origin, Characterization, Fate, and Impacts, Chap.6, pp.151-197, Anthony L. Andrady (Ed. Wiley), 2022.

Gao, Lai, and others. Toxicity evaluation and transcriptome analysis of yellowstripe goby (*Mugilogobius chulae*) in response to 2,7-dibromocarbazole exposure during early development. Toxics, vol. 12, No. 8, art. 609, 2024.

García-Pimentel, Campillo, and others. Occurrence and distribution of contaminants of legacy and emerging concern in surface waters of two Western Mediterranean coastal areas: Mar Menor Lagoon and Ebro Delta. Marine Pollution Bulletin, vol. 187, art. 114542, 2023.

Gauss, Travnikov, and others. EMEP MSC-W *Technical Report* 1/2024.

Ge, Wang, and others. Persistent organic pollutants (POPs) in deep-sea sediments of the tropical western Pacific Ocean. Chemosphere, vol. 277, art 130267, 2021.

GESAMP, 2019. Guidelines for the monitoring and assessment of plastic litter and microplastics in the ocean. In: Kershaw, P.J., Turra, A., Galgani, F. (Eds.). IMO/FAO/ UNESCO IOC/UNIDO/WMO/ IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Reports and Studies GESAMP 99, 130p.,

GESAMP, 2021. Sea based sources of marine litter. Report of the GESAMP Working Group 43. In: Gilardi, K. (ed.), IMO/UNESCO-IOC/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Reports and Studied GESAMP 108, p. 144.

GESAMP, 2024. Sea based sources of marine litter. Report of the GESAMP Working Group 43. In: Gilardi, K. (ed.), IMO/UNESCO-IOC/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Reports and Studied GESAMP in preparation.

Geyer, R. Production, Use, and Fate of Synthetic Polymers. In: Letcher, T.M., Ed., Plastic Waste and Recycling, Academic Press, 13-32, 2020.

Girones, Guida and others. Short- and medium-chain chlorinated paraffins in fish from an anthropized south-western Atlantic estuary, Bahía Blanca, Argentina. Chemosphere, vol. 328, art. 138575, 2023.

Gong, Wang, and others. Blockchain application in circular marine plastic debris management. Industrial Marketing Management, vol. 102, pp. 164 – 176, 2022.

Grimberg, Holsen, and others. Biotransformation of 6:2 fluorotelomer sulfonate (6:2 FTS) in sulfur-rich media by *Trametopsis cervina*. Frontiers in Environmental Science and Engineering, vol. 18, No. 9, art. 107, 2024.

Guo, Lv, and others. Profiling of the spatiotemporal distribution, risks, and prioritization of pharmaceuticals and personal care products in coastal waters of the northern Yellow Sea, China. Journal of Hazardous Materials, vol. 459, art. 132163, 2023(a).

Guo, Lv, and others. Occurrence, Distribution, and Trophic Transfer of Pharmaceuticals and Personal Care Products in the Bohai Sea. Environmental Science & Technology, vol. 57, 21823–21834, 2023(b).

Guo, Pan, and others. Persistent organic pollutants in food: Contamination sources, health effects and detection methods. International Journal of Environmental Research and Public Health, vol. 16, No. 22, art. 4361, 2019.

Gwynn, Hatje, and others. The effects of climate change on sources of radionuclides to the marine environment. Nature Communications, Earth and Environment, vol.5, art. 135, 2024.

Hannah, Megson, and others. A review of the mechanism of by-product PCB formation in pigment, dyes and paints. Science of the Total Environment, vol. 852, art. 158529, 2022.

Harris, Maes, and others. A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution. Continental Shelf Research, vol. 255, art. 104947, 2023.

HELCOM. PFOS and other PFASs in the Blatic Sea, BSEP No. 173, Helsinki Commission, Finland, 27 pp. 2020.

Horricks, Tabin,and others. Organic ultraviolet filters in nearshore waters and in the invasive lionfish *Pterois volitans* in Grenada, West Indies. Plos One, vol. 14, No. 7, art. e0220280, 2019.

Hu, Dingfei and Keri C. Hornbuckle. Inadvertent polychlorinated biphenyls in commercial paint pigments. Environmental Science & Technology, vol. 44, No. 8, 2822 – 2827, 2009.

Hu, Zhao, and others. Occurrence, bioaccumulation and potential risk of polyhalogenated carbazoles in marine organisms from the East China Sea. The Science of the Total Environment, vol. 807, No. 1, art. 150643, 2021.

Hu, Jiang, and others. Spatial distribution characteristics of carbazole and polyhalogenated carbazoles in water column and sediments in the open Western Pacific Ocean. Journal of Hazardous Materials, vol. 469, art. 133956, 2024.

Huang, Hu, and others. Analytical methods for microplastics in the environment: a review. Environmental Chemistry Letters, vol. 21, No. 1, pp 383-401, 2023.

Hutchinson, T.H. Hazardous chemicals and physical contaminants in the marine environment. In: Foresight, Future of the sea evidence review. Foresight, Government Office for Science, 2017.

IAEA 2023a. IAEA Comprehensive Report on the Safety Review of the ALPS-Treated Water at the Fukushima Daiichi Nuclear Power Station, International Atomic Energy Agency, Vienna, 2023.

IAEA 2023b. Energy, Electricity and Nuclear Power Estimates for The Period Up To 2050, International Atomic Energy Agency, Vienna, 2023.

~~IAEA 2024a. IAEA Review of Safety Related Aspects of Handling ALPS Treated Water at TEPCO's Fukushima Daiichi Nuclear Power Station: Report on the Mission to Japan conducted in April 2024, International Atomic Energy Agency, Vienna, 2024.~~

IAEA 2024b. IAEA Power Reactor Information System at https://pris.iaea.org/PRIS/ (accessed 3 September 2024).

Isobe, Azume, and others. A multilevel dataset of microplastic abundance in the world's upper ocean and the Laurentian Great Lakes. Microplastics and Nanoplastics, vol. 1, art. 16, 2021.

Isobe, Atsuhiko and Shinsuke Iwasaki. The fate of missing ocean plastics: Are they just a marine environmental problem? Science of the Total Environment, vol. 825, No. 15, art. 153935, 2022.

JAEA 2023 – Japan Atomic Energy Agency Annual Report 2022/2023, at https://www.jaea.go.jp/english/publication/annual_report/2023.pdf (accessed 21 August 2024).

JNFL 2024 – Japan Nuclear Fuel Ltd website "Reprocessing" at https://www.jnfl.co.jp/en/business/reprocessing/ (accessed 21 August 2024).

Johansson, J. and E. Undeman. Perfluorooctane sulfonate (PFOS) and other perfluorinated alkyl substances (PFASs) in the Baltic Sea – Sources, transport routes and trends. Helcom Baltic Sea Environment Proceedings, vol. 173, 2020.

Jucyte-Cicine, Lorre, and others. Coastal wastewater treatment plants as a source of endocrine disrupting micropollutants: a case study of Lithuania in the Baltic Sea. Marine Pollution Bulletin, vol. 200, art. 116084, 2024.

Kaandorp, Lobelle, and others. Global mass of buoyant marine plastics dominated by large long-lived debris. Nature Geoscience, vol. 16, pp. 689–694, 2023.

Kesic, Elliott, and others. Perfluoroalkyl substances in seabird eggs from Canada's Pacific Coast: Temporal trends (1973–2019) and interspecific patterns. Environmental Science and Technology, vol. 57, No. 29, pp. 10792 – 10803, 2023.

Khan, Burgess, and others. Occurrence and bioaccumulation patterns of per- and polyfluoroalkyl substances (PFAS) in the marine environment. ACS ES&T Water, vol. 3, No. 5, 1243 – 1259, 2023.

Klimczak, Liu, and others. An updated global overview of the manufacture and unintentional formation of polychlorinated naphthalenes (PCNs). Journal of Hazardous Materials, vol. 457, art. 131786, 2023.

Korkmaz, Savun-Hekimoglu, and others. Occurrence, sources and environmental risk assessment of pharmaceuticals in the Sea of Marmara, Turkey. Science of the Total Environment, vol. 819, art. 152996, 2022.

Kucharski, Nalecz-Jawecki, and others. The assessment of environmental risk related to the occurrence of pharmaceuticals in bottom sediments of the Odra River estuary (SW Baltic Sea). Science of the Total Environment, vol. 828, art. 154446, 2022.

Kühn, Van Franeker, and Van Loon. Plastic Particles in Fulmar Stomachs in the North Sea. In: OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic. OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr2023/indicator-assessments/plastic-in-fulmar, 2023.

Lampitt, Fletcher, and others. Stakeholder alliances are essential to reduce the scourge of plastic pollution. Nature Communications vol. 14, art. 2849, 2023.

Langberg, Breedveld, and others. Bioaccumulation of fluorotelomer sulfonates and perfluoroalkyl acids in marine organisms living in aqueous film-forming foam impacted waters. Environmental Science & Technology, vol. 53(18), pp. 10951 – 10960, 2019.

Lebreton, van der Zwet, and others. River plastic emissions to the world's oceans. Nature Communications, vol. 8, art. 15611, 2017.

Leistenschneider, Wolinski, and others. A critical review on the evaluation of toxicity and ecological risk assessment of plastics in the marine environment. Science of the Total Environment, vol. 896, art. 164955, 2023.

Li, Chen and others. What do we know about the production and release of persistent organic pollutants in the global environment? Environmental Science Advances, vol. 2, No. 1, 55-68, 2023.

Liu, Jia, and others. Distribution, composition and ecological risk of surface sedimental polychlorinated naphthalenes in the East China Sea, Marine Pollution Bulletin, vol. 135, pp. 90 – 94, 2018.

Liu, Zhang, and others. A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms, Environment International, vol. 146, art. 106277, 2021

Lu, Wang, and others. Comprehensive profiling of the distribution, risks and priority of pharmaceuticals and personal care products: A large-scale study from rivers to coastal seas. Water Research, vol. 230, art. 119591, 2023.

Luarte, Gomez-Aburto, and others. Levels of persistent organic pollutants (POPs) in the Antarctic atmosphere over time (1980 to 2021) and estimation of their atmospheric half-lives. Atmospheric Chemistry and Physics, vol. 23, No. 14, 8103 – 8118, 2023.

Lyu, Fang, and others. Bioaccumulation of emerging persistent organic pollutants in the deep-sea cold seep ecosystems: Evidence from chlorinated paraffin. Journal of Hazardous Materials, vol. 445, art. 130472, 2023.

Maes, Wienrich, and others. A little less conversation: How existing governance can strengthen the future global plastics treaty. Cambridge Prisms: Plastics,vol. 1, art. e22, 2023.

Maghsodian, Sanati, and others. Occurrence and Distribution of Antibiotics in the Water, Sediment, and Biota of Freshwater and Marine Environments: A Review. Antibiotics, vol. 11, No. 11, art. 1461, 2022.

Meijer, van Emmerink, and others. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, vol. 7, No. 18, art. 5803, 2021.

Mezzelani, M. and F. Regoli. The biological effects of pharmaceuticals in the marine environment. Annual Reviews, vol. 14, 105-128, 2022.

Mikolajczyk, Warenik-Bany, and others. PCDD/Fs and PCBs in Baltic fish – Recent data, risk for consumers. Marine Pollution Bulletin, vol. 171, art. 112763, 2021.

Ministry of the Environment, Japan 2024, Atlas of Ocean MIcroplastics (AOMI), https://aomi.env.go.jp/, 2024.

Mirzaie, Teymori, and others. Occurrence and distribution of azithromycin in wastewater treatment plants, seawater, and sediments of the northern part of the Persian Gulf around Bushehr port: A comparison with Pre-COVID 19 pandemic. Chemosphere, vol. 307, No. 4, art. 135996, 2022.

MoEFCC. G20 Report on Actions Against Marine Plastic Litter. Fifth Information Sharing Based on the G20 Implementation Framework. Ministry of Environment, Forest and Climate Change, New Delhi, India. 1st Edition. 575 pp, 2023.

Mollier, Bustamante, and others. Blood kinetics of lipophilic and proteinophilic pollutants during two types of long-term fast in king penguins. Environmental Science and Technology, vol. 58, No. 14, 6138 – 6148, 2024.

Montano, Pironti, and others. Polychlorinated biphenyls (PCBs) in the environment: Occupational and exposure events, effects on human health and fertility. Toxics, vol. 10, No. 7, art. 365, 2022.

Morales-Caselles, Viejo, and others. An inshore–offshore sorting system revealed from global classification of ocean litter. Nature Sustainability, vol. 4, 484–493, 2021.

MSFD TECHNICAL GROUP ON MARINE LITTER. European Coastline Macro Litter Trends 2015 - 2021, Publications Office of the European Union, Luxembourg, 2024.

Muir, Bossi, and others. Levels and trends of poly- and perfluoroalkyl substances in the Arctic environment – An update. Emerging Contaminants, vol. 5, 240 – 271, 2019.

Nakajima, Tsuchiya, and others. Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the North West Pacific. Marine Pollution Bulletin, vol. 166, art. 112188, 2021.

National Academies of Science, Engineering and Medicine. The role of seafood consumption in child growth and development. Washington, DC: The National Academies Press, 2024.

Nature Communications (2020). Climate change and the remobilization of legacy POP.

Nyberg, Harris and others. Leaving a plastic legacy: Current and future scenarios for mismanaged plastic waste in rivers, Science of The Total Environment, vol. 869, art. 161821,2023.

Ohoro, Adeniji, and others. Occurrence and distribution of pharmaceuticals in surface water and sediment of Buffalo and Sundays River estuaries, South Africa and their ecological risk assessment. Emerging Contaminants, vol. 7, 187-195, 2021.

Ojemaye, Onwordi, and others. Presence and risk assessment of herbicides in the marine environment of Camps Bay (Cape Town, South Africa). Science of the Total Environment, vol. 738, art. 140346, 2020.

Orr, Macaulay, and others. Studying interactions among anthropogenic stressors in freshwater ecosystems: A systematic review of 2396 multiple-stressor experiments. Ecology Letters, vol. 27, art. 14463, 2024.

OSPAR 2023. Radioactive Substances Committee Thematic Assessment. In: OSPAR: Quality Status Report 2023. OSPAR Commission, London, 2023.

OSPAR 2024. Annual Report and Assessment of Discharges of Liquid Discharges from Nuclear Installations in 2022, OSPAR Commission, London, 2024.

Paul-Pont, Ghiglione, and others. Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. Waste Management, vol. 157, pp. 242-248, 2023.

Papp, Anna and Kimberley L. Oremus. Plastic bag bans and fees reduce harmful bag litter on shorelines. Science, vol. 388, No. 6753, art. 9274, 2025.

Patel, Rohan. Aftermath of nuclear testing in the Pacific Islands. Global Oncology, vol. 10, art. 455, 2024.

Pawłowska, Barbara and Robert Biczak. Drugs in the environment - Impact on plants: A review. Environmental Toxicology and Pharmacology, vol. 111, art. 104557, 2024.

Peng, Chen, and others. Microplastics contaminate the deepest part of the world's ocean. Geochemical Perspectives Letters, vol. 9, pp. 1-5, 2018.

Pereira, da Silva, and others. Persistent organic pollutants and polycyclic aromatic hydrocarbons in livers of stranded *Arctocephalus australis* in southern Brazilian beaches. Marine Pollution Bulletin, vol. 200, art. 116129, 2024.

Perfetti-Bolaño, Muñoz, and others. Analysis of the contribution of locally derived wastewater to the occurrence of Pharmaceuticals and Personal Care Products in Antarctic coastal waters. Science of the Total Environment, vol. 851, No. 1, art. 158116, 2022.

Pickard, Criscitiello, and others. Continuous non-marine inputs of per- and polyfluoroalkyl substances to the High Arctic: a multi-decadal temporal record. Atmospheric Chemistry and Physics, vol. 18, No. 7, 5045 – 5058, 2018.

Pichler, Martinho, and others. The environmental impact of medical imaging agents and the roadmap to sustainable medical imaging. Advanced Science, vol. 12, art. 2404411, 2025.

Pierdomenico, Bernhardt, and others. Transport and accumulation of litter in submarine canyons: a geoscience perspective, Frontiers in Marine Science, vol. 10, art. 1224859, 2023.

Pineda, Benavente, and others. Cancer disparities among Pacific Islanders: A review of sociocultural determinants of health in the Micronesian region. Cancers, vol. 15, No. 5, art. 1392, 2023.

Pinheiro, MacDonald, and others. Plastic pollution on the world's coral reefs. Nature, vol. 619, pp. 311–316, 2023.

Pirotta, Thomas, and others. Understanding the combined effects of multiple stressors: A new perspective on a long-standing challenge. Science of the Total Environment, vol. 821, art. 153322, 2022.

Remili, Letcher, and others. Individual prey specialization drives PCBs in Icelandic killer whales. Environmental Science & Technology, vol. 55, No. 8, 4923 – 4931, 2021.

Remili, McKinney, and others. Legacy persistent organic pollutants among multiple cetacean species in the Northwest Atlantic. Science of the Total Environment, vol. 954, art. 176746, 2024.

Rieger, Olmedo, and others. Seasonal hotspots of beach litter in the North-East Atlantic linked to aquaculture and river runoff. Communications Earth and Environment, vol. 5, art. 751, 2024.

Routti, Attwood, and others. State of knowledge on current exposure, fate and potential health effects of contaminants in polar bears from the circumpolar Arctic, vol. 664, 1063 – 1083, 2019.

Sandra, Devriese, and others. A systematic review of state-of-the-art technologies for monitoring plastic seafloor litter. Journal of Ocean Engineering and Science, In press, Corrected Proof, 2023 (https://doi.org/10.1016/j.joes.2023.07.004).

Savvidou, Sha, and others. Horizontal and vertical distribution of perfluoroalkyl acids (PFAAs) in the water column of the Atlantic Ocean. Environmental Science and Technology Letters, vol. 10, No. 5, 418 – 424, 2023.

Moon, Martin, and others. Direct observation and identification of nanoplastics in ocean water. Science Advances, vol. 10, No. 4, art. 1675, 2024.

Sellafield 2022. Press Notice by Nuclear Decommissioning Authority and Sellafield Ltd, 17 May 2022 at https://www.gov.uk/government/news/operations-to-end-at-sellafields-magnox-reprocessing-plant, accessed 21 August 2024.

Shan, Qian, and others. Legacy and emerging per- and poly-fluoroalkyl substances in surface seawater from northwestern Pacific to Southern Ocean: Evidences of current and historical release. Journal of Hazardous Materials, vol. 411, art. 125049, 2021.

Sobek, Abel, and others. Organic matter degradation causes enrichment of organic pollutants in hadal sediments. Nature Communications, vol. 14, art. 2012, 2023.

Sonke, Koenig, and others. A mass budget and box model of global plastics cycling, degradation and dispersal in the land-ocean-atmosphere system. Microplastics and Nanoplastics, vol. 2, art. 28, 2022.

Stockholm Convention on Persistent Organic Pollutants (POPs). UN Environment Programme. https://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx, 2023.

Stockholm Convention Secretariat (2020). POPs Global Monitoring Plan. Retrieved from [Stockholm Convention Secretariat Website].

Suaria, Achtypi, and others. ,Microfibers in oceanic surface waters: A global characterization. Science Advances, vol. 6, No. 23, art. 8493, 2020.

Syberg, Almroth, and others. Informing the Plastic Treaty negotiations on science - experiences from the Scientists' Coalition for an Effective Plastic Treaty. Microplastics and Nanoplastics, vol. 4, art. 14, 2024.

Tamis, Koelmans, and others. Environmental risks of car tire microplastic particles and other road runoff pollutants. Microplastics and Nanoplastics, vol. 1, art. 10. 2021.

Thompson, Courtene-Jones, and others. Twenty years of microplastics pollution research—what have we learned? Science, vol. 386, No. 6720, art. adl2746, 2024.

Tlili, Sofiene and Catherine Mouneyrac. New challenges of marine ecotoxicology in a global change context. Marine Pollution Bulletin, vol. 166, art. 112242, 2021.

Travnikov, Gačnik, and others. Assessment of transboundary pollution with heavy metals and POPs. EMEP Status Report, 2/2024, pp117, 2024.

Turner, Andrew. PBDEs in the marine environment: Sources, pathways and the role of microplastics. Environmental Pollution, vol. 301, art. 118943, 2022.

Undeman, Rasmusson, and others. Micropollutants in urban wastewater: large-scale emission estimates and analysis of measured concentrations in the Baltic Sea catchment. Marine Pollution Bulletin vol. 178, art. 113559, 2022.

UNEP. Global chemicals outlook II: From legacies to innovative Solutions: Implementing the 2030 Agenda for Sustainable Development. United Nations Environment Programme, 2019.

United Nations World Ocean Assessment II. Chapter 11, Changes in liquid and atmospheric inputs to the mariner environment from land (including through groundwater), ships and offshore installations, 2020.

United Nations Environment Programme. From Pollution to Solution: A global assessment of marine litter and plastic pollution. Nairobi, 148 pp, 2021.

United Nations Environment Programme. Mediterranean Quality Status Report: The state of the Mediterranean Sea and Coast from 2018-2023. Athens, 2024.

UNEP. Global Report on Persistent Organic Pollutants. Retrieved from [UNEP Website], 2022.

Unyimadu, John P. and Nsikak U. Benson. Polychlorinated biphenyls (PCBs) in intertidal sediment and water from Lagos lagoon: Baseline report on occurrence, distribution and ecotoxicological risk assessment. Journal of Hazardous Materials Advances, vol. 12, art. 100372, 2023.

Webster, Lynda and Rob Fryer. Status and Trends of Polychlorinated Biphenyls (PCB) in Fish, Shellfish and Sediment. In: OSPAR, 2023: The 2023 Quality Status Report for the North-East Atlantic, OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/indicator-assessments/pcb-biota-sediment, 2022.

Weis, De Falco, and others. Polluting Textiles: The Problem with Microfibres. Routledge Publications, London, UK, 302 pp, 2022.

Wells, Coggan, and others. Per- and polyfluoroalkyl substances (PFAS) in little penguins and associations with urbanisation and health parameters. Science of the Total Environment, vol. 912, art. 169084, 2024.

WHO 2018. Persistent organic pollutants: Impact on child health. World Health Organization, 2018.

WHO 2021. Public Health Impact of POPs. World Health Organization, 2021.

Wilkinson, Boxall, and others. Pharmaceutical pollution of the world's rivers. Proceedings of the National Academy of Sciences of the United States of America, vol. 119, No. 8, art. 2113947119, 2022.

Williams, Brownlow, and others. Spatiotemporal trends spanning three decades show toxic levels of contaminants in marine mammals. Environmental Science and Technology, vol. 57, 20736 – 20749, 2023.

Wilschnak, Cartmell, and others. Septic tanks as a pathway for emerging contaminants to the aquatic environment–Need for alternative rural wastewater treatment? Environmental Pollution, vol. 362, art. 124988, 2024.

Wu, Tan, and others. From sediment to top predators: Broad exposure of polyhalogenated carbazoles in San Francisco Bay (U.S.A.). Environmental Science and Technology, vol. 51, No. 4, 2038 – 2046, 2017.

Wu, Wu, and others. Polychlorinated diphenyl ethers in the environment: A review and future perspectives. International Journal of Environmental Research and Public Health, vol. 20, No. 5, art. 3982, 2023.

Yang, Zhou, and others. Anthropogenic impacts on the contamination of pharmaceuticals and personal care products (PPCPs) in the coastal environments of the Yellow and Bohai seas. Environment International, vol. 135, art. 105306, 2020.

Yeo, Takada, and others. PCBs and PBDEs in microplastic particles and zooplankton in open water in the Pacific Ocean and around the coast of Japan. Marine Pollution Bulletin, vol. 151, art. 110806, 2020.

Zacs, Perkons, and others. Polychlorinated naphthalenes (PCNs) in food products in Latvia: Congener-specific analysis, occurrence, and dietary exposure of the general population. Chemosphere, vol. 264, No. 1, art. 128460, 2021.

Zandaryaa, Sarantuyaa and Dmitry Frank-Kamenetsky. A source-to-sea approach to emerging pollutants in freshwater and oceans: pharmaceuticals in the Baltic Sea region. Water International, vol. 46, No. 2. 195-210, 2021.

Zhang, Wu, and others. Plastic waste discharge to the global ocean constrained by seawater observations. Nature Communications, vol. 14, art. 1372, 2023.

Zhao, Zettler, and others. Large quantities of small microplastics permeate the surface ocean to abyssal depths in the South Atlantic Gyre. Global Change Biology, vol. 28 No. 9, pp. 2991-3006, 2022.

Zhao, Mincer, and others. Pelagic microplastics in the North Pacific Subtropical Gyre: A prevalent anthropogenic component of the particulate organic carbon pool. PNAS Nexus, vol. 2, No.3, art. pgad070, 2023.

Zhao, Kvale, and others. The distribution of subsurface microplastics in the ocean. Nature, vol. 641, 51-61, 2025.

Zimmermann, Dombrowski, and others. Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition. Environment International, vol. 145, art. 106066, 2020.

Section 5 Socio-ecological systems (introduction)

The ocean is more than just a vast body of water—it is a dynamic, interconnected system where human societies and natural ecosystems are deeply interconnected~~in which human societies and natural ecosystems are deeply intertwined~~. Our activities, from fishing and shipping to tourism and energy production, have a profound impact on marine ecosystems~~leave an undeniable imprint on the marine environment~~. At the same time, the ocean's health determines the well-being of communities worldwide, influencing food security, livelihoods, and even public health. This section explores the complex socio-ecological systems of the ocean, emphasizing that sustainable management involves both conserving nature and ensuring the well-being of communities that rely on the ocean for their livelihoods~~recognising that sustainable management is not just about conserving nature but also about ensuring that people, especially those who depend on the ocean for their way of life, can thrive~~.

The challenges facing our oceans today are multi-faceted. Pollution, habitat destruction, overfishing, and climate change place significant strain on marine ecosystems~~all exert immense pressure on marine ecosystems~~. Meanwhile, social and economic factors, such as demographic shifts, governance structures, and technological advances, shape how these pressures play out. The ocean is also a source of opportunity, with emerging solutions offering pathways to a more sustainable and inclusive future. This section aims to provide a holistic perspective on these issues, assessing both risks and opportunities while proposing practical solutions~~considering the risks and opportunities and identifying practical ways to move forward~~.

This section aims not only to document the challenges but also to identify meaningful solutions. By integrating scientific insights, case studies, and socio-economic considerations, this section outlines a roadmap for a future where both people and the ocean prosper~~Through scientific knowledge, real-world case studies, and a focus on social and economic realities, it aims to provide a roadmap to a future where both people and the ocean can thrive together~~.

The first part of this section focuses on ocean economies—how we use marine resources and the systems in place to govern them. It examines key sectors such as fisheries and aquaculture, food trade, energy, shipping, tourism, biotechnology, and coastal development, examining their impact on marine ecosystems and strategies for achieving sustainability~~outlining their pressures on marine environments and how they can evolve to become more sustainable~~.

The concept of a "sustainable and inclusive ocean economy" emphasizes the integration of economic growth, environmental stewardship, and social well-beingrecognises that economic growth and environmental stewardship must go hand in hand with social and individual well-being. Each subchapter applies the concept of Sustainability Pathways to outline strategies for achieving the SDGs, including ecosystem restoration, governance improvements, and sustainable marine resource management for future generationsEach subchapter uses the concept of Sustainability Pathways to set out a viable pathway to achieving the SDGs by implementing successful policies and innovations to restore degraded ecosystems, improve governance, and ensure that marine resources continue to support people and nature for generations to come.

The second part of this section is organized within the framework of "One Health", a holistic approach that sustainably balances and optimizes the health of humans, animals, and ecosystemsan integrated and unifying approach which sustainably balances and optimises the health of people, animals and ecosystems. It recognises that the health of humans, domestic and wild animals, plants and ecosystems are intrinsically connected and interdependent are intrinsically linked while also being interdependent (OHHLEP, 2022). It highlights the importance of a thriving ocean for biodiversity and human health, including access to safe seafood, clean water, and mental well-beingacknowledges that a thriving ocean is essential for marine biodiversity and human health—through safe seafood, clean water, and even mental well-being. Issues such as marine pollution, zoonotic diseases, and the role of coastal ecosystems in carbon sequestration are encompassed within this broad frameworkall come under this broad umbrella.

Equity, gender, justice, and knowledge-sharing are key to shaping sustainable ocean futures. This section will also explore how global challenges, such as pandemics, climate-related disasters, and environmental injustices, affect communities differently. It will highlight the importance of considering Indigenous Peoples', Traditional Owner and Local Community Knowledges in building the evidence base for decision-making and how we can ensure that ocean governance is fair and inclusive.

References

One Health High-Level Expert Panel (OHHLEP), Adisasmito WB, Almuhairi S, Behravesh CB, Bilivogui P, Bukachi SA, et al. (2022) One Health: A new definition for a sustainable and healthy future. PLoS Pathog 18(6): e1010537. ttps://doi.org/10.1371/journal.ppat.1010537

Section 5A A sustainable and inclusive ocean economy (introduction)

This section on the Sustainable and Inclusive Ocean Economy consists of ten chapters, addressing key ocean sectors, the impacts of human activities, socio-economic factors, governance frameworks, and sustainability pathways aligned with global sustainability and inclusivity.~~The Sustainable and Inclusive Ocean Economy section includes ten chapters, covering key ocean sectors, the pressures of human activities on the ocean, socio-economic considerations, sector-relevant governance, and sustainability pathways aligned with global sustainability and socio-economic inclusivity~~. Chapter 1 focuses on the marine food systems and consisted of six subchapters.~~Chapter 1 focuses on the marine food systems and consisted of six subchapters~~. The sustainable management of medium and large-scale fisheries, as highlighted in Chapter 1A, is critical due to their substantial ecological and economic impacts. This chapter examines the severe environmental pressures caused by overfishing and habitat destruction, emphasizing the need for robust governance mechanisms, such as ecosystem-based management and stakeholder collaboration, to facilitate a transition to sustainable practices.~~The chapter highlights severe environmental pressures from overfishing and habitat destruction and underscores the need for robust governance mechanisms such as ecosystem-based management and stakeholder collaboration to transition towards sustainable practices~~. Conversely, small-scale fisheries and aquaculture, discussed in subchapters~~Chapters~~ 1B and 1D, provide essential contributions to food security, livelihoods, and cultural heritage. These chapters focus on the socio-economic importance of small-scale fisheries and aquaculture, which face threats from environmental changes. These chapters emphasize governance strategies that integrate community-based approaches including ecosystem-based management and traditional knowledge to improve resilience and promote fair resource management.

~~They emphasize governance strategies integrating community-based approaches and traditional knowledge to enhance resilience and promote equitable resource management~~.

The role of emerging technologies and the challenges of climate change in aquaculture are explored in Chapter 1C. Pressures from technological advances and climate impacts on medium and large-scale aquaculture, affecting social acceptability and ecological balance, are covered in the chapter. This chapter discusses these pressures, highlighting the importance of governance that actively engages local communities and applies data-driven management strategies.~~It highlights the importance of governance that engages local communities and implements data-driven management~~. subchapters~~Chapters~~ 1E and 1F focus on the processing and trade of seafood, integral components of the ocean economy that link production to global markets. Implementing sustainable practices in these sectors is crucial to minimizing environmental impacts, ensuring economic stability, and advancing multiple SDGs.~~Sustainable practices in these areas are vital for reducing environmental impacts and supporting economic stability, aligning with multiple SDGs~~. These chapters examine the environmental impacts and resource depletion linked to seafood processing, emphasizing the need for governance that enforces strict processing standards and trade regulations.

~~Environmental impacts and resource depletion in seafood processing, requiring governance that enforces strict processing standards and trade regulations, are covered in these chapters.~~

Recreational fishing and the energy sector, including both renewable and non-renewable sources (Chapters 2, subchapters 3A~~,~~ and 3B), highlight the diverse uses of ocean spaces. Recreational Chapter 2 examines the ecological and socio-economic impacts of increased recreational fishing activities in marine environments, while subchapters~~Chapters~~ 3A and 3B contrast the carbon reduction potential of renewable energy with the environmental challenges posed by non-renewables.

~~Fishing (Chapter 2) covers the ecological and socio-economic pressures from increased recreational activities in marine environments, while the Renewables and Non-renewable Energies chapters (Chapters 3A and 3B) contrast the potential of renewable energy to reduce carbon emissions with the environmental challenges of non-renewables~~.

The impacts of tourism, the potential of marine genetic resources, and the sustainability challenges in shipping are elaborated in Chapters 4, 5, and 6. Chapter 4 highlights tourism's dual role as an economic driver and environmental stressor, presenting governance strategies aimed at mitigating its negative effects through sustainable practices and fostering eco-friendly tourism models that benefit local communities.~~Tourism's dual role as an economic pillar and environmental stressor is highlighted in Chapter 4, with governance strategies focusing on reducing impacts through sustainable practices and promoting eco-friendly tourism models that benefit local communities.~~ Chapter 5 explores the utilization of marine genetic resources, emphasizing governance frameworks that safeguard biodiversity and promote equitable benefit-sharing.~~Marine Genetic Resources (Chapter 5) explores the utilization of marine genetic resources and highlights governance frameworks that ensure biodiversity conservation and fair benefit-sharing~~. Chapter 6 examines the significant environmental impacts of the shipping industry, stressing the urgent need for decarbonization strategies.

~~Shipping (Chapter 6) covers its significant environmental impacts, including the urgent need for decarbonization strategies.~~

Chapters 7 and 8 cover the emerging issues around marine mineral resources and the increasing reliance on desalination. The complex challenges of extracting marine minerals and the importance of sustainable practices and international cooperation are highlighted in Chapter 7. Desalination and Salt Production (Chapter 8) highlights technological and environmental challenges facing the sector and the role of technologies that reduce energy consumption and manage waste effectively.

Finally, the themes of sustainable coastal development and the cautious approach to geoengineering are presented in Chapters 9 and 10. In the Coastal Development chapter (Chapter 9),~~,~~ pressures from urbanization and economic activities in coastal zones are discussed, along with the need for sustainable management strategies that protect ecological health and enhance disaster resilience. Geoengineering's contentious aspects as a climate mitigation approach are covered in Chapter 10, which underscores the need for careful governance and international collaboration.

Section 5A Chapter 1: Food systems (introduction)

Food systems are facing a significant challenge: providing sustainable global food security and nutrition for a population that is expected to reach almost 10 billion by 2050~~Food systems face a colossal challenge as they have to provide sustainable global food security and nutrition for a population that is expected to reach nearly 10 billion by 2050~~. Food systems are heavily influenced by climate change, overfishing, infrastructure development and ecosystems degradation. They also contribute significantly to global climate change and biodiversity loss. ~~Food systems are significantly affected by climate change, overfishing, infrastructure development and ecosystem degradation, and are also major contributors to global climate change and biodiversity loss.~~ A food system is defined as all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes (HLPE, 2014).

Seafood sourced from wild fisheries and marine aquaculture accounts for around 20% of the animal protein and 6.7% of the total protein consumed by humans worldwide.~~Seafood is produced from wild fisheries and marine aquaculture and currently accounts for about 20 per cent of animal protein and 6.7 per cent of all protein consumed by humans worldwide.~~ Of the total aquatic animal production (i.e. 223.2 million tonnes), 89 percent is used for human consumption (FAO, 2024). Marine food systems also provide livelihoods for many millions of people along the food supply chain and are strongly linked to cultural heritage and identity. As the world's population grows and average incomes rise, the demand for seafood will continue to increase. However, increasing seafood production depends on many environmental, ecological, social, economic, regulatory/governance and technological factors, as well as the complex interactions between them ~~However, the ability to significantly increase the amount of food coming from the sea will depend on a wide range of environmental, ecological, social, economic, regulatory/governance and technological factors and their complex interactions~~ (Alexander and Kelly, 2024).

Given the significance of marine food systems, WOA III includes a deeper analysis, introducing new subchapters on food processing and trade.~~Because of the importance of marine food systems, it was decided that WOA III would take a more in-depth look at these systems, including, for example, new sub-chapters dedicated to food processing and trade.~~ Chapter 1 comprises six subchapters:~~Accordingly, Chapter 1 is a collection of the following six sub-chapters~~: (1a) Medium and large-scale fisheries, (1b) Small-scale fisheries including subsistence fisheries, (1c) Medium and large-scale aquaculture, (1d) Small-scale aquaculture, (1e) Food processing and (1f) Trade. These subchapters offer an updated assessment and outline key challenges in achieving sustainable marine food systems~~These six sub-chapters provide an up-to-date assessment and identify the challenges that need to be overcome to achieve sustainable marine food systems~~.

References 34

Alexander KA, Kelling I. 2024. Social sustainability in seafood systems: a rapid review. *Cambridge Prisms: Coastal Futures*; 2:e1. doi:10.1017/cft.2023.31

FAO. 2024. The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome. https://doi.org/10.4060/cd0683en

HLPE, 2014. Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014.
https://openknowledge.fao.org/server/api/core/bitstreams/b1949fae-23d4-473c-8b87-18c4359b74d6c/content

Section 5
Sub-chapter 1A: Medium and large scale fishing

Coordinating Author

U. Rashid Sumaila

Writing Team

Farheen Ahmad, Shehu Akintola, Priyal Bunwaree, Sónia Ribeiro, Heejoong Kang, Christopher Narinder Singh Poonian, Victor Restrepo, Patrícia Rendall Rocha, Jamie C. Tam, Ron Vave, Sebastian Villasante, Elizabeth Voges, Easton White

GOE Co-Leads

Renato Quinones & Chang-Ik Zhang

1. Keynotes

- Medium Scale Fishing (MSF) and Large Scale Fishing (LSF) contribute to complex challenges within the marine environment, underscoring the need for tailored, sustainable management approaches.
- While MSF plays a vital role in supporting local economies and livelihoods, LSF operations often present broader environmental and economic impacts.
- The literature emphasizes the importance of ecosystem-based management, transparency, traceability, and stakeholder collaboration to mitigate the negative impacts of MSF and LSF.
- Effective governance structures—such as legal frameworks, co-management arrangements, and adaptive management practices—are deemed to be essential to ensure that these fisheries sectors contribute positively to sustainable development.
- Prioritizing these approaches can help balance ecological preservation with economic objectives, fostering a more sustainable approach to the management of MSF and LSF, and by extension fisheries in general.

2. Introduction

Fisheries are the backbone of many coastal economies and communities, providing livelihoods, food security, and cultural identity (Srinivasan and others, 2012; Pollnac and others, 2015; WOA I &II). Major concerns on the state of fisheries have been reported in the literature, due to overfishing (Pauly and others, 2002; FAO 2024); climate change (IPCC, 2023~~2~~) and pollution such as plastic (Lau and others, 2020). These multiple stressors have resulted in a concerted effort to have scientific understanding of the ecosystems, biodiversity, fishes, and the economic, social and cultural activities dependent on it (Enevoldsen and others, 2022; IOC-UNESCO, 2024; WOA I & II), culminating into the creation World Ocean Assessment (WOA) I and II, and now III of the United Nations on the state of the global ocean and regional seas.

The fisheries sector is diverse, consisting of a wide range of operations that vary significantly in scale, technology, and impact (Sumaila and others, 2001; Gibson and Sumaila, 2017; Basurto and others, 2025). The scale and scope of operation between Large Scale Fishing (LSF) and Medium Scale Fishing (MSF) (and also Small Scale Fishing -SSF-; see S5A.C1b) fisheries are distinct, each with its own set of practices, impacts, and sustainability measures. Fisheries are categorized based on the scale and scope of their operations, which influence their environmental impact, economic contribution, and social dynamics (FAO, 1995; Gibson and Sumaila, 2017; Basurto and others , 2025). LSF and MSF differ in their operational approaches, with each playing a unique role in the global fishing industry (Figure 5A 1.1).

LSF is characterized by their use of large, high-capacity boats, often exceeding 130 meters in length with a hold capacity of more than 2,000 tonnes (FAO, 1985). These vessels are equipped with on-board facilities for freezing and processing seafood at sea, allowing them to remain at sea for extended periods and operate across thousands of miles (Figure 5A 1.1). Many LSF are designated as multipurpose, allowing them to operate with two or more types of fishing gear without requiring significant modifications to the vessel (Thermes~~,~~ and others, 2023). The scope of LSF allows them to fish far from continental shelves and sensitive marine habitats, potentially reducing the overall intensity of fishing in any given area (Jennings, and Kaiser, 1998). However, this also limits the ability of management authorities to monitor their activities in parts of the ocean, especially, in the waters of some Global South countries.

MSF often occurs regionally with moderate-sized vessels FAO (1985). They serve as a bridge between artisanal (or SSF - see S5A.C1b) and LSF, adapting various fishing methods

and technologies (Halimatussadiah and others, 2023). MSF typically employ vessels that are smaller than those used in large-scale operations but larger than traditional fishing boats (see S5A.C1b). MSF are more closely linked to national ownership and markets, often supporting moderate fishing practices and regional economies. SSF and MSF, while more easily monitored due to their smaller operational range, may fish a smaller area with greater intensity, leading to different environmental impacts that require careful management. Therefore, LSF and MSF differ in their scale and scope of operation, with each having its own set of challenges and opportunities.

We present in Figure 5A 1.1 a summary of the comparison between MSF and LSF using some key attributes that are described in the sections that follow.

Attribute	Medium-Scale Fisheries (MSF)	Large-Scale Fisheries (LSF)
Pressure on Fish Stocks	Moderate; concentrated regionally, may exert intense local pressure	High potential due to wide range, but spread over vast areas
Bycatch	Moderate to high; varies with gear type and practices	High; often associated with industrial trawling and purse seining
Overfishing Risk	High locally if not managed; often targets nearshore ecosystems	High due to volume and range; requires robust international oversight
Habitat Impact	Moderate; nearshore ecosystems more vulnerable to gear impacts	Potentially lower per unit area but higher in aggregate; risk to deep-sea and benthic habitats
Pollution (e.g., fuel, waste)	Lower to moderate; limited onboard processing	High; onboard processing and longer trips increase pollution footprint
Biodiversity Impact	Can be significant in confined areas	Potentially significant due to broader ecosystem interactions
Carbon Footprint	Moderate; shorter trips, smaller vessels	High; larger vessels, longer distances, heavy fuel consumption
Ecosystem Disruption	Focused and acute in local habitats	Broad-scale, chronic impacts if not regulated
Socioeconomic Impact	Strongly tied to local economies; supports community livelihoods	Generates large economic returns but benefits often concentrated in fewer hands
Economic Pressure	Medium; dependent on regional markets and subsidies	High; capital intensive, driven by global demand and market volatility
Illegal, Unreported & Unregulated Fishing (IUU)	Lower incidence; easier to monitor regionally	Higher risk due to remote operations and complex jurisdictions
Resilience to Environmental Change	Moderate to high; more adaptable and community-driven	Lower; high operating costs and rigid structures reduce adaptability
Dependence on Natural Resources	High; often lacks alternatives and depends on healthy local ecosystems	High; requires vast biomass to sustain operations
Monitoring & Regulation	Easier to enforce nationally; closer to shore	Difficult in distant waters; reliant on technology (e.g., satellites, observers)
Technology Use	Moderate; mix of traditional and modern gear	High; sophisticated gear, sonar, GPS, onboard processing
Operational Range	Regional; typically coastal or EEZ-based	Global; often in high seas, across jurisdictions
Link to Local Communities	Strong; supports local identity and food security	Weak; less embedded in local cultures
Sustainability Potential	Higher due to flexibility and community engagement	Moderate; scalable monitoring exists but implementation challenges remain

Aspect	Medium-Scale Fisheries	Large-Scale Fisheries
Pressure on Fish Stocks	⊕⊕	⊕⊕⊕
Bycatch	⊕	⊕⊕⊕
Overfishing Risk	⊕	⊕⊕⊕
Habitat Impact	⊕⊕	⊕⊕⊕
Pollution	⊕	⊕⊕⊕
Biodiversity Impact	⊕	⊕⊕⊕
Carbon Footprint	⊕	⊕⊕⊕
Ecosystem Disruption	⊕	⊕⊕⊕
Socioeconomic Impact	Critical for local livelihoods, food security, and culture	Benefits spread globally but with local job losses
Economic Pressure	Market fluctuations, often locally focused	Global market demands, affecting large economies
Illegal, Unreported, Unregulated (IUU) Fishing	⊕⊕	⊕⊕⊕
Resilience to Environmental Changes	⊕⊕⊕	⊕
Dependence on Natural Resources	⊕⊕⊕	⊕⊕⊕⊕

Figure 5A 1.1: Compares medium-scale and large-scale fisheries across various key attributes. ~~Sources: European Commission. (2019). FAO. (1985); FAO. (2022).~~Data s~~S~~ources: FAO, 1985. Jennings, and Kaiser, 1998.Norse and others, 2012. Pauly and others, 2002. Halimatussadiah and others, 2023. Thermes, and others, 2023. ~~European Commission. (2019). FAO. (1985); FAO. (2022).~~

MSF uses moderately advanced technologies and mid-sized fishing gear while LSF deploy highly advanced technology and sophisticated gear (Figure 5A 1.1). Hence, the primary distinction between LSF and MSF lies in their operational scale and technological sophistication. LSF are equipped with the latest technology, enabling them to fish in remote, less-fished areas but also more ecological areas of the ocean (Norse and others, 2012), whereas MSF operate closer to shore and rely on a mix of traditional and modern methods.

It is worth noting that the comparison between LSF and MSF in terms of environmental impacts is not straightforward. Both LSF and MSF have distinct environmental impacts that need careful management. LSFs need to mitigate their potential for widespread

environmental harm, while MSFs need to focus on preserving local ecosystems. MSF can leverage their closer connection to local communities and ecosystems to implement sustainable practices that protect the environment. MSF are often more adaptable and responsive to sustainable practices. LSFs benefit from onboard observers and satellite tracking to ensure responsible operations. Sustainable fishing practices, stringent monitoring, and regulation are vital for both sectors to minimize their environmental footprint and ensure the long-term health of marine ecosystems (Pauly and others, 2002).

3. Pressures and impacts

Pressures and impacts from LSF are higher compared to those from medium fishing operations~~., which~~ MSF are usually limited to Exclusive Economic Zones (EEZs). Sources of pressures and impacts from MSF and LSF are derived from exploitation, seafloor disturbances, pollution, policy consequences, illegal activities, climate, and global seafood demand (Figure 5A 1.1~~2~~; see also S3, S4.C4d and S5A.C1b for complementary discussions of pressures and impacts).

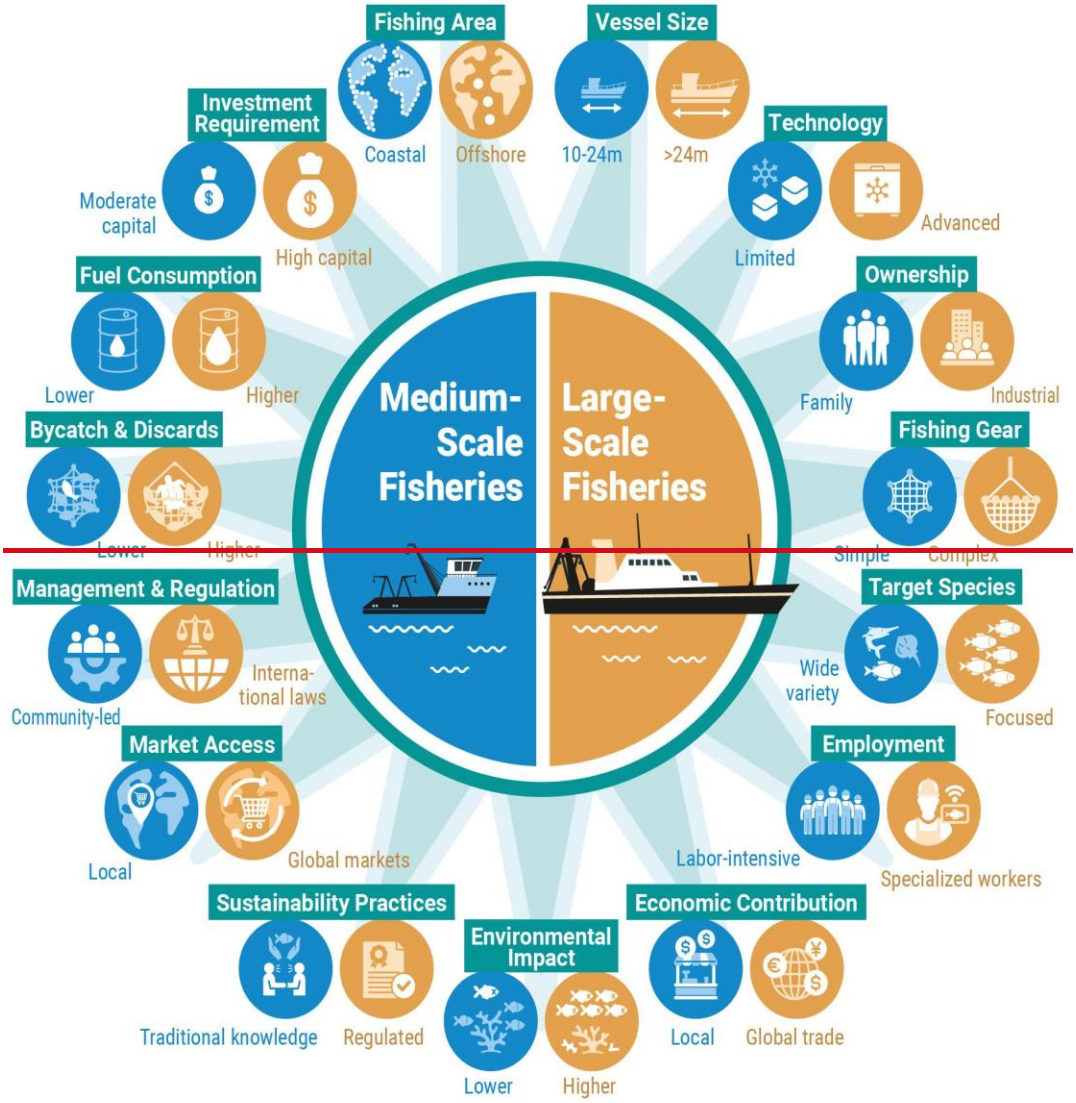


Figure 5A 1.2: Compares the pressures and impacts of medium-scale and large-scale fisheries. Sources: Norse and others, 2012. Tam and others, 2017. Link and Watson, 2019. Gillman and others, 2020. Sumaila and Tai, 2020.

3.1. Overexploitation

The environmental impacts of fishing activities can vary significantly between LSF and MSF operations (Figure 5A 1.1). LSF vessels can stay at sea for extended periods, allowing them

to fish in remote areas (Norse and others, 2012). LSF continue to raise environmental concerns due to their high capacity, including overexploitation of fish stocks, trophic cascades from predator removal, significant bycatch of endangered species, habitat destruction from fishing methods like trawling, increased greenhouse gas emissions, and marine pollution from lost or discarded gear (Gillman and others, 2020). The environmental impact of MSF is often localized, affecting the ecosystems where they operate. While they may not have the same global reach as LSF, their impact on local environments can be significant, particularly if they contribute to overfishing and habitat destruction.

Overfishing of MSF and LSF target species is a major pressure on marine ecosystems, with overfished stocks increasing by 10% to 37% in 2021 (Fig 5A.1.2; FAO, 2024). Overfishing, often assessed at the species level, also depletes entire ecosystems, making them more vulnerable to climate change impacts (Tam and others, 2017; Link and Watson, 2019; Sumaila and Tai, 2020). Reduction of the abundance of high-value, high trophic level fish, modify the trophic chain and the flows of energy across the ecosystems (Pauly and Christensen, 1995), which leads to a social and economic impact in coastal communities.

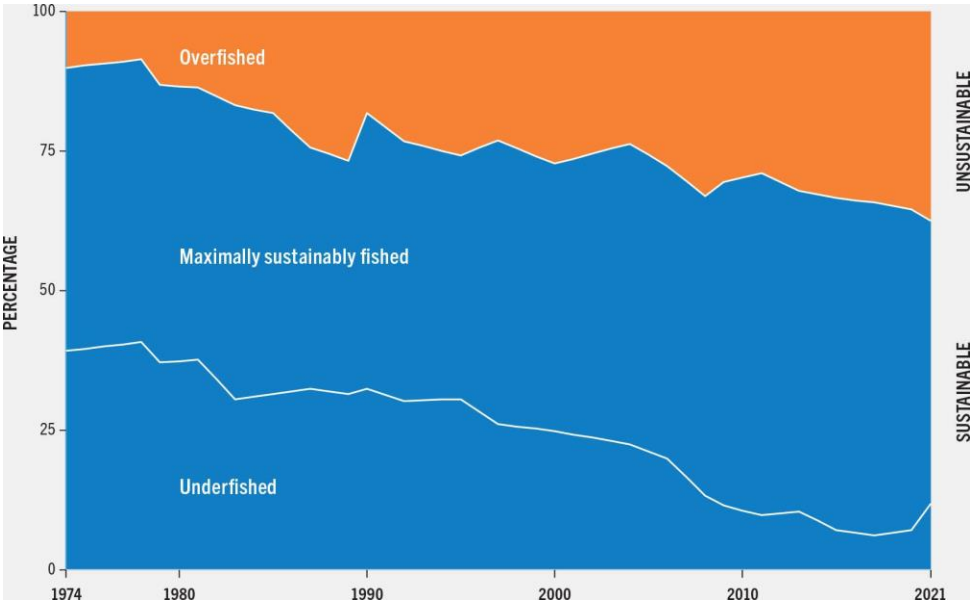


Figure 5A 1.3. Captures the fact that wild fish catch is taken increasing from overfished stock over time. Source (FAO 2024).

Direct pressures from MSF and LSF fishing vary by gear type that include trawling and dredging, purse seining, and longlining, gillnets and traps . The increased use of fish aggregating devices (FADs) that enhance efficiency and effectiveness of fishing gear has increased since the 1990s (Moreno and others 2016). Despite the profitability of fishing

operations (Bailey and Sumaila, 2015), the need to regulate them has become essential due to the pressures they impose on aquatic ecosystems, including habitat disruption and overfishing. (Pittman and others, 2020).

3. 2. Seafloor disturbances

The destruction and disturbance of benthic habitats from MSF and LSF gear (e.g. trawling, dredging) can lead to a reduction (or even dramatic permanent losses) in the abundance and diversity of benthic and demersal organisms, due to changes in habitat structure and sediment displacement and disruption of food-webs (Kaiser, 2019; Moris and others, 2023). Disturbance of carbon storage in the seabed can lead to the release of stored CO2, potentially altering the nutrient cycling and sediment composition (Epstein and others, 2022).

3.3. Non-target species

Even though the increased use of bycatch reduction devices (BRD) incorporated into fishing gears has decreased overall unintended capture of endangered marine life (e.g. birds, mammals, sharks, sea turtles), bycatch still persists in MSF and LSF (Chuenpagdee and others; Phillips and others, 2024; Barz, 2023; O'Keefe and others, 2023). Effectiveness of mitigation measures and BRDs, including visual deterrents, fishing net mesh thickness, turtle excluder devices, circular hooks and ropeless have shown to generally reduce bycatch with little significant effect to target catches (Huang and others, 2024).

Discards in MSF and LSF operations are~~(~~ another source of marine ecosystem impacts from these fisheries. ~~Although discard levels have been in decline since 1989, more recent estimates of global discards are significant, around 10 million tonnes from 2014 (Gilman and others, 2020).~~ In addition to more selective fishing gear, improved monitoring and reporting of discards and increased retention of non-targeted species, will help to better understand and reduce the impacts of discards (Lively and McKenzie, 2023).

3.4. Pollution

Ocean pollution ranging from plastic, to oil spills and underwater noise are a big challenge to marine life and ecosystem health (Sumaila and others, 2012; Abbott and Sumaila, 2019; Lau and others, 2020). Underwater noise pollution is known to negatively impact the behaviour and physiology of marine species including fish, invertebrates, marine mammals, and marine reptiles (Di Franco and others, 2020). Studies have identified that vessel engines and propellers are the main contributors of underwater noise, and

engineering mitigation measures are needed to encourage in the design and specification of new MSF and LSF vessels (Burella and Moro, 2021)

It is estimated that 2936 km3 of gillnets, 75 049 km2 of purse seine nets, 218 km2 of trawl nets, 79 583 km of longlines and more than 25 million traps and pots are lost annually in the ocean making up 2% of all fishing gear (Richardson and others, 2022). These abandoned, lost or discarded fishing gear (ALDFG) represent a substantial source of marine pollution and contribute to the entanglement of marine animals (Nama and others, 2021) . Proportions of gear loss vary across gear characteristics, but generally more gear is estimated to be lost by smaller vessels (Richardson and others, 2022). Biodegradable fishing gear, ghost gear reduction initiatives, and ecolabelling certification programs aim to reduce the impacts of ALDFGs in the global oceans (Mclennan and others, 2023).

3.5. Unintended consequences of policy

Medium and large-scale operations might receive harmful subsidies or capacity enhancement resulting in overcapacity and overfishing leading to social and economic consequences (Sumaila and others, 2024). Since 1950, heavily subsidized fleets have increased the total fished-area from 60% to more than 90% of the world's oceans, doubling the average distance traveled from home ports but catching only one-third of the historical amount per kilometer traveled (Tickler and others, 2018). However, a recent study found that 72–76% of the world's industrial fishing vessels are not publicly tracked, with much of that fishing taking place around South Asia, Southeast Asia and Africa (Paolo and others, 2024).

The latest estimates indicate that global fisheries subsidies totaled USD 35.4 billion in 2018, with USD 22.2 billion allocated specifically to capacity-enhancing subsidies (Sumaila and others, 2019). The World Trade Organization (WTO) adopted an Agreement on Fisheries Subsidies in June 2022, after over 20 years of trying. This Agreement seeks to prohibit subsidies that contribute to ~~overcapacity, overfishing, and~~ Illegal, Unreported, and Unregulated (IUU) fishing, which all threaten fish stocks~~. . In addition, the agreement seeks to reduce distortion in the international trade of seafood (see S5A.C1f).~~ For the Agreement to take effect, however, two-thirds of the 109 WTO members must formally ratify it by depositing their instruments of acceptance (Sumaila and others, 2024).

3.6. Illegal activities and IUU fishing

IUU fishing represents a major threat to global fisheries governance, economic equity, and marine sustainability. Each year, an estimated 8 to 14 million metric tonnes of unreported

fish are traded illicitly on global markets, generating gross revenues of US$9 to 17 billion (Sumaila et al., 2020). The broader economic impact is even more staggering, with global losses due to the diversion of fish from legal markets estimated at US$26 to 50 billion annually, resulting in US$2 to 4 billion in forgone government tax revenues (Sumaila and others, 2020). ~~High-risk areas for IUU fishing and labor abuse include the waters off Argentina, Peru, Chile, West Africa and the Eastern Tropical Pacific (Selig and others, 2022)~~ High-risk areas for IUU fishing and labor abuse include the coasts of South America, Western Africa, around the north western Pacific and eastern tropical Pacific (Selig et al., 2022).~~:~~ Least Developed Countries (LDCs) are disproportionately affected due to systemic constraints—limited financial resources, weak infrastructure, insufficient data systems, and gaps in technical and enforcement capacity. Recognizing these disparities, several funding schemes have been developed to support developing countries and LDC members to address this challenge. Examples include the UNFSA Assistance Fund, the voluntary WTO Fisheries Funding Mechanism Trust Fund (WTO 2024), the FAO, Regional Fisheries Management Organizations (RFMOs) and directed funds within RFMOs, and the provision of direct bilateral support between countries. ~~It is estimated that between 8 and 14 million metric tonnes of unreported catches, globally traded illicitly yearly, suggesting gross revenues of US$9 to US$17 billion per year associated with these catches. The estimated annual economic impact loss due to the diversion of fish from the legitimate trade system is US$26 to US$50 billion, while losses to countries' tax revenues are between US$2 and US$4 billion (Sumaila and others, 2020). For both labor abuse and IUU fishing, there are also high-risk areas for transshipment off the coasts of Argentina, Peru, Chile and West Africa, around the Kamchatka peninsula and in the Eastern Tropical Pacific (Selig and others, 2022). Least Develop Countries (LDCs) face significant challenges in effectively managing their fisheries resources, including limited financial resources, inadequate infrastructure, lack of technical expertise, and insufficient data, to name a few. WTO Agreement on Fisheries subsidies established a voluntary WTO funding mechanism – the WTO Fisheries Funding Mechanism Trust Fund – to assist developing and LDC members with implementing the Agreement. (WTO,2024).~~

In response to the serious threats posed by IUU fishing, the global community has mobilized a suite of international efforts focused on monitoring, control, and surveillance (MCS), enforcement, and capacity-building and sharing. Central among these is the Port State Measures Agreement (PSMA), adopted under the auspices of the FAO, which seeks to prevent illegally caught fish from entering international markets by strengthening port inspection regimes and promoting information sharing among states. The UN Fish Stocks Agreement and RFMOs also play critical roles by promoting cooperative enforcement on the high seas. Satellite-based vessel tracking, the Global Fishing Watch platform, and

observer programs are increasingly being used to monitor activity in remote and transboundary waters. Moreover, consumer-facing traceability initiatives and import regulations in key markets such as the EU's Catch Certification Scheme and the U.S. Seafood Import Monitoring Program are putting additional pressure on IUU actors by tightening access to markets. However, the success of these measures ultimately depends on the political will, legal infrastructure, and technical capacity of coastal states, especially in developing regions, to enforce compliance and prosecute violators.

3.7. Climate change

Fishing operations in both medium and large fishing scales are driven by fossil fuel, contributing to global greenhouse emissions (Tyedmers and others, 2005; WOA II). The world's fishing fleets have released 37.5 ± 7.4 Mts of CO2 into the atmosphere between 1950 and 2014 (Mariani and others, 2020) and the estimate of 159 Mts in 2016 by Greer and others (2019) was much higher than what ~~IPCC~~was suggested earlier. Emissions increase further when considering non-fishing activities like transportation and preservation. Ocean warming, acidification, and sea level rise~~-~~ are~~-~~ impacting fish stocks and fishers in significant ways, including changes in fish stocks' productivity and distribution, human migration to and away from coastal areas, stresses on coastal fisheries infrastructure, and challenge maritime boundaries (Mendelhall and others, 2020, Gill and others, 2023). Climate change has caused substantial damages and increasingly irreversible losses in fisheries yields. Ocean warming and ocean acidification have adversely affected food production from fisheries, rebuilding overexploited or depleted fisheries reduces negative climate change impacts on fisheries and supports food security, biodiversity, human health and well-being (IPCC, 2023)

3.8. Global Seafood demand

Expansion of fishing operations and pressure on the fish stocks and marine ecosystems cannot be dissociated from the rapid increase from global apparent consumption of aquatic animal foods. The world's fish consumption and non-food use have increased from 28 MT in 1961 to the 2022 estimate of 185.4 MT (FAO, 2024). It is well established that fish meal production (ca 17 MT per year) is a major product used in fish feed in aquaculture and adds significantly to pressure on the fish stock and marine ecosystems (FAO, 2024).

4. Socio-economic considerations

This section analyzes the social components of MSF and LSF through several global case studies, providing a perspective on employment, gender dynamics, traditional knowledge,

and the broader social impacts of industrialization and globalization. The social components of MSF encompass various aspects related to the individuals, communities, and societies involved in or affected by fishing activities.

4.1. Employment and livelihoods

Wild fisheries provide significant employment worldwide (Kelleher and others, 2012). For example, in West Africa and Southeast Asia, MSF and LSF create significant employment opportunities in both direct fishing activities and ancillary industries, such as processing and marketing (Belhabib and others, 2015; Teh & Sumaila, 2013). Globally, fisheries employ around 260 million full-time and part-time jobs in the direct and indirect sectors, with the processing and export sectors particularly benefiting from large- and medium-scale operations (Teh & Sumaila, 2013). However, there are differences in the benefits provided by large-scale industrial fisheries compared to the localized impact of SSF to MSF. In the case of the latter, while their fleets may provide some employment opportunities, they often concentrate profits in corporate sectors, further marginalizing local fishers who rely on marine resources for their livelihoods (Srinivasan and others, 2012).In Indonesia, for example, LSF has contributed to declining fish stocks, and has resulted in significant job losses in local communities (Halimatussadiah and others, 2023).

The uneven distribution of benefits from LSF can also exacerbate economic inequalities. LSF fleets operating in developing countries, such as those in the Pacific and Africa, typically benefit foreign companies, with limited reinvestment in local economies (Pauly and others, 2014). The global nature of LSF, especially in regions like the South Pacific and the Indian Ocean, often leads to the extraction of resources from developing regions to satisfy the demands of wealthier markets, creating local economic instability (Eriksson and others, 2015).

4.2. Cultural heritage and identity

Fishing is rooted in the cultural heritage of coastal and island communities worldwide. In many regions, traditional fishing practices have been passed down through generations, providing not only a source of sustenance but also a strong sense of cultural identity (Vave, 2022; Vave and others, 2024). However, the rise of MSF and LSF operations has often displaced these traditional practices, leading to a loss of marine cultural heritage. Similar patterns are evident in regions such as West Africa, where the expansion of LSF has eroded the cultural significance of SSF practices (Belhabib and others, 2015). In addition, traditional knowledge systems, which have long sustained marine ecosystems and fishing communities, are increasingly sidelined by modern, technology-driven methods of LSF

(Teh & Sumaila, 2013). In the Pacific Islands, LSF has reduced the reliance on traditional fishing methods that historically helped maintain ecological balance and sustainability (Eriksson and others, 2015). In parts of the Indian Ocean, the introduction of LSF has also changed the socio-cultural fabric of fishing communities, as younger generations often seek employment in more economically lucrative sectors or leave fishing altogether (Eriksson and others, 2015).

Seafood has been an important component of Indigenous Peoples' nutritional and food security for centuries (Cisneros-Montemayor and others, 2016). Traditional ecological knowledge (TEK) has been a key component of sustainable fishing practices in many regions for centuries. Indigenous Ppeoples and local communities have developed sophisticated systems for managing fish stocks and maintaining ecological balance through practices such as rotational fishing and closed seasons (Drew, 2005). TEK is often closely linked to cultural heritage and plays a key role in the social and environmental sustainability of fisheries. However, the rise of LSF has disrupted these traditional knowledge systems. In the Pacific Islands, for instance, traditional practices have been overshadowed by the more efficient yet ecologically damaging methods employed by LSF fleets (Teh & Sumaila, 2013; Scherrer and others, 2024). The same dynamic is visible in parts of Southeast Asia and Africa, where the expansion of LSF has marginalized the role of TEK in fisheries management (Eriksson and others, 2015).

4.3. Gender dynamics and equity

Gender plays a central role in the social structure of fisheries worldwide (Harper and others, 2013; WOA I). In many regions, women are heavily involved in post-harvest activities such as processing and marketing, while men often dominate fishing at sea (Lentisco and Lee, 2015). In West Africa, for example, women constitute a significant portion of the workforce in fish processing and trade, yet their contributions are often undervalued in policy frameworks (Belhabib and others, 2015), and women frequently face gender-based disparities in employment, income, and decision-making roles in fisheries (Oloko and others, 2024).

LSF activities have further exacerbated gender inequalities because they tend to focus on efficiency and mechanization, which often excludes women from traditionally female-dominated sectors, such as fish processing (Halimatussadiah and others, 2023). In the Pacific Islands, large-scale tuna fisheries have led to significant gender disparities in the workforce, particularly in post-harvest sectors; and in Fiji, though women constitute the majority of the workforce in tuna processing plants, they remain concentrated in low-paying, repetitive roles with limited career advancement opportunities (Syddall and others,

2022). Similarly, in Southeast Asia and the Pacific Islands, women's roles in the fisheries value chain are frequently marginalized as large-scale operations favor male-dominated roles, particularly in the management and technical sectors (Kleiber and others, 2015). Efforts to promote gender equity in fisheries need to focus on ensuring women's access to financial resources, training, and leadership positions, as well as addressing gender-based barriers to employment.

4.4. Social impacts of industrialization and globalization in fisheries

The industrialization and globalization of fisheries have led to significant social impacts, particularly in the developing world where fishing is a major source of livelihood for millions of people. LSF, driven by global demand for seafood, often prioritize export markets, which can lead to the depletion of local fish stocks and threaten food security in developing countries (Pauly and others, 2014). In West Africa, for example, the focus on exporting fish to international markets has reduced the availability of fish for local consumption, exacerbating poverty and malnutrition (Belhabib and others, 2015), and increased income inequality, with the profits from industrial fishing concentrated in the hands of a few multinational corporations (Pauly and others, 2014). Other reported social impacts of industrialization include social challenges such as increased migration, changes in local labor dynamics, and the erosion of social cohesion in traditional fishing communities (Kleiber and others, 2015). The global nature of industrial fishing can lead to conflicts over resource use (Dahlet and others, 2021), particularly in areas where LSF occurs in direct competition with SSF (Pauly and others, 2014).

5. Sector-relevant governance

Effective governance of MSF and LSF requires robust legal and institutional frameworks, supported by science-based management tools, international cooperation, and adaptive policies that can respond to environmental variability, market dynamics, and technological change (Sumaila, 1999; Miller et al., 2013; Grip, 2017). Regulation at this scale must balance maximizing economic yield with minimizing ecological harm, including bycatch, habitat degradation, and stock depletion. As noted in previous sections, regulating MSF and LSF activities is essential for mitigating adverse environmental and social impacts, particularly in shared or transboundary waters. Governance structures for MSF and LSF are embedded within international legal instruments, including the United Nations Convention on the Law of the Sea (UNCLOS), the UN Fish Stocks Agreement, and the Port State Measures Agreement, as well as a suite of binding and voluntary frameworks adopted by RFMOs and other global bodies. These instruments establish the legal foundation for

managing straddling and highly migratory stocks, regulating distant water fleets, enforcing compliance, and supporting transparency and accountability across jurisdictions.

~~The governance of marine fisheries is essential for the sustainable management of global marine resources (Österblom and Folke, 2013). The complexity of marine environments, combined with the migratory nature of many fish species and the varying interests of commercial, recreational, and subsistence fishers, necessitates a diverse approach to governance (Mora, and others, 2009; see S3: Global Overview of Ocean Governance). Effective fisheries management requires robust regulatory frameworks, international cooperation, and adaptive strategies that respond to environmental changes and scientific advancements (Sumaila, 1999; Miller and other, 2013; Grip, 2017). As stated in previous sections, the effective regulation of MSF and LSF activities is key to limiting adverse environmental impacts. Governance of MSF and LSF involves the structures, processes, and mechanisms through which fishing activities are regulated, managed, and governed. At the international level, these are, inter alia, reflected in global international instruments including the United Nations Convention on the Law of the Sea, the United Nations Fish Stocks Agreement, the Port State Measures Agreement and various other binding and non-binding instruments.~~

5.1 Overlaps with previous WOAs

The second WOA (Volume II, United Nations, 2021) highlights the significance of the UN Convention on the Law of the Sea (UNCLOS) in advancing an integrated approach to ocean management and setting out the rights and obligations of States for the conservation and management of marine living resources. It also refers to its second implementing agreement i.e. the 1995 Agreement for the Implementation of the Provisions of the Convention relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA), which builds on the provisions of UNCLOS (Munro, 1996). With respect to fisheries management in particular, the Convention discusses the role of ~~Regional Fisheries Management organizations (~~RFMOs~~)~~ and FAO guidelines but not much about fisheries management in general.

5.2. International regulation

The international governance of marine fisheries is shaped by a constellation of legal instruments, institutions, and policy frameworks that work collectively to manage the sustainable use of marine resources, especially MSF and LSF. This governance regime can

be understood in terms of legally binding agreements, voluntary instruments, and their integration into the broader international environmental system.

At its foundation, fisheries governance is anchored in the United Nations Convention on the Law of the Sea (UNCLOS), which defines the rights and responsibilities of States over maritime zones, including territorial waters and EEZs. UNCLOS requires coastal States to ensure the conservation and sustainable use of fisheries within their EEZs and to cooperate in managing straddling and highly migratory stocks (White & Costello, 2014; Sumaila and others, 2015). Building on this, the 1995 United Nations Fish Stocks Agreement (UNFSA) operationalizes UNCLOS's provisions on transboundary fish stocks. UNFSA is significant for promoting an ecosystem-based and precautionary approach to fisheries management (Pikitch and others, 2004). It mandates cooperation through RFMOs, which are essential in setting and enforcing conservation and management measures across the high seas.

Further strengthening this regime are instruments like the FAO Compliance Agreement, which focuses on flag State responsibilities, and the Port State Measures Agreement (PSMA), which helps prevent IUU-caught fish from entering markets by enhancing port inspections and enforcement (Bethel and others, 2021). These agreements collectively serve to curb IUU fishing and improve accountability in distant water fishing operations. The WTO Agreement on Fisheries Subsidies, adopted in 2022, marks a major advancement by prohibiting subsidies to fleets engaged in IUU fishing, fishing of overfished stocks, and fishing in unmanaged high seas areas (Alger and others, 2023). Meanwhile, the BBNJ Agreement (2023), though not a fisheries treaty per se, introduces mechanisms—such as area-based management tools and environmental impact assessments—that will likely affect MSF and LSF operating in areas beyond national jurisdiction.

Beyond binding agreements, the FAO's Code of Conduct for Responsible Fisheries (1995) is a cornerstone voluntary framework. It encourages science-based stock assessments, selective fishing gear, compliance with international law, and measures to protect coastal livelihoods. Within this framework, the Committee on Fisheries (COFI) and FAO member countries have developed additional voluntary guidelines ,for e.g., on bycatch reduction, small-scale fisheries, and catch documentation are tailored to the evolving needs of global fisheries governance. Fisheries governance is also increasingly influenced by global environmental treaties. CITES regulates international trade in marine species listed in the CITES Appendices, including landing of specimens taken from ABNJ, to ensure legal, sustainable and traceable trade. The Convention on Biological Diversity (CBD) and the Kunming-Montreal Global Biodiversity Framework (KM-GBF) include explicit targets for sustainable fisheries (e.g., Target 10). Likewise, the Paris Agreement under the UNFCCC

recognizes the ocean's role in food security and calls for the protection of marine ecosystems in light of climate change. The UNFCCC's 2023 submissions to the UN General Assembly, as well as dialogues held at the 17th round of Informal Consultations on UNFSA, underscore the relevance of climate-smart fisheries management.

Although fisheries are not formally a standalone sector under the Paris Agreement, they are included within Parties' economy-wide mitigation and adaptation commitments. The outcome of the first Global Stock take stresses the need for cross-sectoral emission reductions, including from fisheries-related activities. This alignment between fisheries and broader environmental governance frameworks demonstrates a growing recognition that sustainable fisheries management is crucial to climate resilience and global food security.

~~In its 2023 report on "Oceans and the Law of the Sea," the UN Secretary-General highlighted the 2023 Intergovernmental Conference's achievement of an agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement), calling it a significant development in ocean management. The written contribution of the UNFCCC secretariat to the United Nations General Assembly resolution entitled "Oceans and the law of the sea" (78/69), of 05 December 2023 highlighted the importance of "The ocean as a source of sustainable food" In addition, the presentation of the UNFCCC secretariat in the discussion panel on "Sustainable fisheries management in the face of climate change" at the Seventeenth round of Informal Consultations of States Parties to the United Nations Fish Stocks Agreement, available here: https://www.un.org/Depts/los//convention_agreements/ICSP17/Videos/Icsp17segment2randhawa.mp4 also emphasized how crucial sustainable management as climate change impacts on the ocean intensifies. The 2023 informal summary report of the ocean and climate change dialogue , which discussed "Fisheries and food security", can be found here: https://unfccc.int/documents/631689.~~

~~UNCLOS defines the responsibilities and entitlements of State Parties regarding fishing within their national jurisdictions, including territorial seas and exclusive economic zones (EEZs). For stocks straddling EEZs and high seas (White and Costello, 2014; Sumaila and others, 2015), cooperation between coastal and Regional Fisheries Management Organizations (RFMOs) and/or countries/political entities fishing in the high seas on conservation measures (Munro, 1996). The 1995 UN Fish Stocks Agreement (UNFSA) adopts an ecosystem-based approach to fisheries management (Pikitch and others, 2004). By mandating measures to combat IUU fishing (Sumaila and others, 2006; Agnew and others, 2009), the UNFSA helps to tackle one of the most pressing issues in fisheries~~

management. Other key international conventions that apply to MSF and LSF include the Convention on Biological Diversity, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972 (London Convention) and its Protocol, the International Convention for the Prevention of Pollution from Ships (MARPOL), which addresses pollution concerns and the Port State Measures Agreement (PSMA) which enhances port state controls to prevent illegally caught fish from entering the market (Bethel and others, 2021). In addition, the Committee on Fisheries (COFI) of FAO plays an important role providing periodic global recommendations and policy advice to governments, regional fishery bodies, civil society organizations, and private sector.

Recent instruments and frameworks adopted are the Kunming-Montreal Global Biodiversity Framework in December 2022, which includes Target 10 on the sustainable management of fisheries. The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ), was adopted in 2023, with the objective of ensuring the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, for the present and in the long term, through effective implementation of the relevant provisions of the Convention and further international cooperation and coordination. While it is not a fisheries management treaty, its provisions on area-based management tools, including marine protected area, and environmental impact assessments are likely to impact MSF and LSF. The WTO Agreement on Fisheries Subsidies adopted in 2022, holds that MSF and LSF fleets cannot be subsidized if they support IUU fishing, the fishing of overfished stocks or of unmanaged high seas stocks (Alger and others, 2023). Moreover, fisheries-specific principles such as total allowable catch (TAC), ITQs and catch shares (Arnason, 1996; Costello and others, 2008; Sumaila, 2018) have developed over time. Principles of international environmental law, such as sustainable development and the precautionary principle, also apply to the management of fisheries (Paterson, 2007).

Parties recognized the fundamental priority of "safeguarding food security" in the 9th preambular paragraph of the Paris Agreement, an evolution of the focus compared to the reference to "food production" in the Convention. Parties have recognized the importance of protecting the ocean and its ecosystems in both the Convention and the Paris Agreement, which underscores the critical role of conservation of marine ecosystems and protection of biodiversity for sustainable fisheries.

Fisheries is not a dedicated sector under the Convention and the Paris Agreement. Fisheries, along with other sectoral themes, is a cross-cutting issue in the Convention and the Paris Agreement, addressed within Parties' mitigation and adaptation-based

~~commitments subject to the principles of common but differentiated responsibilities and respective capabilities, in light of different national circumstances. The outcome of the first Global Stock take highlights the need for ambitious, economy-wide emission reduction targets covering all sectors and categories, including fisheries.~~

~~Finally, a very influential global framework is FAO's Code of Conduct for Responsible Fisheries, adopted in 1995. The framework promotes sustainable fishing practices. It offers a much appreciated voluntary guidelines promoting science-based stock management, ecosystem conservation, and responsible fishing. For medium and large-scale fisheries, it advocates selective gear, science-driven quotas, and compliance with international regulations to combat IUU fishing. In this way, it has served the role of protecting SSF and the food security and livelihood needs of coastal communities worldwide (see S5A.C1b).~~

5.3. Regional and collaborative management

RFMOs play an important role in high seas fisheries management as they facilitate cooperation among states for conservation and management of straddling and highly migratory fish stocks ~~and ensure that fishing operations do not result in a substantial negative effect on marine ecosystems and biodiversity~~. ~~They have the authority under international law to~~ establishing binding regulations to this end~~for the conservation and management of fisheries~~. They regularly adopt Conservation and Management Measures (CMMs) to address the management of fishing methods and impacts of MSF and LSF, such as in longlining and purse seining activities. However, they are not always successful in their efforts ~~-~~(Cullis-Suzuki and Pauly, 2010). Three key reasons for the lack of success are: (i) decision-making by consensus leads to weak or delayed action, e.g., delays in adopting rebuilding measures for overfished tuna stocks in the Western and Central Pacific Ocean due to opposition from distant water fishing nations; (ii) conflicting economic interests and political pressure, e.g., some members under-report or misreport catches, undermining scientific advice; and (iii) weak monitoring, control, and enforcement mechanisms, e.g., the Indian Ocean Tuna Commission (IOTC) continued overfishing of yellowfin tuna despite repeated warnings and catch limits, due in part to weak compliance.

Co-management and adaptive management are integral approaches to the effective governance of LSF (Jentoft, 2005). It involves shared governance, where responsibility and authority for managing fisheries are distributed among various stakeholders, including government agencies, local communities, and industry representatives (Wilson and others, 2003). For instance, Alaska's salmon fisheries are managed through a co-management approach that includes state and federal agencies, native Alaskan organizations, and commercial and sport fishers (Pinkerton, 1994).

~~Adaptive management approaches are characterized by iterative decision-making, allowing for strategies to be continuously updated based on monitoring and evaluation of outcomes (Armitage and others, 2009). For instance, at the International Commission for the Conservation of Atlantic Tunas (ICCAT) quotas and management measures are adjusted in response to fluctuating stock levels and the ongoing threat of illegal fishing. Other RFMOS like the Indian Ocean Tuna Commission (IOTC) take a similar approach, for instance, with the implementation of stock rebuilding plans and strengthening of drifting FAD management measures through the implementation of more environmentally friendly designs, drifting FAD registries, and tracking systems. Approaches to management differ among RFMOs globally. For example, stronger dFAD management measures such as spatio-temporal closures, which have been successfully adopted by other RFMOs, e.g., the Western and Central Pacific Fisheries Commission (WCPFC) since 2016, have not been implemented at the IOTC despite the alarming current overfishing concerns. The effective implementation of CMMs also remains a concern as some technological advances adopted through CMMs still do not effectively mitigate environmental impacts. For example, lower-risk non-entangling FADs can unravel over time which means that the entanglement of marine species, including sharks and turtles, perdures. Lack of selectivity remains an issue as recent research on unobserved mortality showed that juvenile sharks are found in the wells of purse seiners in the tuna fishing industry (San Juan and others, 2024). Pollution remains concerning as plastic continues to be used in FADs and some papers have highlighted concerns on the non-compliance issues presented by FADs that are not retrieved (Schatz, 2024), reflecting the concerns of earlier literature on this subject (e.g. Churchill, 2021).~~

5.4. Management at domestic level

The management of marine fisheries at the domestic level is foundational to achieving sustainability, given that the majority of commercially exploited fish stocks occur within national jurisdictions. Coastal States have sovereign rights and responsibilities over resources within their EEZs, and flag States maintain primary jurisdiction over vessels flying their flag on the high seas (Miller and Sumaila, 2014) . This makes national fisheries regulation essential not only for domestic sustainability, but also for supporting and reinforcing international and regional governance regimes.

National governments deploy a range of management tools—such as licensing schemes, total allowable catch (TAC) limits, gear and spatial restrictions, and enforcement mechanisms—to regulate both medium- and large-scale fisheries (MSF and LSF). However, these policies often prioritize economic growth, foreign exchange earnings, or industrial development, which can marginalize small-scale fisheries and degrade marine

ecosystems. Further challenges arise from weak inter-agency coordination, limited capacity, and political pressures that compromise implementation and enforcement.

In recent years, domestic legal frameworks have been increasingly reformed to address these challenges. For instance, several coastal States—especially in FAO Major Fishing Area 51—have updated national fisheries laws to include specific provisions regulating fish aggregating devices (FADs), responding to concerns over gear proliferation and bycatch (Gomez et al., 2020; Barston, 1999). National legislation has also been key in supporting the establishment and regulation of marine protected areas (MPAs), in alignment with global commitments to protect 30% of the ocean by 2030. Many countries are now strengthening laws that manage the interactions of MSF and LSF with sensitive marine ecosystems.

The effectiveness of domestic fisheries governance increasingly depends on transparency and innovation in MCS. Coastal States are adopting technologies such as the Automatic Identification System (AIS) and Vessel Monitoring Systems (VMS) to enhance real-time vessel tracking and compliance monitoring (Merton et al., 2016; Kuemlangan et al., 2023). While AIS use was initially limited, legal mandates and international cooperation have expanded its uptake and data sharing. For example, under the Copenhagen Declaration, coastal States are granted access to vessel tracking data to better address illegal, unreported, and unregulated (IUU) fishing, and transnational fisheries crimes (Bunwaree, 2023). Other RFMO like the Indian Ocean Tuna Commission (IOTC) take a similar approach, for instance, with the implementation of stock rebuilding plans. Similarly, work is currently underway to establish a TAC based quota allocation process, which is due for adoption in 2027. IOTC has adopted a measure strengthening of drifting FAD management measures through the implementation of more environmentally friendly designs, drifting FAD registries, and tracking systems.

It is worth noting that while RFMOs sometimes revise their Conservation and Management Measures (CMMs), such changes can overwhelm smaller domestic fleets that may lack the capacity to adjust quickly. This highlights the importance of adaptive management, phased implementation, and stakeholder consultation at the national level. National-level fisheries management is not only central to safeguarding marine biodiversity and food security, but also to ensuring equity and resilience in the face of growing challenges like climate change and overfishing. Integrating ecological, economic, and social objectives, including the rights and participation of small-scale fishers and Indigenous ~~communities~~Peoples, can lead to more effective, inclusive, and forward-looking fisheries governance (Sumaila, 2021; Naylor et al., 2021).

~~Environmental concerns linked to MSF and LSF are also being addressed specifically through domestic laws, policies and management. In line with international commitments to protect 30% of the ocean by 2023, laws regulating MPAs from the impacts of MSF and LSF are being strengthened.~~

~~It should be noted that the large majority of commercially exploited fish stocks are within areas under national jurisdiction and therefore fall under the jurisdiction of coastal States, and that flag States have primary jurisdiction over fishing vessels flying their flag on the high seas, thus effective national regulation of fisheries and fishing vessels is critical to sustainability. Therefore, besides implementing international commitments, domestic laws are crucial for addressing gaps in fisheries management at international and regional level. For example, in recent years, some coastal States have introduced FAD-specific provisions in their national laws (Gomez and others, 2020). This is part of broader reforms in fisheries legislation in FAO Major Fishing Area 51 where domestic fisheries laws are being strengthened (Barston, 1999).~~

~~The behavior of fishing vessels has also been increasingly scrutinized over recent years to bolster Monitoring, Control and Surveillance (MCS) in fisheries globally (Kuemlangan and others, 2023), particularly with concerns of IUU fishing. Coastal states are prioritizing transparency by adopting alternative technologies such as Automatic Identification System (AIS) in fisheries management (Merton and others, 2016). When prescribed by international and/or domestic laws, AIS data can provide an additional source of information to complement other systems like Vessel Monitoring Systems (Bunwaree, 2023). The provision and sharing of AIS data has also been made more readily available through cooperation between states. For example, the non-binding instruments, the International Declaration on Transnational Organized Crime in the Global Fishing Industry (Copenhagen Declaration), promotes cooperation and vessel tracking data is made available to coastal states to effectively combat fisheries crimes.~~

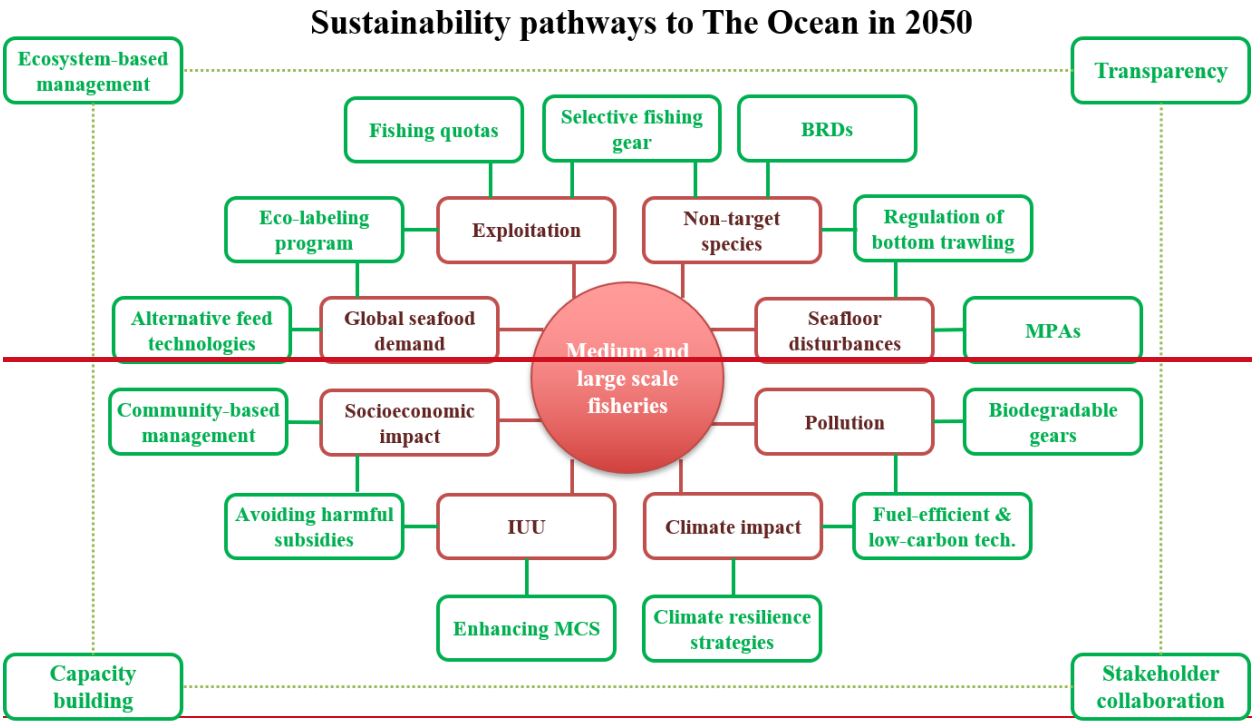
~~It is important to note that the annual review of RFMO Conservation and Management Measures often results in changes for the following year. However, these changes can sometimes be too drastic for smaller fleets, which have limited capacity to adapt quickly. In conclusion, the effective governance of marine fisheries is essential for achieving sustainability and resilience in our ocean ecosystems. By integrating principles of co-management and adaptive management, we can address the diverse challenges facing fisheries, from overexploitation and habitat degradation to climate change and illegal fishing. As global seafood demand increases (Naylor and others, 2021), a strong commitment to effective governance will be crucial in ensuring that marine resources are~~

~~preserved for future generations while supporting the livelihoods and well-being of communities worldwide (Sumaila, 2021).~~

6. Sustainability pathways

The sustainability of MSF and LSF is vital for maintaining the long-term health of marine ecosystems, ensuring the livelihoods of millions dependent on these resources (Teh and Sumaila 2013; FAO, 2024), and supporting the economic stability of global fishing communities. Achieving this requires an interdisciplinary approach that integrates ecological, social, and economic considerations (Murphy, 2011; Sumaila, 2024).

The aim here is to articulate possible pathways to achieve the vision of a sustainable ocean in 2050. We provide information that will assist policymakers and managers to understand what could be utilized (and how) to move from incremental change to existing systems of human use of the ocean (the business-as-usual scenario) to transformative reorganization (Figure S5A C1A_3).



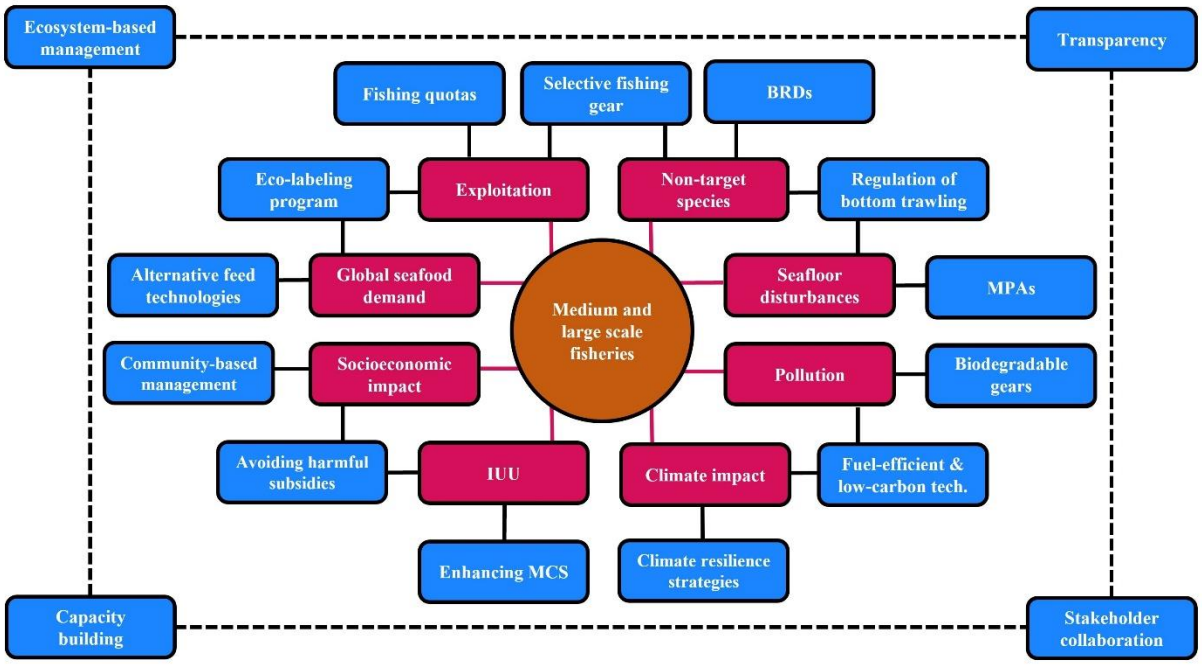


Figure 5A 1.4. Depicts sustainability pathways for medium and large scale fisheries. This diagram matches the sustainability pathways (green) with the pressures and impacts (red) for medium and large-scale fisheries.

Below we present what needs to be done to put fisheries on the path to 'real' sustainability pathways (Roberts and others 2024; UN Decade Vision 2030; S5A.C1b) for MSF and LSF to achieve the vision for Ocean 2050.

6.1. Safeguarding the environment by reducing overcapacity and overfishing

Overcapacity depicts the situation in which fishing fleets have the ability to catch more fish than ecosystems can sustainably produce. Overcapacity is one of the most persistent drivers of overfishing and the degradation of marine ecosystems (Pauly & Christensen, 1995). When too many vessels or too much gear are deployed in pursuit of limited fish stocks, this not only results in biological overexploitation but also intensifies competition, lowers profitability, and increases harmful environmental impacts, such as habitat destruction and excessive bycatch. Reducing overcapacity is therefore essential for restoring ecological balance and ensuring the long-term sustainability of fisheries. Policy interventions such as fleet reduction programs, which may include decommissioning or buy-back schemes, can help align fishing effort with the productive capacity of marine ecosystems. However, such measures must be carefully designed to avoid rebound effects

(e.g., reinvestment in more efficient vessels) and should be paired with socially just transition strategies, including retraining programs, alternative livelihoods, and financial support for affected communities (e.g., Clark and others 2005, 2007). This is particularly important in coastal areas where fishing is a cultural mainstay and economic lifeline.

In addition to reducing fleet size, effort-based management offers a complementary approach to controlling fishing pressure. This includes limits on the number of fishing days, gear restrictions, and closed seasons or marine protected areas that allow stocks to replenish (Roberts et al., 2024). These tools are especially valuable in contexts where data to implement total allowable catch (TAC) systems is limited or unreliable. Rights-based approaches, such as territorial use rights in fisheries (TURFs) and individual transferable quotas (ITQs), can also help align incentives for conservation and reduce the race to fish if designed carefully (Sumaila 2018).

To be effective, efforts to reduce overcapacity must be embedded within transparent governance frameworks that include science-based decision-making, MCS systems, and meaningful participation by small-scale fishers and Indigenous Peoples~~ communities~~. When well-managed, reducing overcapacity not only helps rebuild fish stocks and protect marine biodiversity but also contributes to more stable livelihoods, better food security, and healthier ocean ecosystems.~~Overcapacity, where the fishing capacity deployed exceeds what is needed to sustainably catch fish stocks, leads to overfishing and depletion of marine resources. Reducing overcapacity is crucial for maintaining healthy fish stocks and ensuring long-term sustainability (Pauly and Christensen, 1995). Fleet reduction programs, alongside retraining and alternative livelihood opportunities for fishers, can help address this issue. Effort-based management, such as limiting the number of fishing days or the amount of gear used, can further prevent overfishing and ensure the sustainability of fish stocks (Roberts and others, 2024).~~

~~Monitoring, Control and Surveillance (MCS) systems are essential for enforcing fisheries regulations and preventing illegal activities. Satellite tracking, electronic reporting, and on-board cameras enhance MCS capabilities by allowing real-time monitoring of fishing activities (Paolo and others 2024). Strong enforcement mechanisms, including penalties for non-compliance, ensure that regulations are followed (Le Gallic and Cox, 2006). Collaboration between national authorities and international organizations is necessary to improve enforcement efforts and ensure compliance with global sustainability goals especially in the face of climate change (Miller and others, 2013; Cheung and others, 2024).~~

6.2. Economy

Perverse financial incentives, such as harmful subsidies, promote overfishing and environmental degradation (Milazzo, 1998). Reforming these subsidies is essential for aligning economic incentives with sustainable fisheries management (Sumaila and others, 2010, 2024; Villasante and others, 2024). Incentivizing compliance with conservation measures and participation in sustainable certification programs can promote long-term ecological health (Roberts and others, 2024). Reforming harmful subsidies is a critical step toward achieving sustainable fisheries management and preserving the livelihoods of communities dependent on healthy marine resources (Skerrit and others, 2023).

The decarbonization of the fishing sector will require enormous financial resources that the sector alone cannot provide. The way subsidies or incentives are given should be reviewed. Providing subsidies to energy-efficient vessels or fishing methods, or individual skippers (giving incentive to those skippers that consider other variables to the catch) should be considered, also to those investing in energy-efficient strategies (Bastardie and others, 2022). Having said this, such beneficial subsidies have to be designed carefully or they may backfire (Clark and others, 2005). Investing in education, training, capacity building and sharing. Education and capacity building are crucial for empowering stakeholders to adopt sustainable practices (Lennie, 2005). Training programs on new technologies, sustainable fishing techniques, and resource management are necessary to improve fisheries' management (Bradley and others, 2019). Empowering women and youth through education can lead to more inclusive and resilient fisheries (Stacey and others, 2019). Capacity building and sharing helps communities adopt new technologies, improve safety at sea, and foster innovation, contributing to healthier ecosystems and improved livelihoods (Vierros and others, 2020). By strengthening the skills of those involved in fisheries, education promotes long-term sustainability (Macfadyen and Huntington, 2004).

6.3. Society: Stakeholder collaboration and co-creation

Collaboration among governments, industry, local communities, and NGOs is key to sustainable fisheries management (Pomeroy, 1995). Co-management approaches, where resource management responsibilities are shared, have proven effective in many regions. These partnerships facilitate the sharing of best practices and drive innovation in sustainable fishing practices (Jentoft, 2005). The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) emphasizes co-creating knowledge for the oceans of the future. Co-production of knowledge helps incorporate the perspectives of fishers and local stakeholders in fisheries governance, resulting in better compliance and more effective management strategies (Chambers and others, 2021; Norström and others, 2020). In addition, we highlight the crucial role of consumers in fisheries management through their purchasing choices, advocacy, and demand for sustainable seafood. A good example is the strengthening awareness campaigns of the Ocean Literacy initiative of UNESCO (https://oceanliteracy.unesco.org/?post-types=all&sort=recent).

Indigenous and community-based fisheries management practices, rooted in traditional ecological knowledge, offer valuable insights into sustainable resource management (Berkes and others 2007). Integrating traditional knowledge into modern fisheries governance enhances sustainability and resilience. There is a need for countries to support these practices through policy and funding, recognizing the cultural importance of local knowledge and stewardship. Empowering Indigenous ~~communitie~~Peoples fosters stewardship, protects cultural heritage, and promotes sustainable livelihoods. Community-based management improves compliance and resilience, ensuring conservation measures are culturally appropriate and effective (IPBES, 2019; 2022; 2024). Indigenous and community-based fisheries management (CBFM) is best supported by MSF vessels fishing in open ocean that are infrequently fished by and furthest from communities. Based on community consultations in Fiji, fishers occasionally report seeing large vessels fishing outside outer reef boundaries for bait. This can affect local bait availability, or potentially increased by-catch rates of community important species such as food species in addition to the culturally important species such as turtles and sharks. On a side note, a survey of catch from select landing sites in Fiji showed that most reef fish were consumed by fishers whereas oceanic species were sold (Marre & Hun, 2022).

6.4. Technology

Adopting selective fishing gear. Selective fishing gear plays a crucial role in reducing bycatch—the unintentional capture of non-target species, including juveniles and endangered species (Cook, 2003). The use of selective gear such as circle hooks and turtle excluder devices allows fishers to target specific species and sizes, minimizing harm to marine ecosystems (Condie and others, 2014). Selective fishing gear reduces the capture of juvenile fish, allowing populations to reproduce and grow, thereby supporting the recovery of depleted stocks and maintaining biodiversity. However, incentives are crucial for encouraging fishers to adopt more selective practices, as discard bans alone may not lead to more sustainable outcomes without adequate motivation (Condie and others, 2014; Villasante and others, 2016).

Promoting traceability and transparency. Traceability systems allow for the tracking of fish products from catch to consumer, ensuring that the products are sustainably sourced (Thompson and others, 2005). Electronic Monitoring (EM), which uses cameras, sensors, and GPS, to record fishing activities, offers a cost-effective tool for enhancing compliance, data collection, and transparency in fisheries management. EM can improve oversight where onboard observers are limited. However, barriers to adoption include high upfront costs, concerns over data privacy, lack of technical capacity, and resistance from some fishing operators wary of increased scrutiny and regulatory burden. Technologies such as blockchain and electronic catch documentation enhance transparency in the supply chain and help combat IUU fishing. These technologies also provide consumers with the information necessary to make informed choices, driving demand for sustainable seafood. Transparency in fisheries also reduces IUU fishing, which costs the global economy billions and threatens marine ecosystems (Agnew and others,. 2009; Sumaila and other, 2020). Digital traceability platforms and certification programs enhance trust among stakeholders and promote long-term sustainability (Blaha and others, 2023). Nowadays artificial intelligence is helping different sectors to implement tools for sustainable practices. By leveraging the power of artificial intelligence, these innovative approaches aim to revolutionize the fishing industry by enhancing efficiency, sustainability, and overall productivity (Pereira and others, 2023).

6.5. Governance

The governance of marine fisheries is fundamental to ensuring the sustainability of global marine resources, particularly in the context of medium- and large-scale fisheries (MSF and LSF), which account for a significant share of global catch and economic activity (Österblom & Folke, 2013). The complex and dynamic nature of marine ecosystems—

coupled with the highly mobile behavior of many target species and the diverse and often conflicting interests of industrial, semi-industrial, and artisanal sectors—demands tailored, multiscale governance approaches (Mora et al., 2009; see S3: Global Overview of Ocean Governance).

~~Ecosystem-Based Fisheries Management (EBFM) takes a comprehensive approach by considering the entire ecosystem, including human impacts, rather than managing single species in isolation (Tam and others, 2024). This strategy addresses the interdependencies between species, habitats, and human activities, promoting ecological balance. Protecting critical habitats, such as coral reefs and mangroves, is central to the success of EBFM, which aims to balance ecological, economic, and social objectives. Various practical EBFM approaches have been developed and applied globally as tools to achieve the UN SDG 14 goals (Link and Marshak, 2021; Hobday and others, 2011; Zhang and others, 2011), but its implementation has been slower than expected in many regions (Fletcher and Bianchi, 2014; Patrick and Link, 2015).~~

~~Indigenous and community-based fisheries management practices, rooted in traditional ecological knowledge, offer valuable insights into sustainable resource management (Berkes and others 2007). Integrating traditional knowledge into modern fisheries governance enhances sustainability and resilience. There is a need for countries to support these practices through policy and funding, recognizing the cultural importance of local knowledge and stewardship. Empowering Indigenous communities fosters stewardship, protects cultural heritage, and promotes sustainable livelihoods. Community-based management improves compliance and resilience, ensuring conservation measures are culturally appropriate and effective (IPBES, 2019; 2022; 2024). Indigenous and community-based fisheries management (CBFM) is best supported by MSF vessels fishing in open ocean that are infrequently fished by and furthest from communities. Based on community consultations in Fiji, fishers occasionally report seeing large vessels fishing outside outer reef boundaries for bait. This can affect local bait availability, or potentially increased by-catch rates of community important species such as food species in addition to the culturally important species such as turtles and sharks. On a side note, a survey of catch from select landing sites in Fiji showed that most reef fish were consumed by fishers whereas oceanic species were sold (Marre & Hun, 2022).~~

6.7. Policy

Ecosystem-Based Fisheries Management (EBFM) takes a comprehensive approach by considering the entire ecosystem, including human impacts, rather than managing single species in isolation (Tam and others, 2024). This strategy addresses the interdependencies

between species, habitats, and human activities, promoting ecological balance. Protecting critical habitats, such as coral reefs and mangroves, is central to the success of EBFM, which aims to balance ecological, economic, and social objectives. Various practical EBFM approaches have been developed and applied globally as tools to achieve the UN SDG 14 goals (Link and Marshak, 2021; Hobday and others, 2011; Zhang and others, 2011), but its implementation has been slower than expected in many regions (Fletcher and Bianchi, 2014; Patrick and Link, 2015).

Implementing fishing quotas and catch limits. Fishing quotas and catch limits are fundamental tools for managing fish stocks sustainably (Walters and Martell, 2002). These limits, grounded in scientific data, ensure that fish populations can replenish at sustainable rates. Science-based quotas must be flexible and adaptive, reflecting changes in stock health and ecosystem dynamics (Holsman and others, 2020). Monitoring and enforcement mechanisms such as satellite tracking and on-board observers are necessary to ensure compliance with quotas and to prevent illegal fishing activities (Paolo and others, 2024).

Effective communication of trade-offs, uncertainty, and risks. Clear communication of the trade-offs involved in fisheries management, as well as the uncertainties and risks involved, is essential for informed decision-making (Booshehrian and others, 2012). By involving fishers, scientists, policymakers, and the public, the trade-offs between short-term economic gains and long-term ecological sustainability can be better understood and managed. Developing risk management strategies that account for uncertainties in stock assessments and market fluctuations can mitigate potential negative outcomes (Roux and others, 2022).

All the topics discussed in this section would help~~e~~ ensure the sustainability of LSF and MSF as they work together to preserve marine biodiversity while maintaining global seafood supplies by leveraging innovative technologies, integrating adaptive policies, promoting stakeholder collaboration and providing socio-economic support in the face of changing climate (Sumaila and others, 2024).

Acknowledgements: The writing team extend their gratitude to the many grantors who supported this work, enabling their contribution to WOA III. The writing team also

acknowledges the use of AI tools to clarify ideas, enhance readability, and improve the language of the text. AI was further employed to help condense the content to meet word limits and to translate certain words and sentences from Portuguese to English. Recognizing that AI can generate inaccuracies, the report was thoroughly reviewed and verified by the writing team to ensure its accuracy.

7. References

Abbott, Joshua. K., and Ussif R. Sumaila. Reducing marine plastic pollution: policy insights from economics. Review of environmental economics and policy, vol. 13, No. 2, pp. 327-336, 2019.

Agnew, David J., and others. Estimating the worldwide extent of illegal fishing. PloS one, vol. 4 No. 2, art. e4570, 2009.

Alger, Justin, and others. What would Article 5.1 of the 2022 WTO ministerial agreement on fisheries subsidies accomplish?. Marine Policy, vol. 153, art. 105641, 2023.

Armitage, Derek R., and others. Adaptive co-management for social–ecological complexity. Frontiers in Ecology and the Environment, vol. 7. No, 2, pp 95-102, 2009.

Arnason, Ragnar. On the ITQ fisheries management system in Iceland. Reviews in Fish Biology and Fisheries, vol. 6, pp 63-90, 1996.

Bailey, Megan., and Ussif Rashid Sumaila. Destructive fishing and fisheries enforcement in eastern Indonesia. Marine Ecology Progress Series, 530, 195-211, 2015.

Barston, Ronald. The law of the sea and regional fisheries organisations. The International Journal of Marine and Coastal Law, vol. 14, No. 3, pp 333-352, 1999.

Barz, Fanny. Identifying social practices to inform fisheries management—the case of bycatch practices of marine mammals and seabirds of German gillnet fisheries. ICES Journal of Marine Science, vol. 80, No. 3, pp 458–468, 2023.

Basurto, Xavier and others. Illuminating the multidimensional contributions of small-scale fisheries. Nature, 2025

Belhabib, Dyhia, and others. Feeding the poor: Contribution of West African fisheries to employment and food security. Ocean & Coastal Management, vol. 111, pp 72–81, 2015.

Berkes, Fikret, and others. Collaborative integrated management in Canada's north: The role of local and traditional knowledge and community-based monitoring. Coastal management, vol. 35, No. 1, pp 143-162, 2007.

Bethel, Lonna, and others. Implementing the Port State Measures Agreement to combat illegal, unreported and unregulated fishing in the Caribbean. Marine Policy, vol. 132, art. 104643, 2021.

Blaha, Francisco, and others. Guidance document: advancing end-to-end traceability – critical tracking events and key data elements along capture fisheries and aquaculture value chains. Rome, FAO, 2023.

Bradley, Darcy, and others. Opportunities to improve fisheries management through innovative technology and advanced data systems. Fish and fisheries, vol. 20, No. 3, pp 564-583, 2019.

Booshehrian, Maryam, and others. Vismon: Facilitating analysis of trade-offs, uncertainty, and sensitivity in fisheries management decision making. In Computer Graphics Forum, Oxford, UK: Blackwell Publishing Ltd, vol. 31, No. 3, pp. 1235-1244, 2012.

Burella, Giorgio, and Lorenzo Moro. Design solutions to mitigate high noise levels on small fishing vessels. Applied Acoustics 172 (2021).

Bunwaree, Priyal. The illegality of fishing vessels 'going dark' and methods of deterrence. International and Comparative Law Quarterly, vol. 72, No. 1, 179–211, 2023.

Chambers, Josephine M., and others. Six modes of co-production for sustainability. Nature Sustainability, vol, 4, pp 983–996, 2021.

Cheung, William WL, Daniel Pauly, and U. Rashid Sumaila. "Hope or Despair Revisited: Assessing Progress and New Challenges in Global Fisheries." Fish and Fisheries, 2024.

Chuenpagdee, Ratana, and others. Shifting gears: Assessing collateral impacts of fishing methods in US waters. Frontiers in Ecology and the Environment, vol. 1, No. 10, 517–524, 2003.

Churchill, Robin. Just a harmless fishing fad—or does the use of FADs contravene international marine pollution law? Ocean Development & International Law, vol. 52, No. 2, 169–192, 2021, 2021.

Cisneros-Montemayor, Andres M., and others. A Global Estimate of Seafood Consumption by Coastal Indigenous Peoples. PLoS ONE, vol. 11, No, 12, pp 1-16: art. e0166681, 2016.

Clark, Colin W. and others (2007). Buyback subsidies, the time consistency problem, and the ITQ alternative. Land Economics 83, no. 1: 50-58.

Clark, Colin W., and others (2005). Subsidies, buybacks, and sustainable fisheries. Journal of Environmental Economics and Management 50, no. 1: 47-58.

Condie, Harriet M., and others. Incentivizing selective fishing under a policy to ban discards: Lessons from European and global fisheries. Marine Policy, vol. 45, pp 287–292, 2014.

Cook, Robin "The magnitude and impact of by-catch mortality by fishing gear", *in Responsible Fisheries in the Marine Ecosystem*, Michael Sinclair and Grimur Valdimarsson, eds. (CABI Publishing, Cambridge, MA, USA, 2003).

Costello, Christopher, and others. Can catch shares prevent fisheries collapse?. Science, vol. 321, No. 5896, pp 1678-1681,2008.

Cullis-Suzuki, Sarika, and Daniel Pauly. Failing the high seas: a global evaluation of regional fisheries management organizations. Marine Policy, vol. 34, No. 5, pp 1036-1042, 2010.

Dahlet, Lol I., and others. Fisheries conflicts as drivers of social transformation. Current Opinion in Environmental Sustainability, vol. 53, pp 9-19, 2021.

.

Di Franco, Davide, Katrin Linse, Huw J. Griffiths, Christian Haas, Hanieh Saeedi, and Angelika Brandt. Abundance and distributional patterns of Benthic Peracarid Crustaceans from the Atlantic sector of the Southern Ocean and Weddell Sea. Frontiers in Marine Science 7 (2020).

Drew, Joshua A. Use of traditional ecological knowledge in marine conservation. Conservation Biology, vol. 19, No. 4, pp 1286–1293, 2005.

Enevoldsen, Henrik, and others. State of the ocean report: pilot edition, 2022.

Epstein, Graham, and others. The impact of mobile demersal fishing on carbon storage in seabed sediments. Global Change Biology, vol. 28, No. 9, pp 2875-2894, 2022.

Eriksson, Hampus., and others. Resource degradation of the sea cucumber fishery in the Indian Ocean. Environmental Conservation, vol. 42, No. 4, pp 367–375, 2015.

European Commission. Study on ownership and exclusive rights of fisheries means of production: Final report. Service Contract: EASME/EMFF/2016/1.3.2.1/SI2.766458, 2019.

FAO (Food and Agriculture Organization). Definition and classification of fishery vessel types. Fisheries Technical Paper, 1985.

FAO (Food and Agriculture Organization of the United Nations). Code of Conduct for Responsible Fisheries. Rome, FAO. 41 pp., 1995.

FAO (Food and Agriculture Organization). Fisheries operations: Best practices to improve safety at sea in the fisheries sector. FAO Technical Guidelines for Responsible Fisheries, 2015.

FAO (Food and Agriculture Organization). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO. https://doi.org/10.4060/cc0461en, 2022.FAO (Food and Agriculture Organization) Illuminating Hidden Harvests: The contributions of small- scale fisheries to sustainable development – Executive summary, 2023.

FAO (Food and Agriculture Organization (FAO). The state of world fisheries and aquaculture 2024 – Blue transformation in action, 2024.

Fletcher, Warrick J., and Gabriella Bianchi. The FAO EAF toolbox: Making the ecosystem approach accessible to all fisheries. Ocean & Coastal Management, vol. 90, pp 20–26, 2014.

Gibson, Darah, and Ussif Rashid Sumaila. Determining the degree of small-scaleness using fisheries in British Columbia as an example. Marine Policy, vol. 86, pp 121–126, 2017.

Gill, David. And others. Triple exposure: Reducing negative impacts of climate change, blue growth, and conservation on coastal communities. One Earth, vol. 6, No. 2, pp 118–130, 2023.

Gilman, Eric and others. Benchmarking global fisheries discards. Scientific Reports, vol. 10, art. 14017, 2020.

Gomez, Guillermo., and others. The IUU nature of FADs: Implications for tuna management and markets. Coastal Management, vol. 48, No. 6, pp 534-558, 2020.

1 Greer, Krista, and others. Global trends in carbon dioxide emissions from fuel combustion in
2 marine fisheries from 1950 to 2016. Marine Policy, vol. 107, art. 103382, 2019.

3 Grip, Kjell. International marine environmental governance: A review. Ambio, vol. 46, No. 4, pp
4 413- 427, 2017.

5 Halimatussadiah, Alin, and others. Co-management of large-scale and medium-scale fisheries:
6 An assessment of the fishery tax system in Indonesia. Marine Policy, vol. 148, art. 105458,
7 2023.

8 Harper, Sarah, and others. Women and fisheries: Contribution to food security and local
9 economies. Marine policy, vol. 39, pp 56-63, 2013.

10 Hobday, Alistair J., and others. Ecological risk assessment for the effects of fishing. Fisheries
11 Research, vol. 108, No. (2–3), pp 372-384, 2011.

12 Holsman, Kirsten K., and others. Ecosystem-based fisheries management forestalls climate-
13 driven collapse. Nature Communications, vol. 11, art. 4579, 2020.

14 Huang C, and others. Effects of fishery bycatch-mitigation measures on vulnerable marine
15 fauna and target catch. Nature Sustainability. Vol. 7, No. 11, pp1535-45, 2024.

16 IOC-UNESCO. State of the Ocean Report. Paris, IOC-UNESCO. (IOC Technical Series, 190,
17 2024.

18

19 IPBES (2019). Global assessment report on biodiversity and ecosystem services of the
20 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (pp. 1-
21 1082). Brondízio, E. S., Settele, J., Díaz, S., and Ngo, H. T. (eds). IPBES secretariat, Bonn,
22 Germany. DOI: https://doi.org/10.5281/zenodo.3831673

23 IPBES (2022). Methodological Assessment Report on the Diverse Values and Valuation of
24 Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem
25 Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D.
26 (eds.). IPBES secretariat, Bonn, Germany. DOI: https://doi.org/10.5281/zenodo.6522522

27 IPBES (2024). Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and
28 the Determinants of Transformative Change and Options for Achieving the 2050 Vision for
29 Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and

Ecosystem Services. O'Brien, K., Garibaldi, L., and Agrawal, A. (eds.). IPBES secretariat, Bonn, Germany. DOI: https://doi.org/10.5281/zenodo.11382215

IPCC (Intergovernmental Panel On Climate change. Climate change. Impacts, adaptation and vulnerability. Geneva, Switzerland (2001), 2007.

IPCC (Intergovernmental Panel On Climate change. 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Geneva, Switzerland, 2023.Jennings, Simon, and Michael. J. Kaiser. The effects of fishing on marine ecosystems. In Advances in marine biology (Vol. 34, pp. 201-352). Academic Press, 1998.

Jentoft, Svein. Fisheries co-management as empowerment. Marine policy, vol. 29, No. 1, pp 1-7, 2005.

Kaiser, Michael J. Recent advances in understanding the environmental footprint of trawling on the seabed. Canadian Journal of Zoology, vol. 97, No. 9, pp 755-762, 2019.

Kelleher, Kieran, and others. Hidden harvest: The global contribution of capture fisheries. World Bank; WorldFish, 2012.

Kleiber, Danika. Gender and small-scale fisheries: A case for counting women and beyond. Fish and Fisheries, vol. 16, No. 4, pp 547-562, 2015.

Kuemlangan, Blaise, and others. Enforcement approaches against illegal fishing in national fisheries legislation. Marine Policy, vol. 149, art. 105514, 2023.

Lau, Winnie and others. Evaluating scenarios toward zero plastic pollution. Science, vol. 369, No. 6510, pp 1455-1461, 2020.

Le Gallic, Bertrand, and Anthony Cox. An economic analysis of illegal, unreported and unregulated (IUU) fishing: Key drivers and possible solutions. Marine Policy, vol. 30, No. 6, pp 689-695, 2006.

Lennie, June . An evaluation capacity-building process for sustainable community IT initiatives: Empowering and disempowering impacts. Evaluation, vol. 11, No. 4, pp 390-414, 2005.

Lentisco, Angela., and Robert U. Lee. A review of women's access to fish in small-scale fisheries. FAO Fisheries and Aquaculture Circular, (C1098), I, 2015.

Link, Jason. S., and Anthony R. Marshak. Ecosystem-Based Fisheries Management: Progress, Importance, and Impacts in the United States. Walton Street, Oxford: Oxford University Press, 2012.

Link, Jason S., and Reg A. Watson. Global ecosystem overfishing: Clear delineation within real limits to production." Science Advances 5, no. 6, 2019.

Lively, Julie A., and Jonathan McKenzie. Discards and bycatch: A review of wasted fishing. Advances in Marine Biology, vol. 95, pp 1-26, 2023.

Macfadyen, Graeme, and Tim Huntington. Human capacity development in fisheries, 2004.

McLennan and others. The new Marine Stewardship Council requirements to improve ghost gear management: Insights from the policy development process." Marine Policy 157, 2023.

Mariani, Gaël, and others. Let more big fish sink fisheries prevent blue carbon sequestration-half in unprofitable areas. Science Advances, vol. 6, 2020.

Marre, Jean-Baptiste., and A. Hunt. Coastal fisheries and FAD monitoring project in Kadavu, Fiji: An assessment of data collected from 2017-2020, 2022.

Mendenhall, Elizabeth, and others. Climate change increases the risk of fisheries conflict. Marine Policy, vol. 117, art. 103954, 2020.

Merten, Wessley, and others. Global Fishing Watch: Bringing transparency to global commercial fisheries. arXiv preprint arXiv:1609.08756, https://arxiv.org/abs/1609.08756 , 2016.

Milazzo, Matteo. Subsidies in world fisheries: a reexamination (Vol. 23). World Bank Publications, 1998.

Miller, D. D., & U. Rashid Sumaila (2014). Flag use behavior and IUU activity within the international fishing fleet: Refining definitions and identifying areas of concern. Marine Policy, 44, 204-211.

Miller, Kathy and others. Governing marine fisheries in a changing climate: A game-theoretic perspective. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, vol. 61, No. 2, pp 309-334, 2013.

Mora, Camilo., and others. Management effectiveness of the world's marine fisheries. PLoS biology, vol 7, No. 6, art. e1000131, 2009.

Moreno, Gala, and others. Fish aggregating devices (FADs) as scientific platforms. Fisheries Research, vol. 178, pp 122-129, 2016.

Morris, Kate, and others. Adapting the Marine Stewardship Council's risk-based framework to assess the impact of towed bottom fishing gear on blue carbon habitats. PLOS ONE, vol. 18, No. 11, art. e0288484, 2023.

Munro, Gordon. R. (1996). Approaches to the economics of the management of high seas fishery resources: a summary. The Canadian Journal of Economics/Revue canadienne d'Economique, 29, S157-S164.

Murphy, Brenda L. From interdisciplinary to inter-epistemological approaches: Confronting the challenges of integrated climate change research. The Canadian Geographer/Le Géographe Canadien, vol. 55, No. 4, pp490-509, 2011.

Nama, Suman, and Suchismita Prusty. Ghost gear: the most dangerous marine litter endangering ocean. Food Sci. Rep 2: 34-38, 2021.

Naylor, Rosaline and others. Blue food demand across geographic and temporal scales. Nature communications, vol. 12, No. 1, art. 5413, 2021.

Norse, Elliott A., and others. Sustainability of deep-sea fisheries. Marine Policy, vol. 36, No. 2, 307- 320, 2012.

Norström, Albert V., and others (2020). Principles for knowledge co-production in sustainability research. Nature Sustainability, vol. 3, No. 3, pp 182-190, 2020.

O'Keefe, Catherine E., and others. Efficacy of time-area fishing restrictions and gear-switching as solutions for reducing seabird bycatch in gillnet fisheries. Reviews in Fisheries Science & Aquaculture, vol. 31, No. 1, pp 29–46, 2023.

Oloko, Ayodele and others. Making the case for gender-inclusive fisheries governance, policies and climate adaptation. Discover Oceans, vol. 1, No. 1, pp 1-14, 2024.

Österblom, Henrik and Carl Folke. Emergence of global adaptive governance for stewardship of regional marine resources. Ecology and Society, vol. 18, No. 2, 3013.

Paolo, Fernando S., and others. Satellite mapping reveals extensive industrial activity at sea. Nature, vol. 625, pp 85–91, 2024.

Patrick, Wesley. S., and Jason S. Link. Myths that continue to impede progress in ecosystem-based fisheries management. Fisheries, vol. 40, No. 4, pp 155-160, 2015.

Pauly, Daniel, and others. Towards sustainability in world fisheries. Nature, 418(6898), 689-695, 2002.

Pauly, Daniel, and Villy Christensen. Primary production required to sustain global fisheries. Nature, vol. 374, pp 255–257, 1995.

Pauly, Daniel, and others. Global fisheries: A brief review. In The Oceans Economy, pp. 15-38, Cambridge University Press, 2014.

Paterson, John. Sustainable development, sustainable decisions and the precautionary principle. Natural hazards, vol. 42, pp 515-528, 2007.

Pereira, Laura M., and others. The living infinite: Envisioning futures for transformed human-nature relationships on the high seas. Marine Policy. Vol. 153, article 105644, 2023.

Pikitch, Ellen K., and others. Ecosystem-based fishery management. Science, vol. 305, No. 5682, pp 346-347, 2004.

Pinkerton, Evelyn W. Local fisheries co-management: a review of international experiences and their implications for salmon management in British Columbia. Canadian journal of fisheries and aquatic sciences, vol 51, No. 10, pp 2363-2378, 1994.

Pittman, Jeremy, and others. Governing offshore fish aggregating devices in the Eastern Caribbean: Exploring trade-offs using a qualitative network model. Ambio, vol. 49, pp 2038–2051, 2020.

Phillips Richard A., and others. Incidental mortality of seabirds in trawl fisheries: A global review. Biological Conservation. Vol. 296, art. 110720, 2024.

Pollnac, Richard B., and others. Aspects of fishery management, job satisfaction, and well-being among commercial fishermen in the northeast region of the United States. Society & Natural Resources, vol. 28, No. 1, pp 75-92, 2015.

Pomeroy, Robert S., Community-based and co-management institutions for sustainable coastal fisheries management in Southeast Asia. Ocean & Coastal Management, vol. 27, No. 3, pp 143- 162, 1995.

Richardson, Kelsey, and others. Global estimates of fishing gear lost to the ocean each year. Science Advances 8, no. 41, 2022.

Roberts, Callum, and others. Rethinking sustainability of marine fisheries for a fast-changing planet. npj Ocean Sustainability, vol. 3, No. 41, , 2024.

Roux, Marie-Julie, and others. Consistent risk management in a changing world: Risk equivalence in fisheries and other human activities affecting marine resources and ecosystems. Frontiers in Marine Science, vol. 3, 2022.

San Juan, A. Pérez, and others. Undetected silky sharks (Carcharhinus falciformis) in the wells of the tropical tuna purse seine fleet in the Indian Ocean. Fisheries Research 278 2024.

Schatz, Valentin. Assessing Drifting Fish Aggregating Device (dFAD) Abandonment under International Marine Pollution Law. Transnational Environmental Law, vol. 13, No. 2, pp 243–263, 2024.

Scherrer, Kim J. N., and others. Diminishing returns on labour in the global marine food system. Nature Sustainability, Vol. 7, pp 45-52, 2024.

Selig, Elizabeth R., and others. Revealing global risks of labor abuse and illegal, unreported, and unregulated fishing. Nature Communications, vol. 13, art. 1612, 2022.

Skerritt, Daniel J., and others. Mapping the unjust global distribution of harmful fisheries subsidies. Marine Policy, vol. 152, art. 105611, 2023.

Srinivasan, Thara. U., and others. Food security implications of global marine catch losses due to overfishing. Journal of Bioeconomics, vol. 14, No. 3, pp 183–204, 2012.

Stacey, N., and others. Enhancing coastal livelihoods in Indonesia: an evaluation of recent initiatives on gender, women and sustainable livelihoods in small-scale fisheries. Maritime Studies, vol. 18, pp 359-371, 2019.

Sumaila, Ussif Rashid. A review of game-theoretic models of fishing. Marine policy, vol. 23, No. 1, pp 1- 10, 1999.

Sumaila, Ussif Rashid. Infinity fish: Economics and the future of fish and fisheries. Academic Press, 2021.

Sumaila, Ussif Rashid. Reflections on breaking down silos in fisheries science. Fisheries 49, no. 5, 207-210, 2024.

Sumaila, Ussif Rashid, and others. Small versus large-scale fishing operations in the North Atlantic. Fisheries Centre Research Report, vol. 9, No. 5, pp 28–35, 2001.

Sumaila, Ussif Rashid, and others. Global scope and economics of illegal fishing. Marine Policy, vol. 30, No. 6, pp696-703, 2006.

Sumaila, Ussif Rashid, and others. A bottom-up re-estimation of global fisheries subsidies. Journal of Bioeconomics, vol. 12, pp 201-225, 2010.

Sumaila, Ussif Rashid, and others. Impact of the Deepwater Horizon well blowout on the economics of US Gulf fisheries. Canadian Journal of Fisheries and Aquatic Sciences, vol. 69, No. 3, pp 499- 510, 2012.

Sumaila, Ussif Rashid, and others. Winners and losers in a world where the high seas is closed to fishing. Scientific reports, vol 5, No. 1, art. 8481, 2015.

Sumaila, Ussif Rashid. How to make individual transferable quotas work economically, socially, and environmentally. In Oxford Research Encyclopedia of Environmental Science, 2018.

Sumaila, Ussif Rashid, and others. Updated estimates and analysis of global fisheries subsidies. Marine Policy, Vol. 109, art. 103695, 2019.

Sumaila, Ussif Rashid, and others. Illicit trade in marine fish catch and its effects on ecosystems and people worldwide. Science Advances, vol. 6, No. 9, 2020.

Sumaila, Ussif Rashid, and Travis C. Tai. "End overfishing and increase the resilience of the ocean to climate change." Frontiers in Marine Science 7, 2020.

Sumaila, Ussif Rashid, and others. WTO must complete an ambitious fisheries subsidies agreement. npj Ocean Sustainability, vol. 3, No. 6, 2024.

Sumaila, Ussif Rashid, and others. Sea change: charting a sustainable future for oceans in Canada. University of British Columbia Press, 2024.

Sumaila, Ussif Rashid and others How overfishing handicaps resilience of marine resources under climate change. Frontiers in Marine Science, 10, 1250449, 2003.

Syddall, Victoria. M., and others. What does gender have to do with the price of tuna? Social-ecological systems view of women, gender, and governance in Fiji's tuna fishery. Maritime Studies, vol. 21, pp 447–463, 2022.

Tam, Jamie C., and others. Comparing apples to oranges: common trends and thresholds in anthropogenic and environmental pressures across multiple marine ecosystems. Frontiers in Marine Science, vol. 4, art. 282, 2017.

Tam, Jamie. C., and others. Expanding the scope and roles of social sciences and humanities to support integrated ecosystem assessments and ecosystem-based management. ICES Journal of Marine Science, vol. 81, No. 1, pp 22–42, 2024.

Teh, Lydia, and others. Contribution of marine fisheries to worldwide employment. Fish and Fisheries, vol 14, pp 77–88, 2013.

Thermes, Stefano, and others. Classification and definition of fishing vessel types. Second edition. FAO Fisheries and Aquaculture Technical Paper, No. 267, 2023.

Thompson, Millar, and others. Seafood traceability in the United States: Current trends, system design, and potential applications. Comprehensive reviews in food science and food safety, vol 4, No. 1, pp 1-7, 2005.

Tickler, David, and others. Modern slavery and the race to fish. Nature Communications, vol. 9, art4643, 2018.

Tyedmers, Peter. H., and others. Fueling global fishing fleets. AMBIO: a Journal of the Human Environment, vol. 34, No. 8, pp 635-638, 2005.

UN Decade Vision 2030: The Ocean Decade's strategic ambition setting process on the road to 2030, https://oceandecade.org/vision-2030/, 2021.

Vave, Ron. Five culturally protected water body practices in Fiji: Current status and contemporary displacement challenges. Ambio, vol 51, No 4, pp 1001-1013, 2022.

Vave, Ron and others. Impacts of commercial and subsistence fishing on marine and cultural ecosystem services important to the wellbeing of an Indigenous community in Hawai'i. Ecosystem Services, vol 69, art. 101661, 2024.

Vierros, Marjo K., and Harriet Harden-Davies. Capacity building and technology transfer for improving governance of marine areas both beyond and within national jurisdiction. Marine Policy, 122, 104158, 2020.

Villafáfila Mireia, and others. Mitigating the effect of by-catch on endangered marine life. Animal Conservation, 2024.

Villasante, Sebastian, and others. Fishers' perceptions about the EU discards policy and its economic impact on small-scale fisheries in Galicia (North West Spain). Ecological Economics, vol, 130, pp 130–138, 2016.

Villasante, Sebastian, and others. Strengthening European Union fisheries by removing harmful subsidies. Marine Policy, vol. 136, art. 104884, 2024.

Walters, Carl., and Steve Martell. Stock assessment needs for sustainable fisheries management. Bulletin of Marine Science, vol. 70, No. 2, pp 629-638, 2002.

White, Crow, and Chris Costello. Close the high seas to fishing? PLoS biology, vol. 12, No. 3, art. e1001826, 2014.

Wilson, Douglas. C., and others (Eds.). The fisheries co-management experience: accomplishments, challenges and prospects, 2003.

World Trade Organization: Leveraging Global Partnerships to Implement the WTO Agreement on Fisheries Subsidies for a sustainable and food-secure future https://www.wto.org/english/res_e/publications_e/fishsubsidies624_e.htm, 2024.

Zhang, Chang Ik., and others. An IFRAME approach for assessing impacts of climate change on fisheries. ICES Journal of Marine Science, vol. 68, No. 6, pp 1318–1328, 2011.

Section 5A

Sub-chapter 1b: Small-scale fishing including subsistence fishing

Coordinating Author:

Derek Armitage

Writing Team:

Deborah Prado, Denis Aheto, Beodeul Kang, Tricia Lovell, Melissa Marschke, Ella-Kari Muhl, Prateep Nayak, Ife Okafor-Yarwood, Cristina Pita, Sisir Pradhan, Micaela Trimble, Ron Vave and Nobuyuki Yagi

Key Insights

- Small-scale and subsistence fisheries make substantial contributions to national and global economies, and are of significant social and cultural importance.
- Cumulative effects of a wide range of drivers (e.g., social, economic, environmental and climate) pose significant threats to the viability and resilience of small-scale and subsistence fisheries globally.
- Sustainable pathways for small-scale and subsistence fisheries must respond to the cumulative effects of multiple drivers of vulnerability, build on their knowledge and experience, and address their concerns of equity, human rights and security.

1.0 Introduction

The Food and Agricultural Organization (FAO) Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication were ratified in 2014 (FAO, 2015). The guidelines provide a roadmap to help secure sustainable small-scale and subsistence fisheries (hereafter SSF) and their multi-dimensional contributions (i.e., food security, income generation) across the value chain (i.e., the nodes and networks of activity that yield value from pre- and post-harvest, processing and marketing~~capture/harvest, processing, marketing~~) (Jentoft and others 2017; Arthur and others 2022; Nakamura and others 2021; Basurto and others, 2025). The contributions of SSF to the United Nations Agenda 2030 and Sustainable Development Goals, as well as the implementation of the Global Biodiversity Framework, are increasingly recognized (Charles and others 2024). However, SSF tend to be economically vulnerable and politically marginalised in global policy debates (Jentoft et al. 2022).

There is no globally agreed definition of SSF but they can be characterised as ~~The FAO defines SSF as~~ place-based and for primarily family consumption (low production), ~~characterized by~~with limited capital or resource inputs, but labour intensive, and based on trips that are spatially and temporally limited (i.e., close to shore, completed within a day) (FAO, 2018). Individual nation states have adopted a wide range of definitions linked to gear type (i.e., type and size of nets), length of boat and means of power, vessel ownership, trip duration, and area of fishing activity (i.e., inshore, nearshore, etc.) (Pita and others 2020; Smith and Basurto, 2019) (see Table 5a.C1b.1). SSF include pre-harvest (preparing gear, planning), harvest of fishery resources, and post-harvest activities (marketing, trading). Activities across the value chain are undertaken by men and women (Rosales and others 2017; Pradhan and others 2022; Galappaththi and others 2023).

Table 5a.C1b.1: Selected attributes and elements of small-scale fisheries

ATTRIBUTE	RELATED ELEMENTS	EXAMPLES
Indicative gear	Fishing gear	Labour intensive gear
		Passive gear
	Mechanization	No mechanization
		Small power winch (hauler powered off engine)
Vessel	Size of fishing vessel	No vessel
		Less than 12 metres or 12-24 metres
	Motorization	No engine
		Engine less than 100 hp; engine 100-400 hp
Operations	Fishing trip duration	Less than 6 hours
		Day trip
		One to four days
	Fishing location and range	Less than 100 metres from shore
		Up to 10 km offshore
		10-20 km offshore

Storage / Preservation	Refrigeration/storage	No cold storage
		Ice box on board
		Ice hold below deck
Employment / Labour	Labour crew	Individual or family
		Cooperative group
		Small number of employed crew
	Ownership	Owner or owner – operator
		Lease arrangement
	Time commitment	Occasional
		Full-time seasonal or part-time all year
		Full-time
Use of Catch	Disposal of catch	Household consumption or barter exchange
		Direct sale at landing site(s)
		Sale to traders (middlepersons)
	Utilization of catch, value addition, preservation	For direct human consumption
		Chilled, locally processed, cured/salted/dried
		Frozen (temporarily)
	Integration into economy and/or management system	Informal, non-integrated (no fees)
		Integrated (registered, un-taxed)
		Formalized (licensed, landing fees)

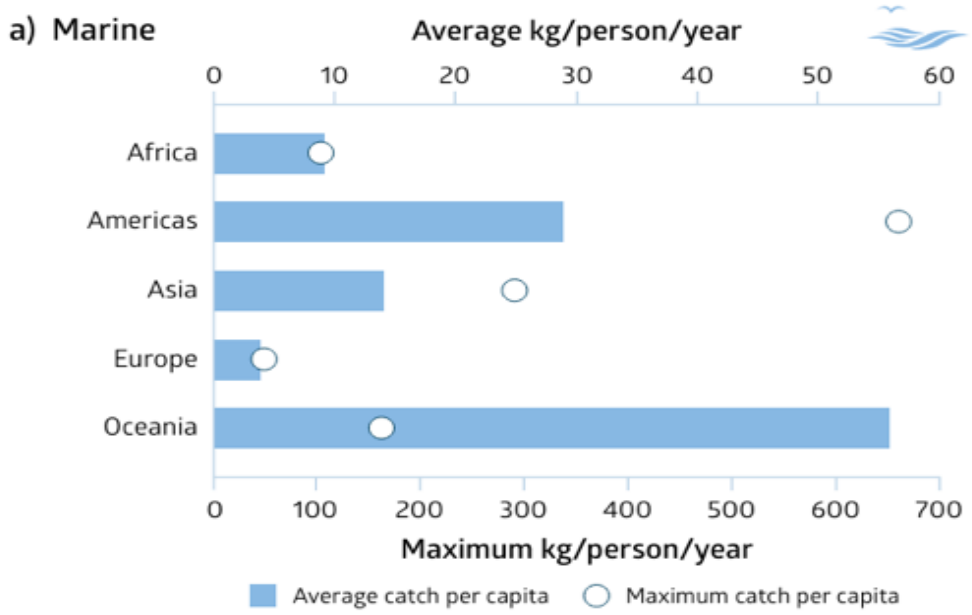
Source: Adapted from: (FAO, Duke University & WorldFish, 2023)

There are numerous exceptions to the attributes reflected in Table 5a.C1b.1 (see FAO, 2015; Smith and Basurto, 2019). Identification of the size, scope and scale of fishery operations is recommended to improve policy implementation (e.g., access and tenure, marketing, economic policy, regulation and enforcement, etc.), and to enhance evidence-based and comparative assessment. However, definitions of SSF are not an immutable category fixed in time and space. Rigid adherence to a specific definition is neither possible nor desirable.

The economic, social and cultural importance of SSF is very well established (Chuenpagdee and others 2017; Dias and others, 2023; Berkes and Franz, 2025). Total landings (all species) of marine small-scale

fisheries are estimated at 25.1 million tonnes per year, or approximately 40 percent of the global landings (FAO, 2023), with an estimated annual revenue of approximately USD 77 billion (FAO, Duke University and WorldFish, 2023:30). There are significant regional variations in total catch per capita (see Figure 5a.C1b.1). Oceania has the largest average annual marine catch per capita, while Europe has the lowest. However, regional variations in catch per capita do not necessarily indicate their relative importance, especially in unregulated and unreported fishing. Despite lower catch per capita levels, small-scale fisheries in Africa and Asia are crucially important because of the overall number of fishers in the sector.

Figure 5a.C1b.1: Global estimates of marine small-scale fisheries catch per capita, by region (average annual values, 2013–2017)



Source: FAO, Duke University & WorldFish. 2023

Contributions of SSF are gendered (i.e., there are differences between men and women), highlighting the importance of gender analysis in SSF policy (Lawless and others 2021; Okafor-Yarwood and others 2024a). SSF contribute to poverty alleviation, viable livelihoods, and are linked to cultural identity and stewardship (Arthur and others 2022; Béné and others 2016; Mangubhai and others 2021). SSF are also ~~contribute~~ important to food security and nutrition, contributing an average of 17% of the nutrient supply globally, ~~including~~ and are source of vitamin B12, calcium, and important fatty acids ~~, and comprise up to 100% of nutrition needs in some countries~~ (Viana and others 2023; Basurto and others, 2025).

2.0 Pressures and impacts

Pressures and impacts on SSF are significant and include (i) economic growth and coastal development (Brent and others 2020), (ii) overfishing, environmental impacts and climate change (Ruiz-Díaz and others 2020), (iii) competition with medium or large-scale fisheries sectors, including Illegal, Unreported and Unregulated (IUU) fisheries and marine security/boundary issues (Ayilu and others 2023; Okafor-Yarwood and others 2024b), (iv) loss of access catalyzed by efforts to meet marine conservation targets (Bennett and others 2021), (v) global trade and competition for market access (Schuhbauer and others 2019), and (vi) policy and governance shifts (Sowman and Sunde, 2021; Berkes and Franz, 2025) (see chapter S4.C1). The heterogeneity of SSF, non-standardized approaches to data collection and analysis, and lack of data collection generally across a range of environmental drivers affecting SSF limits fine-grained assessments necessary to support targeted policy interventions.

Most member nations with ocean areas under their national jurisdiction have or are adopting strategies or regulatory frameworks related to ocean use and planning to catalyze economic growth and coastal development. Investments in marine sectors by financial institutions and other donors in Latin America, for example, have expanded considerably between 2012 and 2020 (Gerhardinger and others 2022). Investment strategies rarely include the participation of SSF organizations (Schuhbauer and others 2020). Evidence that poorly structured coastal and ocean economic development policies negatively impact SSF communities is established but incomplete (Bennett and others 2021a; Ertör, 2023; Jentoft, 2022; Okafor-Yarwood and others 2020). Ocean 'grabbing' (i.e., securing ocean space) by private and/or state actors may create significant injustices through a set of displacement and dispossession processes targeting fisher communities, and may sometimes be in conflict with customary tenure and access rights (Ertör, 2023; The Ocean Defenders Project, 2025). Such social processes exacerbate the ~~impacts~~ effects of sea level rise, including tidal flooding and erosion (Gonzalez-Mon and others 2021) that already drive displacement and migration decisions. The displacement and/or migration of communities from their fishing territories to different locations creates social challenges given the strong sense of place of most small-scale communities (Cánovas-Molina and García-Frapolli, 2022; FAO, Duke University and WorldFish 2023; Okafor-Yarwood and others 2020; Queffelec and others 2021).

Plans for new ports, tourist facilities, shipping lanes and security zones, oil rigs, mining areas, wind farms, and new aquaculture ponds can also encroach on the geographic, political, and economic territorial spaces (i.e., creating new maritime boundary disputes augmented by climate change) and negatively impact the environment upon which small-scale fishers rely. Offshore hydrocarbon operations impact wild-capture fisheries by displacing fish stocks and altering fish biochemistry, while submarine pipelines and cables may also hinder SSF activity (Jouffray and others 2020). The growth in offshore sea mining will generate significant habitat impacts and discharge sediments and metals into the water column (UNEP, 2022), negatively affecting ecosystems and SSF. The negative effects of underwater noise,

vibration, and electromagnetic waves from large wind farms on fisheries resources have also been identified (Oh and others 2021).

The cumulative effects of environmental and climate drivers on the viability of SSF is very well established (Brent and others, 2020; Evans and others 2023; Louey 2022). Fish disease, habitat degradation, invasive species, and loss of species diversity were identified as important environmental drivers impacting small-scale fishers across 12 focal countries in Asia and Africa (Dias and others 2023). SSF livelihoods depend on aquatic and marine environments and the conditions of these ecosystems (such as water quality, temperature and salinity) are crucial for their sustainability. Environmental degradation, such as pollution from domestic, industrial, agricultural, and aquaculture wastes, and poor watershed management can adversely impact these conditions, threatening the viability of SSF (Nayak and others 2014; Martínez-Vázquez and others 2021; Evans and others 2023). Variations in water quality across geographical areas can affect the accessibility and availability of fish.

Macro and micro-plastic pollution (fragments and fibres) has emerged as a crucial coastal and fisheries challenge, with human health implications (Barboza and others 2018; Rochman and others, 2015; Smith and others 2021). Evidence of the relationship between microplastics and SSF is established but incomplete, yet research points to an environmental driver affecting a diverse range of fisheries and ecosystems (e.g., pelagic, demersal, benthic zones) with negative implications for SSF. For example, Savoca and others (2021) estimate that plastic ingestion is occurring in 386 species of marine fish globally, while Pellini and others (2018) indicate that about 95 percent of fish that were analyzed from the Adriatic Sea were observed to contain microplastics. A 2024 study in Puerto Morelos, Mexico recorded high levels of microplastics in commercial reef species, many of which make up a significant component of landings for small-scale fisheries in the Mexican Caribbean (Rivera-Garibay and others 2024). Regional variations in the impacts of plastic pollution are likely and may disproportionately affect SSF, although evidence on this relationship is incomplete.

SSF are overlooked in the climate change literature, and ~~as a focal point~~ in IPCC assessments (Villasante and others 2022). However, projected effects of climate change (IPCC, 2023) will disproportionately impact small-scale fishing communities, with varying levels of intensity in different regions associated with shifts in sea surface temperatures, range shifts and stock composition change, sea-level rise, changes in rainfall patterns, shifts in salinity associated with saltwater intrusion from higher levels of freshwater inflow, an increase in extreme weather events and associated coastal erosion, ocean acidification and coral reef bleaching (Bell and others 2013; Mimura, 1999; IPBES 2019, 2024). Abnormally warm water temperatures and other climate stressors directly affect the quantity and the quality of SSF catch (FAO, Duke University and WorldFish, 2023) with correlating socioeconomic impacts for thousands of vulnerable households. Total maximum catch potential in the world's exclusive economic zones (EEZs) is likely to decrease 7 to 12% by 2050 if a "business-as-usual" greenhouse gas

emission scenario is followed, strongly driven by changes in plankton productivity (Monnier and others 2020). The decrease could be up to 40% in some areas of the intertropical zone, largely impacting countries that are most dependent on fisheries as a source of protein (Monnier and others 2020). SSF are likely to suffer the most significant impacts from these climate-driven changes, and compound the effects of increasing industrialization, urbanization and the multiple uses of aquatic spaces (see FAO, Duke University and WorldFish, 2023; Berkes and Franz, 2025).

Competition with other fisheries sectors, including IUU fishing, generate a range of pressures and impacts. For instance, it is well established that competition and conflicts with industrial fishing boats are a major threat to small-scale fishing livelihoods in some regions (Horta and Defeo, 2012; Okafor-Yarwood and others, 2022; Seto and others, 2023) (see chapter S5A.C1a). Many countries have pursued the expansion of industrial fisheries as a development strategy for decades (Ayilu and others, 2023; Schuhbauer and others, 2019). This has intensified the overexploitation of resources and increased pressure on small-scale fishing, leading to significant inequities and evidence of conflict between small-scale and industrial fisheries (Crona and others, 2021; Seto and others, 2023). SSF frequently compete for market share with products from industrial fisheries, aquaculture and imports (Crona and others, 2016; Pita and others 2020), posing a range of livelihood challenges. Further, IUU fishing, piracy and unsustainable fishing practices are closely connected to lack of enforcement ~~of regulations~~ and limited public involvement in management (Widjaja and others, 2023). IUU fishing is a major threat to marine ecosystems and fishery resources, and can lead to significant loss of local fisheries, with SSF in developing countries known to be particularly vulnerable (FAO, 2024; Song and others, 2020; WIOMSA, 2022). However, complicating assessments of the impacts of IUU on SSF are the various forms and drivers of IUU, the role of SSF in IUU, as well as the lack of consensus on what constitutes IUU in some regions (WIOMSA, 2022; FAO, 2024). Regional~~ly~~ variation complicates the development of guidelines to address IUU and common monitoring indicators (see FAO, 2024).

Globally, the impact of maritime safety interventions and security policies, often in tandem with blue economy strategies, is established but incomplete. In West Africa, for example, security zones are being imposed around sensitive maritime areas (e.g., enforcing closed areas ranging from three nautical miles around offshore hydrocarbon exploration platforms to seven nautical miles around onshore oil and gas infrastructure) (see Adjei and Overå, 2019; Beseng, 2019). Artisanal fishers may be detained or harassed if they enter these areas. A ban on fishing within 500m of oil rigs similarly limits the activities of artisanal fishers in Ghana and Nigeria, and reduces access to traditional fishing grounds (Okafor-Yarwood and others, 2022; Bell and others, 2021), thus requiring fishers to go further out to sea with concomitant safety risks.

Disruptions to sea lines of communication through acts of piracy and armed robbery in strategic regions (e.g., the Gulf of Aden, the Gulf of Guinea, the South China Sea, and the Red Sea) further limit freedom

of navigation for small-scale fishers (Liss, 2014; Secure Fisheries 2020; Bell and others, 2021 Guilfoyle, 2013). Numerous UN Security Council Resolutions on Piracy and Armed Robbery at Sea have been enacted to mitigate these dangers. At the national level, anti-piracy measures ~~include~~ may include prohibit~~in~~gions on ~~-~~small-scale fishers from using certain harbours, imposition of curfews (Bell and others, 2021) and no-fishing zones. Increased law enforcement presence at sea may reduce piracy and armed robbery, but it results in the loss of traditional fishing grounds or restricts access to fishing areas at specific times to fishers, often without compensation (Bell and others, 2021). In some situations, small-scale fishers are mistaken for pirates and either reported as suspicious (as is mostly the case in the Gulf of Guinea) or targeted in the Southern Indian ~~Sea~~Ocean. Many artisanal fishers operate at night (Mills and others, 2014), generating further uncertainty and livelihood impacts.

Marine conservation policies and specific interventions (e.g., marine protected areas, MPAs) can contribute to the sustainability of SSF, for example, from spill-over effects, and protection of habitat and species at specific life stage. There is evidence that well-managed MPAs may result in 'co-benefits' for fisheries and coastal communities ~~associated with well-managed MPAs~~ (Ban and others 2019; Nowakowski and others 2023; Costello 2025). However, increased efforts to achieve 30x30 targets in the Global Biodiversity Framework may exacerbate the challenges faced by SSF. More than 190 countries committed to the 30x30 ~~goal~~ target of protecting at least 30% of ~~-~~ terrestrial and inland water areas, and of marine and coastal areas by 2030 ~~the environment by 2030~~ (Eckert and others, 2023). Contemporary marine conservation efforts can marginalize coastal and small-scale fishing communities (Cinti and others, 2024; Tafon and others, 2022) via implementation of fishing bans and no-take zones, enclosure and access constraints, or top-down enforcement of conservation regulations (Muhl and others, 2020; Trimble and others, 2014; Bennett and others, 2021b; Ertör, 2023). In South Africa, for example, conservation efforts have displaced SSF communities from historically important fishing areas (Peer and others, 2022; Sowman and Sunde, 2018). Such conservation initiatives can further alienate the under-researched, and largely undocumented, cultural fisheries management strategies for funerals or chiefly investiture of Indigenous Peoples and local communities (IPLCs), resulting in further displacement and exclusion (Vave, 2022). Negative impacts include the loss of community harvesting in conservation zones for funerary feasts, and the loss of IPLCs cultural practice which can impact access rights and identity (Vave, 2022).

3.0 Social components

Across the fish value-chain (i.e., harvest/capture, processing and marketing) ~~(i.e., the nodes and networks of activity that yield value from pre- and post-harvest and marketing)~~, small-scale capture fisheries provide full or part time employment opportunities for approximately 60.2 million people, or about 90 percent of the total number of people employed in capture fisheries globally (FAO, Duke University and WorldFish, 2023; FAO, 2024). As of 2016 (latest projections), close to 500 million people

are estimated to have some dependence on SSF for their livelihood, with an estimated 53 million people directly involved in fishing for subsistence (i.e., primarily for family food needs (FAO, 2024). Notably, FAO technical guidelines for responsible fishing place emphasis on fish processing, trade, and poor-friendly market systems to enhance economic efficiency and welfare gains in developing countries (Bjorndal and others, 2014; Pradhan and others, 2022).

Key social attributes influence the distribution of economic and livelihood benefits within SSF communities, including gender and identity (Galappaththi and others, 2022), displacement and labour precarity (Marschke and others, 2019), security/safety at sea (Guilfoyle 2014), social protection (FAO, 2019; Tabe-Ojong and others, 2025) and wellbeing (Trimble and Johnson, 2013; Weeratunge and others, 2014). Efforts to build socially viable SSF must engage more fully with place-based knowledges of fishers (Kitolelei and others, 2021; Pascua and others, 2017). A focus on value chains also enables a coherent assessment on equity and distribution of benefits. There is evidence of traders and processors accessing exclusive market information that facilitates exploitative social relationships and constrains the power of small-scale fishers (Ferrol-Schulte 2014; Pradhan and others, 2022).

Financial viability of SSF is influenced by other sectors and actors, including informal finance providers (e.g., fish buyers or gear suppliers) through high-interest loans and unfavorable repayment structures, including selling catches when market prices are at their lowest (Kleih and others, 2013; Okafor-Yarwood and others, 2024a). Fish buyers provide defacto controls on the amount and price of SSF catches, serving as a driver for overexploitation (Kamiyama and others, 2015). There is limited reporting on specific terms and conditions of such fund providers. Informal financing of SSF is common because formal banks are reluctant to lend money to perceived high-risk or unstable borrowers, including SSF (Jimenez and others, 2020). In many cases, opportunities for SSF upgrading are structured by social relationships and local embeddedness (Adhuri and others, 2016).

Gender dimensions of SSF are significant (see chapter S5B.C6). An estimated 53 million people are directly involved in fishing for subsistence; 39.6 percent of those engaged in the SSF value chain through direct employment or subsistence fishing are women (FAO, Duke University and WorldFish, 2023). Close to 50% of post-harvest workers are women (FAO, Duke University and WorldFish, 2023). Compared to other industries, SSF significantly contribute to gender equality (Harper and others, 2020; Kleiber and others, 2017). Both women and men perform complementary roles: men are primarily involved in marine capture fisheries, while women focus on processing, trade, and marketing (Pedroza-Gutiérrez and Hapke, 2022).

Globally, women catch approximately 2.9 million (± 835,000) tonnes of fish and invertebrates annually, with an estimated landed value of USD 5.6 billion (Harper and others, 2020; FAO, Duke University and

WorldFish, 2023). This accounts for 12% of the total landed value of SSF catches and generates an overall economic impact of USD 14.816.7 billion annually (+/- 4 billion) (Harper and others, 2020). Women may also have prominent leadership roles in all aspects of the fishery, including in management and governance (Chambon and others, 2024; Galappaththi and others, 2022). However, women tend to have more unstable positions within fishery value chains despite their roles (EUROSTAT, 2023; Chambon and others, 2024). Women in SSF are also subjected to wage inequalities (Aini, 2022), domestic and/or workplace violence (Mangubhai and others, 2023), and limited acknowledgement of their work which is often viewed as an extension of their household responsibility (UN Women, 2020). Opportunities to enhance environmental and human wellbeing outcomes require ongoing efforts to address gender inequities across the SSF value chain (Cohen and others, 2024).

In addition to gender issues, SSF are increasingly characterized by precarious working conditions (including extreme weather events) and labour relations that can undermine the significant contributions they make (Marschke and Vandergeest, 2016; Belton and others, 2019; Cruz and Rigg 2019). Further, in developing countries, SSF may lack social protection programs or receive limited support to mitigate vulnerabilities (Tabe-Ojong and others, 2025). Small-scale fishers are often forced to fish further from shore for longer periods of time, particularly given general stock declines; workers in SSF rarely have contracts, work long hours, are often paid on a share of the catch system, which is based on how much fish is caught, and fish seasonally. Depending on context, boat ownership can be next to impossible in some coastal communities, resulting in some fishers migrating for work elsewhere. For example, former Cambodian SSF households can be found in Thailand working in pre-processing (women) and as fish workers (men) on crab boats. In Indonesia, SSF fishers migrate for work ~~into Taiwan's EEZ fisheries,~~ with men being separated from their families for years at a time ~~(Vandergeest and Marschke 2021)~~. Investments around labor protection, individual and collective control, and decent work are critical for SSF (Marschke and Vandergeest, 2016; Bavinck and others, 2024; Lozano and others, 2022).

Small-scale fishers, including Indigenous small-scale fishers, are keen ~~observers~~ stewards of their environments (e.g., patterns of change, seasonal variability) (Galappaththi and others, 2021) (see chapter S5B.C8). A systems-oriented understanding of their environments emerges from the accumulation of shared knowledge over generations within communities, often transmitted orally (Galappaththi and Schlingmann, 2023; Silvano and others, 2023). The importance of greater attention to knowledge systems is reflected in evidence that aquatic food dependence among coastal Indigenous P~~p~~eoples worldwide is much higher than it is among non-Indigenous peoples (Cisneros-Montemayor and others, 2016). This dependence was greatly impacted by the COVID-19 pandemic which was addressed through barter exchanges with goods such as dried fish (Nhiwatiwa and Matanzima, 2023) (see chapter S5B.C7). In West Africa, the responses to the COVID-19 pandemic highlights the level of resilience in the SSF communities where fisherfolk have been forced to innovate amidst limited support (Okafor-Yarwood

and others, 2022). In other global assessments ~~(e.g., IPCC)~~, there is a reluctance to draw on fisher knowledge and observations (Ford and others, 2016).

4.0 Governance

Small-scale fisheries are complex social-ecological systems (Charles 2023; Berkes and Franz, 2025), requiring governance approaches that are collaborative, adaptive and multi-level (see ~~chapter~~ section S3). Governance of SSF also requires transparency, accountability and focus on equity (see chapter~~Section~~ 5B.Ch.5). Globally, small-scale fishers and partner civil society organizations have a long history of documenting inequities associated with coastal development policies. Policies that impact SSF should seek more inclusive outcomes that align with the Sustainable Development Goals (see Small-Scale Fisheries Call for Action; www.ssfcalltoaction.org). The Ocean, Water and Fisher Peoples' Tribunals (World Forum of Fisher Peoples - WFFP) is one example in which forums of justice have been established to voice testimonies and experiences of human rights abuses faced by fishing communities. As well, the Independent People's Tribunals on the implications of Blue Economy, were carried out in at least six Indian ocean countries and in Brazil (Satizábal and others, 2024). Similar initiatives have emerged in Latin America and the Caribbean, and internationally (Gerhardinger and others, 2023; García-Lorenzo and others, 2024).

At the global level, the SSF Guidelines (FAO, 2015), represent the first international policy instrument entirely dedicated to SSF. However, experiences with implementation of the SSF Guidelines in different jurisdictions has been *ad hoc* (Chuenpagdee and others, 2017; Said and Chuenpagdee, 2019). There is established but incomplete evidence that a key obstacle to the full implementation of the guidelines is incoherence with existing national policies, and requirements for national governments to adapt or adjust existing regulatory frameworks (Cohen and others, 2017). Efforts to increase policy coherence with the SSF Guidelines are being supported through the development of National Plans of Action for Small-scale Fisheries (NPOA-SSF) with support from the FAO.

The implementation of SSF Guidelines is a pathway to achieving the 2015 United Nations Sustainable Development Goals (SDGs) of Agenda 2030. SSF are explicitly addressed in SDG 14 (Life below water) - Target 14b: "Provide access for small-scale artisanal fishers to marine resources and markets". However, preferential access for SSF globally is very low (Said and Chuenpagdee, 2019). Aligning SSF policy frameworks at the local, subnational and national levels with the SDG and SSF Guidelines provides a foundation for multi-level interventions (Smallhorn-West and others, 2022). With reference to SSF, and Indigenous SSF in particular, there is increasing attention on human rights-based approaches (FAO, 2015), including links between SSF and rights to food security (FAO, 2020). The basis for a human-rights based approach is expressed in the United Nations Declaration on the Rights of Indigenous Peoples

(UNDRIP, 2007) and the 2018 United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas (UNDROP). Other global governance ~~processes~~ dialogues and ~~regimes~~ multi-lateral environmental agreements will increasingly affect SSF (s~~S~~ee s~~S~~ection ~~WOA 3.0 – Global Overview~~S3), ~~including~~ as reflected in the findings and evidence provided by ~~outcomes and recommendations from the~~ IPBES assessments, ~~and~~ or in the emerging global plastics treaty.

At national and sub-national levels, evidence that co-management and participatory governance of SSF yields more equitable outcomes is well established, although strongly context dependent (d'Armengol and others, 2018; Evans and others, 2023; Ruano-Chamorro and others, 2023). Success requires the active involvement of fishers and diverse stakeholders, strong government support, sustainable financial resources, and transparent and adaptive decision-making processes (d'Armengol and others, 2018; Livingstone and Anthony, 2023). The SSF Guidelines, and several international and national policy instruments, already advocate for increased participation of men and women in decision-making processes. Co-management, involving SSF, government, and other stakeholders, is now widely considered a best practice governance approach (Prado and others, 2022; Smallhorn-West and others 2022). The most frequent goal of co-management is to improve fisheries management through increased participation, increased legitimacy and/or compliance with fishing rules, the definition or enforcement of fishing rights, and the incorporation of customary management norms in formal management (d'Armengol and others, 2018). Evidence showing that co-management leads directly to better ecological outcomes is unresolved.

Evidence in support of co-management and participatory governance of SSF is often aligned with recognition of tenure. The Voluntary Guidelines on Responsible Governance of Tenure of Land, Fisheries and Forests (FAO, 2022) clearly articulate the importance of tenure in regulating how societies make decisions about who can use which resources, for how long, and under what conditions, including rights of decision making. Effective and equitable governance of tenure is a critical variable in SSF outcomes, including for biodiversity (Cohen and others, 2024; Tholan and others, 2024). Groups with secure tenure can advance cost-effective management strategies. Secure tenure also makes it more likely that activities along the SSF value chain will be compliant with international protocols and achieve positive environmental outcomes (IPBES, 2022a, 2022b). Secure governance of tenure for SSF must extend to land for storing boats and gear, engaging in post-harvest activities, including space to sort or dry fish, and permit related economic activities such as marketing and selling (FAO, 2024). Despite a recognition of tenure implications, regional experience shows that the governance of tenure for SSF in many jurisdictions is under threat from diverse development (e.g., infrastructure, industrial aquaculture) and conservation pressures (Okafor-Yarwood and others, 2022; Cohen and others, 2019). There is evidence of arbitrary evictions and conflict in many SSF contexts despite legal and policy frameworks established to limit such situations (FAO 2015; Courtney and Jhaveri, 2017). Secure systems of tenure established through customary law and/or Indigenous Peoples' systems of governance are particularly vulnerable.

Loss of tenure can undermine the sense of place and area-specific knowledge of small-scale fishers (Bavinck and Gupta, 2014).

Data availability and information on diverse SSF activities and catch levels remains an ongoing governance issue, and one that is amplified further by the wide range of targeted species (Pita and others, 2019). There are also regional and national variations in how data-poor fisheries are defined, although some basic criteria provide a foundation for the development of monitoring programs (Dowling and others, 2015). Fishers themselves provide valuable data and information on fisheries stocks, trends, harvest pressures and livelihood/food security implications which can counter perceptions about data-poor SSF (Gill and others, 2019). Efforts to enhance governance of SSF, however, require ongoing efforts to improve low-cost methodologies that access a wide range of social and ecological knowledge to overcome data-poor situations (Pita and others, 2019).

Data-poor fisheries is linked in part to compliance and traceability concerns in the SSF sector, including IUU fisheries. Compliance at the individual fisher level remains poorly understood (Battista and others, 2018). Perceptions of legitimacy, fairness and equitability of rules plays a key role in compliance, and mediated by social norms and collective obligations. The participation of small-scale fishers in developing and applying rules has a significant effect on compliance (FAO, 2024). The role of technology in improving data collection for marine management is worth acknowledging, noting the vulnerability of some SSF to targeted monitoring. For example, in West and Central Africa, the close proximity of SSF to the shore and their visibility to law enforcement personnel makes them an easy surveillance and enforcement target (Okafor-Yarwood and others, 2024cb; Paes and Okafor-Yarwood 2024), and may restrict SSF activities in comparison to the monitoring measures applied in the industrial sector (Okafor-Yarwood and others, 2022).

The value of ecosystem-based fisheries management (EBFM) to support governance is increasingly well-established. Implementation of ecosystem approaches, such as the ecosystem approach to fisheries (EAF), over the past decade has helped to re-orient management objectives and establish new methods relevant for data-limited contexts (Zhang and others, 2011; Link and Brown, 2017) (see Chapter 27 of WOA II). Integrated fisheries risk analysis methods for ecosystem approaches (Zhang and others, 2009; 2011) explicitly consider the status of local fish stocks, habitats, biodiversity measures and economic indicators for fisheries (see Chapter 25 of WOA II). Ecosystem approaches have recently been applied in several SSF, such as Egyptian fisheries in the Red Sea (Alsolami and others, 2020), local fisheries on the south coast of the Republic of Korea Korea (Kang and Zhang, 2023) and in Indonesian waters (Tirtadanu and others, 2024). Efforts to improve traceability and certification also aim to increase transparency in value chain governance and adherence to sustainable harvesting norms. However, global eco-label standards in general remain expensive, struggle to include social sustainability criteria, and most importantly, have not effectively included SSF (Purcell and others, 2018; Bailey and others, 2016). Similar

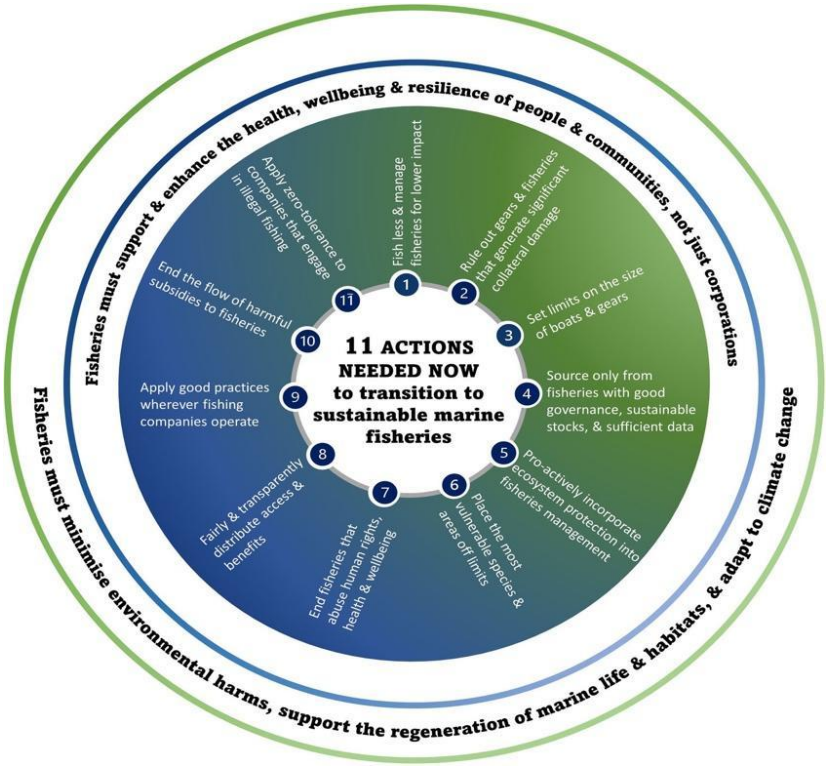
governance mechanisms like Fair Trade Certification have a stronger emphasis on repositioning and empowering producers by mandating fair pricing standards. A growing number of local and national certification and labelling schemes for SSF are emerging (e.g., Abalobi in South Africa, Pesca de Rias in Spain). However, certification processes are not fully developed in SSF contexts and rarely focus on ecological sustainability dimensions (Purcell, 2017).

5.0 Sustainable pathways

The FAO (2015) SSF Guidelines outline diverse pathways to help secure sustainable small-scale fisheries. Efforts to amplify and extend these pathways must centre the calls to action from small-scale fishers themselves, and the 'Rules of conduct for working with small-scale fishers and fishworkers' (CFFA, 2023). Indeed, small-scale fisheries are a crucial economic sector, employ millions of people, support food security for millions more, and exhibit significant resilience despite numerous challenges (Basurto and others, 2025; Berkes and Franz, 2025). Transition pathways for sustainable SSF that build on the ~~FAO (2015)~~SSF G~~-g~~uidelines and align with the Ocean 2050 scenario are emerging but incomplete.

Roberts and others (2024) provide a roadmap to fisheries reform and 11 actions to transition to sustainable marine fisheries, most of which are of direct relevance to SSF (Figure 5a.C1b.2). The Illuminating Hidden Harvest report (FAO, Duke University and WorldFish, 2023) outlines several pathways to secure the role of SSF in sustainable development, including acting on existing policy commitments and improving how SSF data and information are collected, analysed and used. Nayak and others (2021) outline a suite of domains and perspectives around which SSF vulnerability, viability and sustainable development transitions can be navigated, with an emphasis on social struggles and contested arrangements of power (Figure 5a.C1b.3). Muhl and others (forthcoming) document five key transition pathways from vulnerability to viability of SSF based on experiences from 12 countries in Africa and Asia, including building governance networks and partnerships; centering small-scale fisheries tenure and rights; advancing a gender and intersectional perspective on viability pathways; enhancing opportunities for nature-based livelihoods; and co-creating or co-producing the knowledge needed for transition pathways. A range of other empirical analyses and policy assessments further articulate elements of transition or transformation pathways for SSF (see Saunders and others, 2016; Salgueiro-Otero and others, 2022; Villasante and others, 2022; Gianelli and others, 2024; Berkes and Franz, 2025). The transition pathways outlined here build on existing assessments, but with specific consideration of the Ocean 2050 scenario. Emphasis is placed on the innovations, structural/regime changes, and narrative shifts needed to catalyze the technological, governance and social/economic dimensions of sustainable pathways (Figure 5a.C1b.4).

Figure 5a.C1b.2: Road map and actions to transition to sustainable marine fisheries

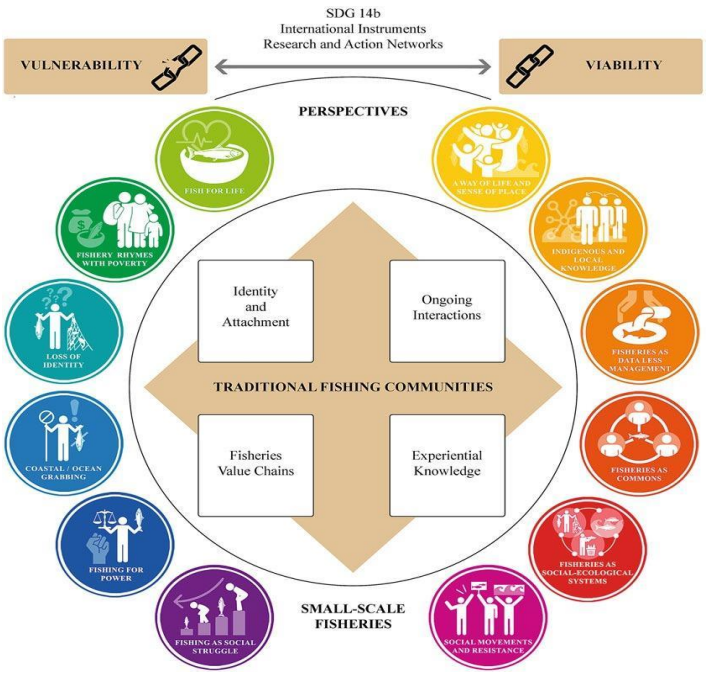


Source: Roberts and others (2024)

Social and economic mechanisms for sustainable pathways to the Ocean 2050 scenario are diverse, and will vary across the value chain. Participation, collaboration and mutual support, partnerships, and networks of SSF and others are a core feature of any successful transition pathway. Pathways must also reflect a commitment to principles of equity and justice, drawing connections to human rights and security (e.g., labour, safety, security of access) (Reis-Filho and others 2024). The significant knowledge and capacity of SSF to lead transitions must be emphasized, along with a commitment to principles and practices of knowledge co-production (Mills and others, 2022; Muhl and others, 2023). ~~As well~~Further, pathways for sustainable SSF must reflect the strong connections within and across sectors (e.g., the links between SSF and industrial fisheries through IUU and trawling practices are significant). More generally, a core principle in considering sustainable pathways is recognition of the deep relationship among SSF practices, socio-economic prosperity (e.g., food security and employment), and ecological systems (see Charles, 2023).

Providing stronger financial and economic support to SSF is necessary to catalyze innovative practices, such as creating new markets, or diversifying or augmenting livelihoods. Several measures (e.g., saving groups, microfinance or insurance schemes) have been introduced to change the relationship between fishers and informal financial providers (i.e., fish buyers or gear suppliers) (Pomeroy and others, 2020). These interventions face challenges with complex, long-standing social relationships in small local communities, but they help to shift the narrative of SSF as vulnerable. Saving groups organized by local communities provide innovative pathways for SSF in Cambodia, Tanzania, and other jurisdictions (Lieng and others, 2018; Nakamura and others, 2024). Advancing local, bottom-up initiatives, assisted by outside resources, are one pathway to disentangle the complex problems associated with informal finance providers, particularly at the harvest and marketing stages of the value chain (Pradhan and others, 2022). Further, more financial support is needed to ensure individuals and SSF organizations can engage with the growth of digitalization and e-commerce in the marketplace. An important social sustainability pathway also includes communities retaining and supporting traditional practices of bartering goods and services in lieu of monetary payments - a process that re-emerged during the COVID-19 pandemic (Nhiwatiwa and Matanzima, 2023). Traditional or customary practices serve as an important safety net as SSF incomes are typically low, may be the sole income contribution to households, and/or support extended multi-generational families.

Figure 5a.C1b.3: Transitions from vulnerability to viability



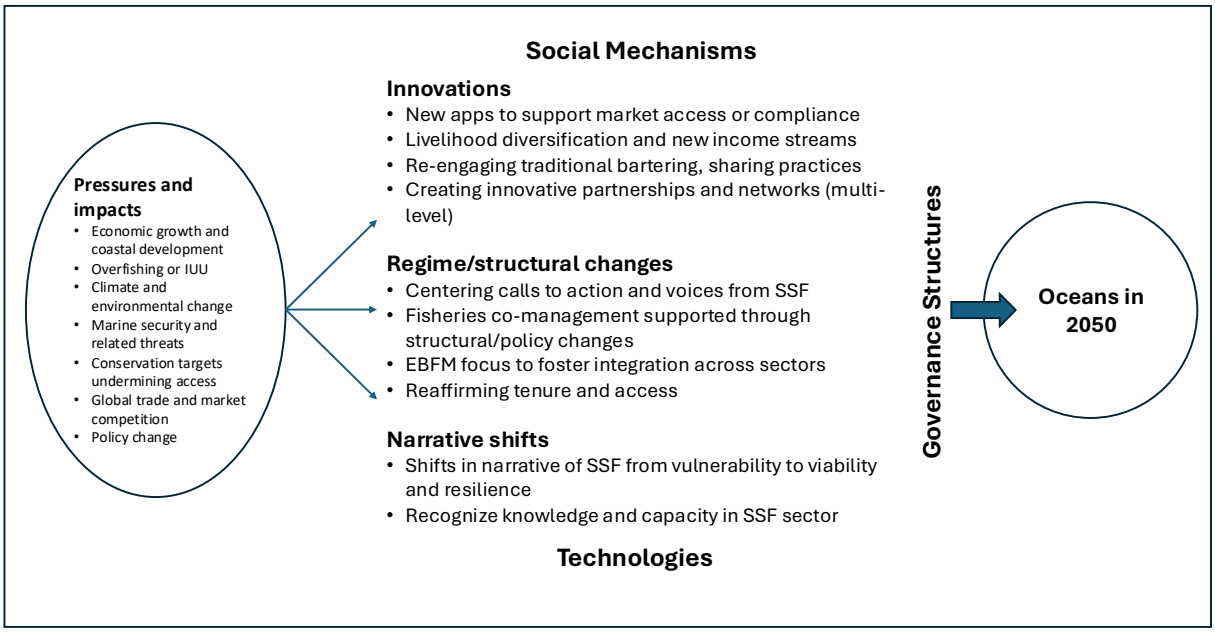
Source: Nayak and others (2021)

Governance processes related to SSF for an Ocean 2050 scenario must be adaptive, collaborative and multi-level. They must also be transparent and inclusive, and support more decentralized and/or bottom-up decision-making processes. The implementation of the 2030 Agenda for Sustainable Development requires management grounded in a social-ecological systems approach to achieve the integrated set of global priorities and objectives set out in the Sustainable Development Goals (SDGs) (see Chapter 27 of WOA II), and which provide a foundation for the Ocean 2050 scenario. There are still gaps in implementation and incomplete uptake across regions and stakeholders. Common frameworks and criteria for SSF governance based on demonstrated best practice are necessary.

Governance changes align with ***technological*** tools and opportunities. Advances in technology enable SSF to play an active role in fisheries governance and co-management systems – a crucial pathway for sustainability. In Liberia, for example, the DASE APP, a smartphone application developed and maintained by the Environmental Justice Foundation has been used by local fishers as part of the co-management process to collect data on possible IUU fishing infractions of trawlers. The mobile app enables users to capture video or photo evidence of destructive IUU fishing in real-time, regardless of their internet connection. However, its effectiveness is contingent on the training of fishers on safe use and willingness of government departments to take appropriate action when possible infractions are reported (see Livingstone and Anthony 2023).

Pathways to sustainability will require further investments in ***governance*** and ***technological*** innovations and transfers applied at scale, and with the aim to support market access, security and management by fishers. Technology uptake in the service of SSF requires system-level changes, and a shift away from narratives that SSF are risk averse, or disconnected from other related sectors. In particular, technology changes are closely linked to issues of access (i.e. access to knowledge, markets, credit, resource/space) that catalyze sustainable pathways.

Figure 5a.C1b.4: Sustainable pathways for SSF under the Ocean 2050 scenario



6.0 Conclusions

SSF are highly variable and also distinct from other fisheries. They are of significant social, economic, cultural and ecological importance, and have a crucial role in fostering food and nutritional security for millions of people (Basurto and others, 2025). Yet, SSF face progressively significant pressures from many stressors as noted, and the viability of SSF in many regions is increasingly threatened. Sustainable pathways for SSF must be guided by the knowledge of fishers, and along with others, their active participation in decision making. SSF governance should be guided by principles of equity, justice and human rights. Further, sustainable pathways must reflect the deep integration of the SSF sector in a range of national and global governance processes, economic development policies and conservation agendas. There is a clear opportunity for governments to support the knowledge, practices and capacity of SSF, and to recognize the crucial role of SSF in meeting global sustainable development goals.

Statement on Artificial Intelligence

No artificial intelligence (AI) was used in the development, synthesis of information or writing associated with this chapter.

7.0 References

Adhuri, Dedi Supriadi, and others. Green market for small people: Markets and opportunities for upgrading in small-scale fisheries in Indonesia. Marine Policy, *63*, 198-205. 2016.

Adjei, Moses, and Ragnhild Overå. Opposing discourses on the offshore coexistence of the petroleum industry and small-scale fisheries in Ghana. The Extractive Industries and Society, 6(1), 190–197. 2019.

Aini, Yulinda Nurul. The Gender Wage Gap in Fisheries Labour Market: The Analysis of Sociodemographic and Work-Related Factors in Indonesia. *Sawwa: Jurnal Studi Gender*, *17*(2), 145-172. 2022.

Alsolami, Lafi, and others. An ecosystem-based fisheries assessment approach and management system for the Red Sea. Fisheries Research, 227, 105551. 2020.

Arthur, Robert. I., and others. Small-scale fisheries and local food systems: Transformations, threats and opportunities. Fish and Fisheries, 23(1), 109–124. 2022.

Ayilu, Raymond K., and others. Blue economy: Industrialisation and coastal fishing livelihoods in Ghana. Reviews in Fish Biology and Fisheries, 33(3), 801–818. 2023.

Bailey, Megan, and others. Fishers, fair trade, and finding middle ground. Fisheries Research, 182, 59-68. 2016.

Ban, N.C., Gurney, G.G., Marshall, N.A. *et al.* Well-being outcomes of marine protected areas. Nature Sustainability. 2: 524–532. 2019.

Barboza, Luís Gabriel Antão, and others. Marine microplastic debris: An emerging issue for food security, food safety and human health. Marine Pollution Bulletin, 133, 336–348. 2018.

Bassett, Hannah R., and others. A comparative study of small-scale fishery supply chains' vulnerability and resilience to COVID-19. Maritime Studies, 21(2), 173–192. 2022.

Basurto, X., Gutierrez, N.L., Franz, N. *et al.* Illuminating the multidimensional contributions of small-scale fisheries. Nature. 637: 875–884. 2025.

Battista Willow, and others. Behavior Change Interventions to Reduce Illegal Fishing. Front. Mar. Sci. 5:403. 2018.

Bavinck, Martin. and Joyeeta Gupta. Legal pluralism in aquatic regimes: a challenge for governance. Current Opinion in Environmental Sustainability. 11: 78-85. 2014.

Bavinck, Martin, and others. Maximum sustainable employment: Adding to the beacons of wild fisheries governance. Fish and Fisheries—Wiley Online Library. Fish and Fisheries. 2024.

Bell, Johann D., and others. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nature Climate Change, 3(6), 591–599. 2013.

Bell, Curtis, and others. Pirates of the Gulf of Guinea: A Cost Analysis for Coastal States. 2021.

Belton, Ben, and others. Fisheries development, labour and working conditions on Myanmar's marine resource frontier. Journal of Rural Studies, 69, 204-213. 2019.

Béné, Christophe, and others. Contribution of Fisheries and Aquaculture to Food Security and Poverty Reduction: Assessing the Current Evidence. World Development, 79, 177–196. 2016.

Bennett, Nathan J. and others. Advancing Social Equity in and Through Marine Conservation. Frontiers in Marine Science, 8. 2021a.

Bennett, Nathan J. and others. Blue growth and blue justice: Ten risks and solutions for the ocean economy. Marine Policy, 125, 104387. 2021b.

Berkes, Fikret and Nicole Franz (Eds). Governing for transformation towards sustainable small-scale fisheries. Rome, FAO. 2025.

Beseng, Maurice. Cameroon's choppy waters: The anatomy of fisheries crime in the maritime fisheries sector. Marine Policy, 108, 103669. 2019.

Bjorndal, Trond, and others. Value chain dynamics and the small-scale sector: Policy recommendations for small-scale fisheries and aquaculture trade. FAO. 2014.

Brent, Zoe W., and others. The Blue Fix: What's driving blue growth? Sustainability Science, 15(1), 31–43. 2020.

Cánovas-Molina, Almudena., and others A review of vulnerabilities in worldwide small-scale fisheries. Fisheries Management and Ecology, 29(5), 491–501. 2022.

CFFA. Rules of conduct for working with small-scale fishers and fishworkers to save our ocean. Coalition for fair fisheries arrangements. 2023.

Chambon, Mouna, and others A synthesis of women's participation in small-scale fisheries management: Why women's voices matter. Reviews in Fish Biology and Fisheries, 34(1), 43–63. 2024.

Charles, A. *Sustainable fishery systems*. John Wiley & Sons. 2023.

Charles, Anthony, and others. Environmental stewardship by small-scale fisheries. FAO. 2024.

Chuenpagdee, Ratana, and others. Small-scale fisheries guidelines: Global implications. The MARE Publication series No.14. Springer. 2017.

Cinti, Ana, and others. Small-scale fisheries in ecologically sensitive areas in Latin America and the Caribbean: Do marine protected areas benefit fisheries governance? Ambio. 2024.

Cisneros-Montemayor, Andrés. M., and others. A Global Estimate of Seafood Consumption by Coastal Indigenous Peoples. PLOS ONE, 11(12). 2016.

Cohen, Philippa J., and others. Policy Coherence with the Small-Scale Fisheries Guidelines: Analysing Across Scales of Governance in Pacific Small-Scale Fisheries. In S. Jentoft, and others (Eds.), The Small-Scale Fisheries Guidelines: Global Implementation (pp. 57–77). Springer International Publishing. 2017.

Cohen, Philippa. J., and others. Securing a just space for small-scale fisheries in the blue economy. Frontiers in Marine Science, *6*, 171. 2019.

Cohen, Philippa J., and others. Marine, Coastal and Shoreline Tenure [Report]. Meridian Institute, USA. 2024.

Costello, M.J. Evidence of economic benefits from marine protected areas. Sci. Mar. 88(1): e080. 2024.

Courtney, C. A., and Jhaveri, N. J. Marine Tenure and Small-scale Fisheries: A Sourcebook on Good Practices and Emerging Themes. Washington, DC: USAID Tenure and Global Climate Change Program. 2017.

Crona, Beatrice I., and others. Towards a typology of interactions between small-scale fisheries and global seafood trade. Marine Policy, 65, 1–10. 2016.

Crona, Beatrice, and others. Sharing the seas: A review and analysis of ocean sector interactions. Environmental Research Letters, 16(6), 063005. 2021.

Cruz-Del Rosario, Teresita, and Jonathan Rigg. Living in an age of precarity in 21st century Asia. Journal of Contemporary Asia, 49, 517–527. 2019.

d'Armengol, Laia, and others. A systematic review of co-managed small-scale fisheries: Social diversity and adaptive management improve outcomes. Global Environmental Change, 52, 212–225. 2018.

Dias, Ana Carolina E., and others. From vulnerability to viability: A situational analysis of small-scale fisheries in Asia and Africa. Marine Policy, 155, 105731. 2023.

Dowling, N.A., and others. Guidelines for developing formal harvest strategies for data-poor species and fisheries. Fisheries Research. 171: 130-140. 2015.

Eckert, Isaac., and others. 30×30 biodiversity gains rely on national coordination. Nature Communications, 14(1), 7113. 2023.

Ertör, Irmak. 'We are the oceans, we are the people!': Fisher people's struggles for blue justice. The Journal of Peasant Studies, 50(3), 1157–1186. 2023.

EUROSTAT (Statistical Office of the European Union). Share of women working part-time higher than men. In: EUROSTAT News Articles. Luxembourg. 2023.

Evans, Louisa. S., and others. Putting coastal communities at the center of a sustainable blue economy: A review of risks, opportunities, and strategies. Frontiers in Political Science, 4. 2023.

FAO. The code of conduct for responsible fisheries. FAO of The United Nations. , Rome. 1999.

FAO. Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication. Rome. 2015.

FAO. The State of World Fisheries and Aquaculture: Meeting the sustainable development goals. Rome. 2018.

FAO. Social protection in small-scale fisheries and aquaculture in Latin America and the Caribbean. Santiago de Chile 48 pp. Rome. 2019.

FAO. Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security. First revision. Rome. 2022.

FAO, Duke University & WorldFish. Illuminating Hidden Harvests. 2023.

FAO. The State of World Fisheries and Aquaculture. 2024.

Ferrol-Schulte, Daniella, and others. Patron–client relationships, livelihoods and natural resource management in tropical coastal communities. Ocean & Coastal Management, 100, 63-73. 2014.

Ford, James. D., and others. Including indigenous knowledge and experience in IPCC assessment reports. Nature Climate Change, 6(4), 349–353. 2016.

Galappaththi, Eranga K., and others. Adapting to climate change in small-scale fisheries: Insights from indigenous communities in the global north and south. Environmental Science & Policy, 116, 160–170. 2021.

Galappaththi, Eranga K., and Anna Schlingmann, A. The sustainability assessment of Indigenous and local knowledge-based climate adaptation responses in agricultural and aquatic food systems. Current Opinion in Environmental Sustainability, 62, 101276. 2023.

Galappaththi, Madu, and others. Gendered dimensions of social wellbeing within dried fish value chains: Insights from Sri Lanka. Ocean & Coastal Management, 240, 106658. 2023.

Galappaththi, Madu, and others. Women's experiences in influencing and shaping small-scale fisheries governance. Fish and Fisheries, 23(5), 1099–1120. 2022.

García-Lorenzo, Ira, and others. Social and solidarity economy in small-scale fisheries: An international analysis. Ocean & Coastal Management. 253: 107166. 2024.

Gerhardinger, Leopoldo C., and others. Challenging the Blue Economy: Voices from Artisanal Fishing Communities in Latin America and the Caribbean. Development, 66(1–2), 95–104. 2023.

Gerhardinger, Leopoldo C., and others. International Collective in Support of Fishworkers (ICSF). Baffling Shades of Blue: Addressing the Impacts of the Blue Economy on Small-Scale Fisheries in Latin America. 2022.

Gianelli, Ignacio, and others. Envisioning desirable futures in small-scale fisheries: a transdisciplinary arts-based co-creation process. Ecology and Society, 29(1). 2024.

Gill, David A., and others. Making the most of data-poor fisheries: Low cost mapping of small island fisheries to inform policy. Marine Policy. 101: 198-207. 2019.

Gonzalez-Mon, Blanca, and others. Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries. Environmental Science & Policy, 116, 246–257. 2021.

Guilfoyle, D. Prosecuting pirates: The contact group on piracy off the coast of Somalia, governance and international law. *Global Policy*, *4*(1), 73-79. 2013

Harper, Sarah, and others. Valuing invisible catches: Estimating the global contribution by women to small-scale marine capture fisheries production. PloS one, 15(3). 2020.

Horta, Sebastián, and Omar Defeo. The spatial dynamics of the whitemouth croaker artisanal fishery in Uruguay and interdependencies with the industrial fleet. Fisheries Research, 125–126, 121–128. 2012.

~~Intergovernmental science-policy platform on biodiversity and ecosystem services (~~IPBES~~)~~. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES Secretariat, Bonn, Germany. 2019.

~~Intergovernmental science-policy platform on biodiversity and ecosystem services (~~IPBES~~)~~. Summary for Policymakers of the Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Pascual, U., Balvanera, P., Christie, M., Baptiste, B., González-Jiménez, D., Anderson, C.B., Athayde, S., Barton, D.N., Chaplin-Kramer, R., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Martin, A., Mwampamba, T.H., Nakangu,

B., O'Farrell, P., Raymond, C.M., Subramanian, S.M., Termansen, M., Van Noordwijk, M., and Vatn, A. (eds.). IPBES secretariat, Bonn, Germany. 2022a.

~~Intergovernmental science-policy platform on biodiversity and ecosystem services (~~IPBES~~)~~. Thematic Assessment Report on the Sustainable Use of Wild Species of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Fromentin, J. M., Emery, M. R., Donaldson, J., Danner, M. C., Hallosserie, A., and Kieling, D. (eds.). IPBES Secretariat, Bonn, Germany. 2022b.

~~Intergovernmental science-policy platform on biodiversity and ecosystem services (~~IPBES~~)~~. Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Harrison, P. A., McElwee, P. D., and van Huysen, T. L. (eds.). IPBES Secretariat, Bonn, Germany. 2024.

Intergovernmental Panel on Climate Change (IPCC). Climate Change – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. 2023.

Jentoft, Svein, and others. (Eds.). The Small-Scale Fisheries Guidelines: Global Implementation (Vol. 14). Springer International Publishing. 2017.

Jentoft, Svein, and others (Eds.), Blue Justice: Small-Scale Fisheries in a Sustainable Ocean Economy. Springer International Publishing. 2022.

Jentoft, Svein. Small-Scale Fisheries in the Blue Economy. In S. Jentoft, and others (Eds.), Blue Justice: Small-Scale Fisheries in a Sustainable Ocean Economy (pp. 3–15). Springer International Publishing. 2022.

Jimenez, Érica. A., and others. Value chain dynamics and the socioeconomic drivers of small-scale fisheries on the amazon coast: A case study in the state of Amapá, Brazil. Marine Policy, 115. 2020.

Jouffray, Jean-Baptiste, and others. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth, 2(1), 43–54. 2020.

Kamiyama, Ryutaro, and others. The impact of distribution change on fisheries in Southeast Asia: A case study in the Batan Estuary, Aklan, Central Philippines. Fisheries Science, 81(2), 401–408. 2015.

Kang, Beodeul, and Chang-Ik Zhang. A semi-quantitative ecosystem-based assessment of the Jukbangryum fishery in the south coast of Korea. The Journal of Fisheries and Marine Sciences Education, vol. 35, No. 1, pp. 63-72. 2023.

Kitolelei, Salanieta, and others. Na Vuku Makawa ni Qoli: Indigenous Fishing Knowledge (IFK) in Fiji and the Pacific. Frontiers in Marine Science, 8. 2021.

Kleiber, D., and others. Gender and small-scale fisheries: A case for counting women and beyond. Fish and Fisheries, 16(4), 547–562. 2015.

Kleiber, Danika, and others. Promoting Gender Equity and Equality Through the Small-Scale Fisheries Guidelines: Experiences from Multiple Case Studies. In Svein Jentoft, and others (Eds.), The Small-Scale Fisheries Guidelines: Global Implementation (pp. 737–759). Springer International Publishing. 2017.

Kleih, Ulrich, and others. Financial services for small and medium-scale aquaculture and fisheries producers. Marine Policy, 37, 106–114. 2013.

Lawless, Sarah, and others. Gender equality is diluted in commitments made to small-scale fisheries. World Development, 140, 105348. 2021.

Lieng, Sopha, and others. Savings-Group Improvements Contribute to Sustainable Community-Fisheries Management: A Case Study in Cambodia. Sustainability 2018, 10, 2905. 2018.

Link, Jason, and Howard Brown. Operationalizing and implementing ecosystem-based management. ICES Journal of Marine Science, vol. 74, No. 1, pp. 379–381, 2017.

Liss, Carolin. Assessing contemporary maritime piracy in Southeast Asia: Trends, hotspots and responses. Hessische Stiftung Friedens- und Konfliktforschung. 2014.

Livingstone, Olivia, and Brandon P. Anthony. Documenting fisheries co-management in action: Case of the Grand Cape Mount County Co-Management Association, Liberia. Marine Policy, 157, 105844. 2023.

Louey, Philippa. The blue economy's retreat from equity: A decade under global negotiation. Frontiers in Political Science, 4. 2022.

Lozano, Alejandro. J., and others. Decent work in fisheries: Current trends and key considerations for future research and policy. Marine Policy, 136, 104922. 2022.

Mangubhai, Sangeeta, and others. Gender-based violence: Relevance for fisheries practitioners. Fish and fisheries, 24(4), 582-594. 2023.

Marschke, Melissa, and Peter Vandergeest. Slavery scandals: Unpacking labour challenges and policy responses within the off-shore fisheries sector. Marine Policy, 68, 39–46. 2016.

Marschke, Melissa, and others. Precarious livelihoods: Examining the intersection of fish work and ecological change in coastal Jamaica. People and Nature, 2(1), 152–162. 2019.

Martínez-Vázquez, Rosa María and others. Challenges of the Blue Economy: Evidence and research trends. Environmental Sciences Europe, 33(1), 61. 2021.

Mills, Evan, and others. Solar-LED alternatives to fuel-based Lighting for night fishing. Energy for Sustainable Development, 21, 30–41. 2014.

Mills, K., Armitage, D., Eurich, J., Kleisner, K., Pecl, G. and K. Tokunaga. Co-production of knowledge and strategies to support climate resilient fisheries. ICES Journal of Marine Science. 80, 358–361. 2022.

Mimura, Nobuo. Vulnerability of island countries in the South Pacific to sea level rise and climate change. Climate Research, 12(2/3), 137–143. 1999.

Monnier, Léa, and others. Small scale fisheries in a warming ocean (Doctoral dissertation) International WWF Centre for Marine Conservation, Hamburg. 2020.

Muhl and others (forthcoming). Transition pathways from vulnerability to viability of small-scale fisheries in Africa and Asia. Submitted to People and Nature.

Muhl, Ella K., and others. Experiences With Governance in Three Marine Conservation Zoning Initiatives: Parameters for Assessment and Pathways Forward. Frontiers in Marine Science, 7. 2020.

Muhl, Ella K., and others. Transitioning toward “deep” knowledge co-production in coastal and marine systems: examining the interplay among governance, power, and knowledge. Ecology and Society, 28(4). 2023.

Nakamura, Julia., and others. Unpacking legal and policy frameworks: A step ahead for implementing the Small-Scale Fisheries Guidelines. Marine Policy, 129, 104568. 2021.

Nakamura, Julia., and others. Implementation of the Small-Scale Fisheries Guidelines -A Legal and Policy Scan-. Springer Nature, Switzerland. pp483. 2024.

Natale, Fabrizio, and others. Defining small-scale fisheries in the EU on the basis of their operational range of activity The Swedish fleet as a case study. Fisheries Research, 164, 286–292. 2015.

Nayak, Prateep, and others. Resource degradation, marginalization, and poverty in small-scale fisheries: Threats to social-ecological resilience in India and Brazil. Ecology and Society, 19(2). 2014.

Nayak, P.K., Dias, A.C.E., Pradhan, S.K. Traditional Fishing Community and Sustainable Development. In: Leal Filho, W., Azul, A.M., Brandli, L., Lange Salvia, A., Wall, T. (eds) Life Below Water. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. 2021.

Nhiwatiwa, Tamuka, and Joshua Matanzima. The Covid-19 Pandemic: Limited Water Access and the Precarity of Women Fishers at Lake Kariba, Zimbabwe. Journal of Asian and African Studies, 58(5). 2023.

Nowakowski, A.J., Canty, S.W.J., Bennett, N.J. *et al.* Co-benefits of marine protected areas for nature and people. Nature Sustainability. 6: 1210–1218. 2023.

Oh, Hyun-Taik, and others. Review of the marine environmental impact assessment reports regarding offshore wind farm. Fisheries and Aquatic Sciences, 24(11), 341–350. 2021.

Okafor-Yarwood, Ifesinachi, and others. The Blue Economy–Cultural Livelihood–Ecosystem Conservation Triangle: The African Experience. Frontiers in Marine Science, 7. 2020.

Okafor-Yarwood, Ifesinachi, and others. Survival of the Richest, not the Fittest: How attempts to improve governance impact African small-scale marine fisheries. Marine Policy, 135, 104847. 2022.

Okafor-Yarwood, Ifesinachi, and others. Understanding women's roles and trade potential along the fisheries and aquaculture value chains: Case studies from Ghana and Nigeria. FAO; International Trade Centre (ITC). 2024a.

Okafor-Yarwood, Ifesinachi, and others. The fallacy of *uti possidetis juris*: transboundary fishing in disputed maritime boundaries as a threat to Africa's peace and security. Conflict, Security and Development, 24(5), 451–477. 2024b.

Okafor-Yarwood, Ifesinachi, and others. Technology and maritime security in Africa: Opportunities and challenges in Gulf of Guinea. Marine Policy, 160, 105976. 2024c

Paes, Lucas de Oliveira and Ifesinachi Okafor-Yarwood. Techno-optimism versus techno-reality: an analysis of internationally funded technological solutions against illegal unreported and unregulated (IUU) fishing in Ghana and Guinea-Bissau. Environmental Politics, 1-28. 2024.

Pascua, Pua'ala, and others. Beyond services: A process and framework to incorporate cultural, genealogical, place-based, and indigenous relationships in ecosystem service assessments. Ecosystem Services, 26, 465–475. 2017.

Pedroza-Gutiérrez, Carmen, and Holly M. Hapke. Women's work in small-scale fisheries: A framework for accounting its value. Gender, Place & Culture, 29(12), 1733–1750. 2022.

Peer, Nasreen, and others. Community and Marine Conservation in South Africa: Are We Still Missing the Mark? Frontiers in Marine Science, 9. 2022.

Pellini, Giulio, and others. Characterization of microplastic litter in the gastrointestinal tract of Solea solea from the Adriatic Sea. Environmental Pollution, 234, 943–952. 2018.

Pita, Cristina, and others. Managing small-scale fisheries under data poor scenarios: lessons from around the world. Marine Policy. 101: 154-157. 2019.

Pita, Cristina, and others. Small-Scale Fisheries in Europe: Challenges and Opportunities. In J. J. Pascual-Fernández, C. Pita, & M. Bavinck (Eds.), Small-Scale Fisheries in Europe: Status, Resilience and Governance (pp. 581–600). Springer International Publishing. 2020.

Pomeroy, Robert, and others. Financial inclusion to build economic resilience in small-scale fisheries. Marine Policy 118, 103982. 2020.

Pradhan, Sisir K., and others. A social-ecological systems perspective on dried fish value chains. Current Research in Environmental Sustainability, 4, 100128. 2022.

Prado, Deborah S., and others. Catalytic and structural factors behind advancements of co-management in protected areas: Contributions for its evaluation. Journal of Environmental Management, 311, 114825. 2022.

Purcell, Steven. W., and others. Distribution of economic returns in small-scale fisheries for international markets: A value-chain analysis. Marine Policy, 86, 9-16. 2017.

Purcell, Steven. W., and others. Small-scale fishing income and fuel consumption: Fiji's artisanal sea cucumber fishery. ICES Journal of Marine Science, 75(5), 1758-1767. 2018.

Queffelec, Betty, and others. Marine spatial planning and the risk of ocean grabbing in the tropical Atlantic. ICES Journal of Marine Science, 78(4), 1196–1208. 2021.

Reis-Filho, José A., and others. Navigating blue justice: Policy gaps and conflicts in coastal development from small-scale fisher perspectives. One Earth, 7(10), 1786-1802. 2024.

Rivera-Garibay, Omar, and others. Presence of microplastic in target species of small-scale fisheries and possible social implications on the local communities. Marine Biology, 171(4), 78. 2024.

Roberts, Callum, and others. Rethinking sustainability of marine fisheries for a fast-changing planet npj Ocean Sustainability. 3(41): 1-11. 2024.

Rochman, Chlesea M., and others. Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Scientific Reports, 5(1), 14340. 2015.

Rosales, Rina Maria, and others. Value chain analysis and small-scale fisheries management. Marine Policy, 83, 11–21. 2017.

Ruano-Chamorro, Cristina, and others. Disparities in the impacts of co-management on fishers' livelihoods. Sustainability Science, 18(6), 2723–2733. 2023.

Ruiz-Díaz, Raquel, and others. Social-ecological vulnerability to climate change in small-scale fisheries managed under spatial property rights systems. Marine Policy, 121, 104192. 2020.

Said, Alicia, and Ratana Chuenpagdee. Aligning the sustainable development goals to the small-scale fisheries guidelines: A case for EU fisheries governance. Marine Policy, 107, 103599. 2019.

Salgueiro-Otero, Diego, and others. Climate adaptation pathways and the role of social-ecological networks in small-scale fisheries. Scientific Reports, 12(1), 15526. 2022.

Satizábal, Paula, and others. Ocean, Water and Fisher Peoples' Tribunals Cutting the nets of capital and weaving nets of solidarity. Transnational Institute. 2024.

Saunders, Fred P., and others. Transformation of small-scale fisheries—critical transdisciplinary challenges and possibilities. Current Opinion in Environmental Sustainability, 20, 26-31. 2016.

Savoca, Matthew S., and others. Plastic ingestion by marine fish is widespread and increasing. Global Change Biology, 27(10), 2188–2199. 2021.

Schuhbauer, Anna, and others. Assessing the economic viability of small-scale fisheries: An example from Mexico. Marine Ecology Progress Series, 617–618, 365–376. Scopus. 2019.

Schuhbauer, Anna, and others. The Global Fisheries Subsidies Divide Between Small- and Large-Scale Fisheries. Frontiers in Marine Science, 7. 2020.

Seto, Katherine L., and others. Evidence of spatial competition, over resource scarcity, as a primary driver of conflicts between small-scale and industrial fishers. Ecology and Society, 28(1). 2023.

Silvano, R.A.M., I. G. Baird, A. Begossi, G. Hallwass, H.P. Huntington, P.F.M. Lopes, B. Parlee and F. Berkes. Fishers' multidimensional knowledge advances fisheries and aquatic science. Trends in Ecology & Evolution 38: 8-12. 2023.

Smallhorn-West, Patrick, and others. Linking small-scale fisheries co-management to U.N. Sustainable Development Goals. Conservation Biology, 36, e13977. 2022.

Smith, Hillary, and Xavier Basurto. Defining Small-Scale Fisheries and Examining the Role of Science in Shaping Perceptions of Who and What Counts: A Systematic Review. Frontiers in Marine Science, 6. 2019.

Smith, Hilary, and others. Ecology and the science of small-scale fisheries: A synthetic review of research effort for the Anthropocene. *Biological Conservation*, *254*, 108895. 2021.

Song, Andrew M., and others. Collateral damage? Small-scale fisheries in the global fight against IUU fishing. Fish and Fisheries, 21(4), 831–843. 2020.

Sowman, Merle, and Jackie Sunde. A just transition? Navigating the process of policy implementation in small-scale fisheries in South Africa. Marine Policy, 132, 104683. 2021.

Sowman, Merle, and Jackie Sunde. Social impacts of marine protected areas in South Africa on coastal fishing communities. Ocean & Coastal Management, 157, 168–179. 2018.

Tabe-Ojong, Martin Paul, and others. Social protection and aquatic food systems. Environmental Science & Policy. 168. 104043. 2025.

Tafon, Ralph., and others. Oceans of Conflict: Pathways to an Ocean Sustainability PACT. Planning Practice & Research, 37(2), 213–230. 2022.

The Ocean Defenders Project. Ocean Defenders: Protectors of our ocean environment and human rights. The Peopled Seas Initiative, Vancouver, Canada.2025.

Tirtadanu, undefined, and others. Assessing risk status for some commercial fisheries in Gunungkidul waters, Indonesia: An ecosystem-based fisheries approach. The Egyptian Journal of Aquatic Research, vol. 50, Issue. 1, pp. 141-147, 2024,

Trimble, Micaela and Derek Johnson. Artisanal fishing as an undesirable way of life? The implications for governance of fishers' wellbeing aspirations in coastal Uruguay and southeastern Brazil. Marine Policy, 37, 37–44. 2013.

Trimble, Micaela, and others. One party does not tango! Fishers' non-participation as a barrier to co-management in Paraty, Brazil. Ocean & Coastal Management, 92, 9–18. 2014.

UNEP. Harmful marine extractives: Deep-Sea Mining. 2022.

United Nations. United Nations Women, The world for women and girls annual. 2020.

United Nations. UN Declaration on the Rights of Indigenous Peoples. 2007.

United Nations. UN Declaration on the Rights of Peasants and Other People Working in Rural Areas. 2018

~~Vandergeest, Peter, and Melissa Marschke. Beyond slavery scandals: Explaining working conditions among fish workers in Taiwan and Thailand. Marine Policy, 132, 104685. 2021.~~

Vave, Ron. Five culturally protected water body practices in Fiji: Current status and contemporary displacement challenges. Ambio. 2022.

Viana, Daniel F., and others. Nutrient supply from marine small-scale fisheries. Scientific Reports, 13(1), 11357. 2023.

Villasante, Sebastián, and others. Resilience and Social Adaptation to Climate Change Impacts in Small-Scale Fisheries. Frontiers in Marine Science, 9. 2022.

Weeratunge, Nireka, and others. Small-scale fisheries through the wellbeing lens. Fish and Fisheries, 15(2), 255–279. 2014.

Widjaja, Sjarief, and others. Illegal, Unreported and Unregulated Fishing and Associated Drivers. In J. Lubchenco & P. M. Haugan (Eds.), The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy (pp. 553–591). Springer International Publishing. 2023.

Zhang, Chang Ik, and others. An IFRAME approach for assessing impacts of climate change on fisheries. ICES Journal of Marine Science, vol. 68, No. 6, pp. 1318–1328. 2011.

Zhang, Chang Ik., and others. An ecosystem-based fisheries assessment approach for Korean fisheries. Fisheries Research, 100, pp. 26-41. 2009.

Section 5A

Sub-chapter 1c: Medium and large-scale aquaculture

Lynne Falconer (Co-ordinating author), Karen Alexander, Hans Bjelland, Ling Cao, Ramón Filgueira, Tonje Osmundsen, Nikos Papandroulakis, Pablo Sanchez-Jerez, Doris Soto

Key findings

- Digitalisation and emerging technologies are playing increasingly important roles in many different parts of aquaculture production.
- Social acceptability issues are emerging in species that were previously accepted, e.g. molluscs.
- Future development requires meaningful engagement with local communities when planning and managing aquaculture.
- Across all topics there is a need for more detailed and disaggregated data to allow more informed assessments at local, national and international level.
- Climate change will bring new challenges throughout the aquaculture value chain and there needs to be increased attention on climate change adaptation and mitigation.

Introduction

Over the last two decades, aquaculture production has increased at a rapid pace, and the sector has become more integrated within the global food system (Naylor and others, 2021). During this time there have been many changes in farming methods as well as major developments throughout aquaculture value chains, with aquaculture products now amongst the most globalised food items (Ababouch and others, 2023). Marine aquaculture is a major component of the global aquaculture sector (FAO, 2024b), and an important contributor to food and nutrition security, supplying essential fatty acids, vital nutrients and desirable foods, often with lower environmental impacts than other forms of animal protein production (Tigchelaar and others, 2022). In 2023 the UN General Assembly adopted the resolution entitled "Oceans and the law of the sea" (78/69), which noted "*the need for actions to support sustainable fisheries and sustainable aquaculture for sufficient, safe and nutritious food, recognizing the central role of healthy oceans in resilient food systems*

and for achieving the 2030 Agenda" (United Nations General Assembly, 2023). The United Nations Framework Convention on Climate Change (UNFCC) recommend national climate policies are linked with blue food production (Cordano and O'Dea, 2023). Such emphasis underscores the importance of sustainable marine aquaculture in global food production both now and the future.

Previous World Ocean Assessments (WOA) had single chapters dedicated to aquaculture but in WOAIII aquaculture has been divided into small-scale aquaculture (See Section 5A Sub-Chapter 1D) and this chapter on medium and large-scale aquaculture. There are no formal definitions that separate small, medium and large-scale aquaculture, and scale can refer to a range of production, technological economic, social and environmental considerations and contexts (Krause et al., 2020). In WOAIII, medium and large-scale aquaculture refers to commercial orientated production for domestic or export markets, conducted by companies ranging from medium-scale enterprises through to large-scale multi-national companies. The focus is primarily sea-based production (e.g fish cages, longlines for seaweed and shellfish) as this is directly linked to the ocean, although land-based systems that interact with the marine environment (e.g. seawater use or effluent discharge), including coastal ponds and recirculating aquaculture systems (RAS) are also included where relevant. Although sea-based production still relies on more traditional technology, there are other emerging technologies (Føre and others, 2022) including closed and semi-closed containment (CCS) (Nilsen and others, 2020), submerged production (Sievers and others, 2022), and aquaculture vessels (Long and others, 2024).

There are gaps and discrepancies in how aquaculture data are collected and reported (Kebede and others, 2024). Datasets rarely distinguish between small, medium, and large-scale, and marine production is not easily disaggregated from general aquaculture statistics that also include freshwater and brackishwater. Nevertheless, data from the Food and Agriculture Organization of the United Nations (FAO) provide an overview of the aquaculture sector (FAO, 2024b, FAO, 2024a). Records classed as marine environment in the 'Global aquaculture production 1950 – 2022' dataset in the FAO's fishery and aquaculture data platform (FishStatJ), indicate that between 2018 and 2022, marine aquaculture production increased from 55.7 million tonnes to 60.2 million tonnes, and the overall value increased from $76 billion USD to $89.2 billion USD (FAO, 2024a). There is no noticeable impact on total production from the COVID-19 pandemic (FAO, 2024b), but at a finer scale, the actual consequences of the pandemic were more complex, with challenges for some companies but opportunities for others (Nielsen and others, 2023).

The aim of this chapter is to provide an overview of the present status of medium and large-scale marine aquaculture and present a vision for the future. The first three sections (Pressures, Social/economics, Governance) focus on the WOAIII assessment period, covering 2018 to 2023. In the final section (Sustainability pathways), we consider what future decades to 2050 could look like under a business-as-usual scenario and identify potential actions for a more sustainable future.

Pressures and impacts

Most medium and large-scale aquaculture takes place within a few kilometres from the coastline (Papageorgiou and others, 2021, McIntosh and others, 2022, Liu and others, 2023, Harvey and others, 2024), but new technologies, industry expansion and intensification, are changing how aquaculture utilises ocean space (Bjelland and others, 2024, Buck and others, 2024), and changes are not homogenous around the world. In China, estimates suggest that the area used for marine aquaculture in 2020 was almost three times greater than in 2010 (Liu and others, 2023). Whereas in the Mediterranean, over a similar period, the total number of cages only increased very slightly, but the number of small cages decreased, and there was an increase in the number of medium and large cages (Papageorgiou and others, 2021). In many areas, coastal space is becoming increasingly scarce (Sanchez-Jerez and others, 2016) and conflict with other marine users has also been highlighted as a constraint to further development and expansion of marine aquaculture (Galparsoro and others, 2020). Marine Spatial Planning (MSP) and zoning are frequently promoted to manage conflict over space and resources, but lack of data, insufficient tools and poor governance are barriers in some locations.

Climate change also brings challenges for aquaculture production and the wider supply chain (Stavrakidis-Zachou and others, 2021, Fuentes-Santos and others, 2021, Falconer and others, 2022, Kim and others, 2024). Over the assessment period, there are examples of studies describing climate related events affecting marine aquaculture, including marine heatwaves in the Mediterranean (Atalah and others, 2024), harmful algal blooms (HABs) in Chile (Soto and others, 2021), storms in Vietnam (Pham Thai and others, 2023) and typhoons in China (Li and others, 2024, Yin and others, 2024). Since the frequency and intensity of climate stressors are projected to increase over the next decades (IPCC, 2023), this will have implications for future planning of the sector. There is increasing emphasis on the need for aquaculture companies to monitor their own contributions to climate change and implement mitigation measures throughout the entire value chain to reduce emissions (Jones and others, 2022). Studies have shown that feed production (MacLeod and others, 2020) and transport to market (Ziegler and others, 2024) are amongst the highest contributors to greenhouse gas emissions. Knowing where emissions occur along the value chain will allow the sector to act, for example, Ziegler and others (2024) estimated a 10% reduction in farmgate emissions for 1kg of Norwegian salmon between 2017 and 2021 due to changes in feed ingredients.

Since WOAII there has been increased attention on low-trophic marine species, including farming of molluscs and seaweed at large-scale. Low-trophic farming is one of the oldest types of aquaculture and is a large contributor to total production (FAO, 2024b, FAO, 2024a), but the renewed focus promotes further expansion to meet demands for sustainable food production (Krause and others, 2022). However, there is also recognition that there are many challenges that need to be addressed if large-scale low-trophic aquaculture is to significantly increase, especially as some parts of the world have been

experiencing stagnation or declines in production of low-trophic species (Avdelas and others, 2021, Botta and others, 2020). One of the main barriers in many areas is the availability of farming locations that can provide sufficient resources to sustain large-scale production over many years. In the case of mussels, challenges with wild seed supply, have been reported in Spain (Padin and others, 2024), New Zealand (Skelton and others, 2022) and in Chile (Molinet and others, 2021). At present, mussel hatcheries are unable to meet the demands of the sector as they are too small-scale, not cost-effective or not permitted by authorities (Avdelas and others, 2021, South and others, 2022). Trials are underway to improve efficiency of collectors (van Broekhoven and others, 2024) and increase seed retention through management techniques (Reyden and others, 2024). In Chile, mussel collectors seem to be extremely efficient, although there are concerns on the potential impact of overfishing of larvae (Molinet and others, 2021).

For fed aquaculture (e.g. fish and shrimp), concerns remain over the use of marine ingredients (fishmeal and fish oil), overexploitation of wild stocks (Colombo and others, 2023, Eroldoğan and others, 2023), and feed-food competition (van Riel and others, 2023). See Section 5A Subchapter 1A. Over the last three decades there has been a significant reduction in the proportion of marine ingredients in aquaculture feeds, particularly salmon feed (Aas and others, 2022). Since WOAII, despite considerable research and development efforts, there have been no major breakthroughs. Research is focusing on alternative ingredients such as insect meal, single cell proteins, and microalgae (Colombo and others, 2023, Glencross and others, 2024) but in 2020, only 0.4% of salmon feed ingredients were from such sources (Aas and others, 2022). Use of alternative ingredients is very likely to increase in future years for salmon and other species (Albrektsen and others, 2022, Colombo and others, 2023), but there are many factors that will affect the rate at which this will happen, and this field of research is very dynamic since feed is the major expense during the farming cycle (Iversen and others, 2020).

Over the assessment period there has been increased use of digitalisation and precision fish farming techniques (Føre and others, 2018, Føre and others, 2024) to optimize feeding practices (e.g.(Georgopoulou and others, 2024)), helping to reduce environmental impacts (Mustapha and others, 2021). For traditional cages, collection of wastes remains challenging and is rare in commercial settings due to the volume of waste and depths involved. Waste collection is likely to be more feasible in semi-closed or closed containment systems (Schumann and Brinker, 2020, Føre and others, 2022), as well as RAS (Sánchez and Checa, 2023), although most of these systems are still in their infancy and not a significant part of commercial scale production. Integrated Multi-Trophic Aquaculture (IMTA), where non-fed species like bivalves and seaweed utilise the waste from fed-species like finfish, has also been identified as a potential route to increase production and reduce environmental impacts, but there are limited examples of commercial scale IMTA farms due to planning, regulatory and operational barriers (Stenton-Dozey and others, 2021, Sickander and Filgueira, 2022). However, there is a potential for a more regional approach to IMTA, and landscape scale/water body scale integration (Sanz-Lazaro and Sanchez-

Jerez, 2020), as seen in Chile where large-scale salmon farming occurs in the same areas where intensive mussel farming takes place (Camelo-Guarín and others, 2021).

During the assessment period, there has been considerable attention on antimicrobials, and the potential for antimicrobial resistance (AMR) due to the implications for human health (Reverter and others, 2020, Schar and others, 2020, European Food Safety Authority and others, 2024). In 2015 UN Member states committed to producing AMR National Action Plans (AMR NAPs) and, by 2020, many of the major aquaculture producing states included aquaculture within their AMR NAPs (Caputo and others, 2023). Significant efforts over the past decade have focused on reducing antimicrobial dependency in aquaculture (Bondad-Reantaso and others, 2023). Alternative prevention and therapeutic strategies have been developed, including vaccination (Barnes and others, 2022), functional feeds, and also phage therapy, a natural, targeted biocontrol method using species-specific bacteriophages (viruses of bacteria) to treat bacterial infections, offering an alternative to antibiotics (Kalatzis and others, 2018). However, these methods face challenges in large-scale adoption due to high development costs and strict regulatory requirements. Hence, although some countries are seeing a decline in antimicrobial use, there is increasing use in others (Lulijwa and others, 2020). Further work is needed to meet the recommendations and standards set by international organisations and certification schemes (Luthman and others, 2024), and a critical issue is the need for more reliable data, particularly in the shrimp sector (Thornber and others, 2020).

Escapes from farms are a concern, as they represent an economic loss to producers and can also have adverse ecological impacts, such as interbreeding with wild populations and spreading disease to wild populations (Sawayama and others, 2019; Atalah and Sanchez-Jerez, 2020). It is difficult to determine the status of aquaculture escapes since many countries do not have formal reporting requirements, and surveillance schemes are often inadequate or absent (Soto and others, 2023, Toledo-Guedes and others, 2024). In the Mediterranean, escapes of Gilthead seabream (*Sparus aurata*) have been significantly correlated with seabream landings from fishing vessels, suggesting escapes contribute to this fishery (Toledo-Guedes and others, 2024). In some locations there have been reductions in the number of escapes, for example over the last two decades there has been a significant effort in Norway to reduce escapes through strict regulations and technical standards (Afewerki and others, 2023) and recent estimates suggest about 0.04% of Norwegian farmed salmon are registered as escapes (Føre and Thorvaldsen, 2021). In Norway, there have also been considerable efforts to develop and use triploid salmon that are sterile and unable to reproduce, but there are challenges in their use and in 2023, due to welfare concerns, the Norwegian Food Authorities banned commercial triploid production (de Fonseka and others, 2022). Escape concerns are often greater where non-native species are used (Soto and others, 2023), as escaped species can become invasive, outcompeting local species and impacting ecosystem structure and functioning. A recent worldwide assessment revealed that approximately 26% of marine fish production involves species that are not native to their marine ecoregion (Atalah and Sanchez-Jerez, 2020).

Social/economics

Compared to the years covered by WOAI and WOAII, 2018-2023 has seen a lot more attention to aquaculture in the media (Condie and others, 2022, Machado and others, 2023, Sutherland and Armbrecht, 2024). Negative media articles have focused more on salmon production and its environmental effects than any other species. In some cases, previous high-profile events, for example environmental problems in Macquarie Harbour in Tasmania leading to an increased public focus on environmental sustainability and governance, caused this uptick (Condie and others, 2022). Mainstream media has tended to be more negative in developed countries than developing countries (Budhathoki and others, 2024). Local settings influence the portrayal, limiting the ability to make generalizations; for example, in New Zealand, it has been suggested that the tendency towards negative media portrayals occurs as the industry reaches maturity (Condie and others, 2022); contrarily, in Atlantic Canada, social acceptability increased with the age of the industry (Kraly and others, 2022).

Strongly linked to changing public perceptions of aquaculture, in the period 2018-2023 (and starting in the years just preceding), the concept of Social License to Operate (SLO) became firmly embedded in societal discussions on commercial aquaculture, evident in government policy and industry strategy (Alexander, 2022). Efforts to explore the SLO for aquaculture products has primarily focused on salmon (e.g. ((Weitzman and others, 2023, Eriksen and Mikkelsen, 2024, Olsen and others, 2024) and seaweed (e.g. ((Billing and others, 2021, Rostan and others, 2022)). A key finding across these studies is that SLO is local in nature and the need for efforts to secure and maintain SLO should be adapted to the local context.

The importance of understanding the broader social impacts of aquaculture is also coming to the fore and includes aspects such as consideration of issues such as livelihoods and human development, human rights, social and cultural needs, flow-on economic benefits and improved infrastructure (Alexander and Kelling, 2024). However, data are lacking in relation to many of these aspects (Krause and others, 2020, Mikkelsen and others, 2021), making it difficult to assess what has changed in the 2018-2023 period. What we do know is that social and human concerns are insufficiently addressed in the aquaculture sector (Brugere and others, 2023). An example is the increasing awareness of the need to address gender equality in the aquaculture sector (see also Section 5B, Chapter 6 on Gender), aligning with the UN Sustainable Development Goals (SDGs) (Troell and others, 2023), but assessment of gender-related issues in the aquaculture sector is difficult due to the lack of gender disaggregated data (Kruijssen and others, 2018, Gopal and others, 2020, Brugere and others, 2023, Troell and others, 2023). Nevertheless, research has shown that female practitioners in the aquaculture industry chain face issues related to worker safety, unequal pay, as well as constraining gender norms and discrimination (Rao and others, 2024).

Data suggests that aquaculture employment may have slightly decreased globally during the period, although the picture on a regional basis shows significant increases in Latin America and the Caribbean and a decrease in Asia (FAO, 2024b). In Europe, Northern America and Oceania, which primarily focus on large-scale commercial aquaculture, employment figures have remained stable. The traditional skills required for employment in the sector are not easily transferable as new technologies such as sensors, big data, machine learning and Artificial Intelligence have become more prominent (McDonald and others, 2024). It is not clear if this digital capability training was underway during 2018-2023, although during this period, the EU launched the 'Blue careers for a sustainable blue economy' programme aimed at developing of the next generation of blue skills for sustainable maritime careers (European Commission, 2022).

The social considerations associated with aquaculture also extend to working conditions. Globally, several occupational health and safety problems are prevalent among aquaculture workers, including ergonomic hazards, musculoskeletal complaints, diseases and injuries (Fry and others, 2019, Kaustell and others, 2019, Mitchell and Lystad, 2019, Moreau and Neis, 2009, Myers, 2010, Ngajilo and Jeebhay, 2019, Watterson and others, 2020). Norwegian studies of salmon farming have found that employees worry about strain and injuries and that organizational challenges related to goal conflicts, work pressure and employee participation can be found (Kongsvik and others, 2018, Thorvaldsen and others, 2020). As the mitigation of these risks have received little attention globally, researchers have called for a global commitment for occupational health and safety in aquaculture (Cavalli and others, 2019). Working conditions for aquaculture workers was also a topic at the Sixth International Fishing Industry Safety and Health Conference (IFISH 6) held in January 2024 which aims to help advance safety and health research and increase awareness of safety and health issues in fishing, aquaculture and seafood processing (Lincoln and others, 2024). Sadly, human rights abuses can be found everywhere, but during the 2018-2023 period, issues faced in the aquaculture sector increasingly became an issue, with certification schemes particularly being challenged by third sector organisations such as charities and non-profit organisations (see e.g Human Rights at Sea, 2023). Making the headlines, a 2024 report, based on data collection commencing in 2021, detailed pervasive systematic abuse throughout the Indian supply chain including exploitation of vulnerable workers and forced labour and dangerous conditions (Corporate Accountability Lab, 2024).

Over the assessment period there has been increased attention on sustainable food production and the societal benefits of different food types. With increasingly stringent constraints on terrestrial land use driven by climate change and biodiversity conservation, a well-managed ocean is poised to become a primary source of food to meet humanity's growing demand, and marine aquaculture will account for most of this growth (Costello and others, 2020). Seafood provides the most dominant source of omega-3 long-chain polyunsaturated fatty acids and holds significant potential to reduce micronutrient deficiencies (Golden and others, 2021). Additionally, many forms of marine aquaculture have a smaller environmental footprint than industrial beef and chicken production, not to

mention red meat, which has significantly higher resource demands (Gephart and others, 2021). There are also calls to recognise the range of purposes that aquaculture can have beyond food production (Mizuta and others, 2023). For example, the rise of stock enhancement aquaculture has aided in the recovery of some wild fish populations, as evidenced by the initial success of large yellow croaker population recovery in China's coastal waters (Yuan and others, 2021). Furthermore, ocean-reliant communities worldwide are facing increasing pressures to shift their livelihoods, and marine aquaculture provides a reliable alternative livelihood source (Gentry and others, 2020). Low-barrier entry aquaculture practices enable marginalized groups, often women, who previously lacked access to means of production, to directly participate in production, thereby improving gender equality (McClenachan and Moulton, 2022; Wurmann et al., 2022).

Governance

Aquaculture governance is paramount to securing sustainable production and industry, but has been implemented differently across the globe (Naylor and others, 2023) with public regulation both starkly absent and highly present. Public governance of aquaculture requires scientifically founded regulation which is adaptable and flexible to the type of aquaculture present and its development, capable of nurturing the abilities of the private sector, public regulators and NGOs alike, and in a manner which supports control, transparency and accountability (Ababouch and others, 2023). FAOs guidelines for assessing legal frameworks for aquaculture (ALART) support such an approach while identifying the necessary regulatory mechanisms for advancing sustainable aquaculture (Hodgson, 2023). Between 2016 and 2018, Galparsoro and others (2020) conducted a large-scale global stakeholder consultation to identify the major obstacles preventing development and expansion of marine aquaculture, and found almost 40% of the responses were related to administrative challenges, including licensing and regulation. A literature review also found that complicated and fragmented approaches to planning and licensing were frequently highlighted as barriers for marine aquaculture expansion (Falconer and others, 2023). Studies have also emphasised that many existing regulatory frameworks may not be suitable for new technologies, alternative locations, and innovative production methods including farming in more exposed or offshore waters (Davies and others, 2019, Watson and others, 2022, Krause and others, 2024).

Since WOAII, there have been examples of proactive governance initiatives to encourage responsible aquaculture development at national and international level. A notable international development was the adoption of the Guidelines for Sustainable Aquaculture (GSA) in 2024 (FAO, 2025), a framework that aims to help UN Member States and stakeholders to develop and intensify aquaculture sustainably. The GSA were prepared by FAO and align to the UN 2030 Agenda for Sustainable Development and relevant SDGs (UN General Assembly, 2015), and other key policies and agreements. At a more regional scale, The General Fisheries Commission for the Mediterranean (GFCM) of the FAO has taken significant steps to support the Mediterranean and Black Sea aquaculture sector. The GFCM's 2030 Strategic Plan (FAO, 2021), aligned with the SDGs, envisions a sustainable,

resilient, and fully realized sector. As Mediterranean aquaculture-producing countries generally adhere to a vertically integrated system of legal requirements established at national, EU, sub-regional, and Mediterranean levels (FAO/GFCM) (Papageorgiou and others, 2021), the GFCM plays a crucial role in guiding this sector. Effective governance is encouraged through enhanced collaboration with both GFCM member and cooperating countries (FAO GFCM, 2025) alongside stakeholders, to create supportive legal and administrative frameworks.. Ensuring sustainability also depends on effective spatial planning, embracing digitalization i.e. the integration of digital technologies, data analytics, and automation (IoT, sensors, AI, remote monitoring systems, big data analytics) to support data driven decisions, and promoting diversification toward lower environmental impact. Knowledge-sharing is facilitated through dedicated demonstration centers, and the creation of Technical Advisory Groups in different thematics (such as, Animal Health and Welfare or Innovation and Technology) are enabling the involvement of experts and the dissemination of the actions.

During the assessment period there have been several notable actions within the salmon farming sector that could affect where and how salmon are produced, including changes in tax regimes (Misund and others, 2024) and regulatory restrictions in some locations (Mather, 2024). Such interventions have been driven by a complex interplay of rightsholders and stakeholders in the management of aquaculture and balancing environmental concerns and socio-economic impacts. Since these are recent developments, the consequences are inconclusive at present.

Alongside national regulation, private certification schemes have emerged as a response to the perceived inefficiency of public regulation, and mainly for securing transparency in and access to a global market. Certification schemes act as a mechanism to increase transparency and accountability across different producers. Recent years have seen the number of schemes increase in parallel with an expansion of potential applications and increased uptake. The Aquaculture Stewardship Council (ASC) is an example of a certification scheme, and globally, the number of certified ASC farms has almost tripled during the reporting period, from 800 farms in 2018 to 2085 farms in 2023, and there is reason to believe that also other schemes have increased in use. However, data on the proliferation of most schemes are not made public, and comparisons are difficult across schemes as the entity certified varies from production sites to entire companies. Depending on the scheme, they currently serve as decision-making information to investors, politicians, and public authorities, as a risk reducing mechanisms for retailers, a filter distinguishing between sustainable and unsustainable choices for consumers, and they provide access to markets and price premiums for producers (Bush and others, 2013, Bush and Oosterveer, 2015, Olsen and others, 2021, Tlusty, 2012). Topics relevant for different schemes are food safety risks, degree of sustainability, fish welfare practices, working conditions, transparency and many more. However, the specific definitions of sustainability as promoted by different schemes are often strongly skewed towards environmental topics and food safety, and less towards socio-economic sustainability

(Osmundsen and others, 2020). Recently, schemes like ASC appear to be strengthening their standards in social and ethical domains.

The impact of certification on sustainability is hard to evaluate, but there is reason to believe that the development still follows the progress identified by Naylor and others (2021), in that environmental performance is improving as a response to increased regulation, including private certifications. Following the increased fame of certifications, there is great variation in how assessments are carried out ranging from desktop ratings on a narrow set of indicators to multiple onsite visits by professional auditors looking into every aspect of production. Some schemes intend to give companies incentives to improve their practices and require improvements from audit to audit. While private certification schemes often are portrayed as voluntary mechanisms, they are de facto mandatory as purchasers and certain markets expect producers to comply with specific schemes, emerging as a corporate social responsibility strategy (Rector and others, 2024). The high number of labels and certification may cause confusion and label fatigue among consumers, thus weakening the effect of stimulating sustainable food choices. Other concerns relate to how certification may act as a barrier to trade for smaller companies or companies from developing countries who cannot afford the costs and documentation requirements (Bush and others, 2013). Certifications are often expensive to attain, and multiple certifications are required when targeting different markets (Amundsen and Osmundsen, 2020). Furthermore, global certification schemes catering for an international market may be disconnected from local sustainable practices and knowledge (Jolly and others, 2023, Little and others, 2018). Creation of standards that reflect the interests of consumers rather than the local realities of aquaculture production may shift focus away from practices that are sustainable in a local context.

Sustainability pathways

Medium and large-scale marine aquaculture will play an increasingly important role in future food and nutrition security, so it is important to identify factors that would support sustainable and responsible development and reduce negative impacts (Crona and others, 2023, Tigchelaar and others, 2022, Willett and others, 2019). Scenario analysis is a tool to identify pathways to a healthy and productive ocean in the future (Nash and others, 2022, Pecl and others, 2022), including aquaculture (Couture and others, 2021, Farmery and others, 2022). Here, we use scenario analysis to describe two potential pathways for medium and large-scale marine aquaculture and link directly to the SDGs and contribute to a more sustainable ocean in 2050. The Business-as-Usual pathway describes a plausible future that is likely to occur based on current trends in the absence of any major interventions or shocks. In contrast, the Sustainable Future pathway describes a more sustainable future that could occur with deliberate actions that change the current trajectory. Using the information on the present status of medium and large-scale aquaculture from the previous three sections of this chapter (Pressures, Social/economics, Governance), together with the information from the WOAIII regional workshops, we

identified two key drivers of change: 1) governance and regulation, and 2) skills and capacity building. We then used the PESTLE (Political, Economic, Societal, Technological, Legal, Environmental) framework to identify actions that could support the move to a more sustainable future (Table 1). Our approach was adapted from the more comprehensive Future Seas 2030 project (Farmery and others, 2022, Nash and others, 2022, Pecl and others, 2022). These examples could be further developed by UN Member States and aquaculture stakeholders to develop more detailed Sustainability Pathways using context-specific information.

Business-as-Usual: The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing towards achieving zero hunger (SDG2). Regulatory systems are improving but are still slow to reform compared to the pace of technological development, which limits overall production potential. Insufficient progress is made on environmental and social impacts across all forms of production system due to reliance on outdated monitoring and assessment methods. Whilst certification schemes start to move the industry towards more sustainable outcomes (SDG12), these continue to be incremental and only occur in those more sustainability-minded corporations. A lack of skills and capacity training leads to a decreasing and disillusioned workforce as traditional skills cannot be transferred to newer technologies and locations.

Sustainable Future: The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing towards achieving zero hunger (SDG2). Significant financial investments in new and revised regulatory frameworks provide a more holistic and evidence-based approach to aquaculture licensing, increasing transparency in planning and management decisions for all stakeholders and the public. Environmental and social impacts are reduced due to innovative monitoring and revised approaches which consider the system holistically (addressing SDG12, SDG13, and SDG14). Certification schemes push the sector above and beyond compliance requirements leading to increasingly sustainable and responsible production (SDG12). Government and industry-incentivised capacity building schemes provide decent work opportunities that keep pace with industry development (SDG8).

Table 1: Potential actions for each driver of change that could accelerate progress towards a *Sustainable Future* scenario where medium and large-scale marine aquaculture contributes to increased production of high-quality protein in a responsible manner and supports decent work and economic growth

PESTLE category	Governance and regulation	Skills and capacity building

Political	Produce novel governance frameworks that incentivize sustainable development, collaboration, and transparency. Minimize potential conflict of interests within government agencies, i.e. as promoter and regulator.	Establish and support initiatives that facilitate transdisciplinary co-production and sharing of knowledge and international cooperation related to new technology, novel production systems, and governance.
Economic	Provide financial support to address bottlenecks in licensing and regulatory frameworks via streamlined administrative procedures. Financial support should also be used to update existing regulations, or develop new licensing frameworks for novel farming systems. Improve collection and analysis of disaggregated economic data to support more informed assessments and improvements in governance and regulation.	Allocate financial support for capacity building and skills training throughout the industry and associated activities. Include schemes that will enable upskilling and retraining in new technologies and novel production systems. Improve collection and analysis of disaggregated workforce data to support targeted financial support for capacity building where required.
Societal	Co-develop marine spatial planning (MSP) strategies with other activities, local stakeholders and communities to ensure trust, procedural fairness, and redistribution of profits. Enable processes that minimize conflicts with other ocean users. Promote aquaculture literacy. Improve collection and analysis of disaggregated social data (including better data on gender) to support more informed assessments and improvements in governance and regulation.	Increase awareness of the roles, experience and skills required in aquaculture, e.g. precision farming. Ensure that training programs emphasize occupational health and safety. Provide accessible career mentoring schemes for new entrants, returners and the long-term workforce.
Technological	Incentivize novel and improved farming systems, particularly in new areas, e.g. open ocean, that optimize species health and welfare, are safe for workers, and reduce negative effects on the environment.	Create infrastructure to support capacity building and skills training. Enhance collaborative opportunities for data collection, analysis and sharing to inform decision-making. Strengthen access to educational resources such as digital content. Support hatcheries and breeding programs.
Legal	Revise licensing and regulatory frameworks to address bottlenecks based on evidence, ensuring that regulations are adjusted to fit scale and risk of the farming	If required, develop enabling legislation to support relevant infrastructure for support capacity building. Develop training schemes to support the implementation of

	operation. Develop and revise legal frameworks for novel farming systems. Provide legal mechanisms to co-develop marine spatial planning (MSP) strategies with other activities, local stakeholders and communities.	health and safety regulation. Ensure cross-sectoral training schemes align with regulatory requirements for MSP.
Environmental	Promote environmental data collection and analysis, including climate change modelling, to enhance site selection to minimize antibiotics and chemical use, interactions with wild species (via escapes or diseases), and reduce CO_2 emissions.	Organise exchange programmes that facilitate visits and placements across the aquaculture sector (including existing and new technology) for industry, researchers, policymakers, external stakeholders and wider society. Ensure there are knowledge exchange opportunities with other sectors to improve MSP.

The following sections explore some of the 'governance and regulation' and 'skills and capacity building' actions suggested in Table 1 that UN Member States could use to help move towards the Sustainable Future scenario. The ability to implement such initiatives, and associated timescale, will depend on the aquaculture-specific context in each Member State.

Governance and regulation

The Sustainable Future relies on governance and regulatory frameworks that have strong social credentials, generated through greater trust and transparency amongst all actors and a better understanding of how aquaculture operates within the environment and overall societal contributions. Ocean literacy has been defined as a catalyst that can accelerate systemic change and support sustainability goals (McKinley and others, 2023). In a similar way, aquaculture literacy could be a route to increased understanding of aquaculture's role and responsibilities within the marine environment and how this links to other activities, which could then strengthen governance and regulatory frameworks. In Norway there are several initiatives aimed at increasing public knowledge of aquaculture, including visitor centres, and a web-portal that includes facts, data and information for the general public (Mikkelsen and others, 2021).

Governance and regulation must be underpinned by scientific evidence as this increases the legitimacy and trust in the rules and practices that are implemented. In this sense, the use of precision farming techniques (Føre and others, 2018) and large-scale monitoring, supported by remote sensing and satellite data integration, will be crucial for predicting conditions not only in farms but also in aquaculture zones (Chatziantoniou and others,

2023), allowing better planning for aquaculture and better coordination with other activities, optimising use of space and resources, for example through MSP. In addition, increased dialogue and knowledge sharing between sectors and marine users, will lead to better understanding of requirements for marine space across all user groups to support co-development of plans that reduce conflict. Digitalisation of the aquaculture sector will support evidence-based co-development of spatial management plans and strategies with other activities and communities. Vast amounts of data collected at farms will provide greater insight into climate change for all marine activities (Falconer and others, 2025). Better understanding of the farming environment will allow development of adaptive management strategies, such as early warning systems and flexible farm designs, to increase resilience to climate change (Sanchez-Jerez and others, 2023). Where possible, climate adaptation measures should be mainstreamed into aquaculture planning and practices, especially in regions that are vulnerable to marine heatwaves and algal blooms.

Skills and capacity building

The pressing need for increased amounts of responsibly produced food requires a significant boost in production at a rapid pace, which in turn demands a ready workforce equipped with the necessary knowledge, skills and experience. The aquaculture sector must consider new and innovative ways to attract new entrants and support the existing workforce in both reskilling and upskilling. Lifelong learning will be important for increased resilience in the future workforce, supported by fair and equitable access to new knowledge and training opportunities. Networking initiatives such as Women in Scottish Aquaculture (WiSA) could provide routes to mentoring and career support for new entrants, returners, and longer-term workforce (Kelling and Lawan, 2023).

Transformative change rarely occurs in silos, so actions are required that will support diverse and inclusive knowledge exchange and co-learning opportunities (Partelow and others, 2023). However, research infrastructure is expensive to install and maintain, which can exclude parts of the sector and limit potential for upskilling or new knowledge generation. Within the research and innovation landscape the EU funded AQUAEXCEL3.0 project (AQUAEXCEL3.0, 2023) is an example of a mechanism that encourages new partnerships and widens access to research infrastructure that would otherwise be unavailable to many individuals and groups.

Aquaculture companies that intend to develop in more remote offshore locations will require the development of more robust structures, advanced technologies, and production systems with increased automation and reduced maintenance needs. There may be opportunities to co-operate with other sectors, sharing knowledge and research infrastructure. For example, the Australian government have partnered with industry and academia to establish the Blue Economy Cooperative Research Centre, a 10-year funded

initiative that supports research and training initiatives across aquaculture, offshore engineering, and renewable energy (Blue Economy Cooperative Research Centre, 2022).

Summary

Medium and large-scale aquaculture is an important part of the ocean economy and an essential contributor to food and nutrition security. Since WOAII production increased, but there are still bottlenecks and challenges that need to be addressed if the sector is to significantly increase production and contribute further to sustainability goals. Data gaps and lack of consistent reporting across species, systems and locations is an issue that makes it difficult to understand the scale and importance of some topics. Nevertheless, across the sector there are many examples that show how innovative solutions have been used to address previous challenges.

Statement on Artificial Intelligence (AI): AI was not used to write this chapter.

References

Aas, Turid Synnøve and others. Utilization of feed resources in the production of rainbow trout (Oncorhynchus mykiss) in Norway in 2020. Aquaculture Reports, vol. 26, art. 10131, 2022.

Ababouch, Lahsen and others. Value chains and market access for aquaculture products. Journal of the World Aquaculture Society, vol. 54, pp. 527-553, 2023.

Afewerki, Samson and others. Innovation in the Norwegian aquaculture industry. Reviews in Aquaculture, vol. 15, pp. 759-771, 2023.

Albrektsen, Sissel and others. Future feed resources in sustainable salmonid production: A review. Reviews in Aquaculture, vol. 14, pp. 1790-1812, 2022.

Alexander, Karen A. A social license to operate for aquaculture: Reflections from Tasmania. Aquaculture, vol. 550, art. 737875, 2022.

Alexander, Karen A and Ingrid Kelling. Social sustainability in seafood systems: a rapid review. Cambridge Prisms: Coastal Futures, vol. 2, art. e1, 2024.

Amundsen, Vilde Steiro and Tonje Cecilie Osmundsen. Becoming certified, becoming sustainable? Improvements from aquaculture certification schemes as experienced by those certified. Marine Policy, vol. 119, art. 104097, 2020.

AQUAEXCEL3.0. AquaExcel3.0 – AQUAculture infrastructures for EXCELlence in European fish research towards 2020. https://aquaexcel.eu/, 2023 .

Atalah, Javier and others. Marine heatwaves in the western Mediterranean: Considerations for coastal aquaculture adaptation. Aquaculture, vol. 588, art. 740917, 2024.

Atalah, Javier and Pablo Sanchez-Jerez. 2020. Global assessment of ecological risks associated with farmed fish escapes. Global Ecology and Conservation, vol. 21, art. e00842, 2020.

Avdelas, Lamprakis and others. The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities. Reviews in Aquaculture, vol. 13, pp.91-118, 2021.

Barnes, Andrew C and others. Autogenous vaccination in aquaculture: A locally enabled solution towards reduction of the global antimicrobial resistance problem. Reviews in Aquaculture, vol. 14, pp. 907-918, 2022.

Billing, Suzannah-Lynn and others. Is social license to operate relevant for seaweed cultivation in Europe? Aquaculture, vol. 534, art. 736203, 2021.

Bjelland, Hans Vanhauwaert and others. Exposed Aquaculture Operations: Strategies for Safety and Fish Welfare. Reviews in Aquaculture, 2024.

Blue Economy Cooperative Research Centre. Blue Economy CRC: Underpinning the Growth of the Blue Economy. https://blueeconomycrc.com.au/, 2022

Bondad-Reantaso, Melba G and others. Review of alternatives to antibiotic use in aquaculture. Reviews in Aquaculture, vol. 15, pp. 1421-1451, 2023.

Botta, Robert and others. A review of global oyster aquaculture production and consumption. Marine Policy, vol. 117, art. 103952, 2020.

Brugere, C and others. Humanizing aquaculture development: Putting social and human concerns at the center of future aquaculture development. Journal of the World Aquaculture Society, vol. 54, pp. 482-526, 2023.

Buck, Bela H and others. Resolving the term “offshore aquaculture” by decoupling “exposed” and “distance from the coast”. Frontiers in Aquaculture, vol. 3, art. 1428056, 2024.

Budhathoki, Mausam and others. Societal perceptions of aquaculture: Combining scoping review and media analysis. Reviews in Aquaculture, vol. 16, pp. 1879-1900, 2024.

Bush, SR and others. Certify Sustainable Aquaculture? Science, vol. 341, pp.1067-1068, 2013.

Bush, Simon R And Peter Oosterveer. Vertically Differentiating Environmental Standards: The Case of the Marine Stewardship Council. Sustainability, vol. 7, pp. 1861-1883, 2015.

Camelo-Guarín, Stefany and others. Recommendations for implementing integrated multitrophic aquaculture in commercial farms at the landscape scale in southern Chile. Aquaculture, vol. 544, art. 737116, 2021.

Caputo, Andrea and others. Antimicrobial resistance in aquaculture: A global analysis of literature and national action plans. Reviews in Aquaculture, vol. 15, pp. 568-578, 2023.

Cavalli, Lissandra and others. Scoping Global Aquaculture Occupational Safety and Health. Journal of Agromedicine, vol. 24, pp. 391-404, 2019.

Chatziantoniou, Andromachi and others. Aquasafe: A Remote Sensing, Web-Based Platform for the Support of Precision Fish Farming. Applied Sciences, vol. 13, art. 6122, 2023.

Colombo, Stefanie M and others. Towards achieving circularity and sustainability in feeds for farmed blue foods. Reviews in Aquaculture, vol. 15, pp. 1115-1141, 2023.

Condie, Corrine M and others. The long-term evolution of news media in defining socio-ecological conflict: A case study of expanding aquaculture. Marine Policy, vol. 138, art. 104988, 2022.

Cordano, J and O’Dea, N. Informal summary report of the ocean and climate change dialogue 2023. Available: https://unfccc.int/documents/631689 , 2023.

Corporate Accountability Lab. Hidden Harvest: Human Rights and Environmental Abuses in India’s Shrimp Industry. https://corpaccountabilitylab.org/hidden-harvest, 2024.

Costello, Christopher and others. The future of food from the sea. Nature, vol. 588, pp. 95-100, 2020.
Couture, Jessica L. and others. Scenario analysis can guide aquaculture planning to meet sustainable future production goals. ICES Journal of Marine Science, vol. 78, pp. 821-831, 2021.
Crona, Beatrice I and others. Four ways blue foods can help achieve food system ambitions across nations. Nature, vol. 616, pp. 104-112, 2023.
Davies, Ian P and others. Governance of marine aquaculture: Pitfalls, potential, and pathways forward. Marine Policy, vol. 104, pp. 29-36, 2019.
de Fonseka, Raneesha And others. Triploidy leads to a mismatch of smoltification biomarkers in the gill and differences in the optimal salinity for post-smolt growth in Atlantic salmon. Aquaculture, vol. 546, art. 737350, 2022.
Eriksen, Katrine and Eirik Mikkelsen. What affects the level of local social acceptance of salmon farming in Norway? Aquaculture, vol. 588, art. 740926, 2024.
Eroldoğan, Orhan Tufan and others. From the sea to aquafeed: A perspective overview. Reviews in Aquaculture, vol. 15, pp. 1028-1057, 2023.
European Commission. EMFAF Call for Proposals - Blue careers for a sustainable blue economy.https://cinea.ec.europa.eu/funding-opportunities/calls-proposals/emfaf-call-proposals-blue-careers-sustainable-blue-economy_en, 2022.
European Food Safety Authority and others. Technical specifications for a EU-wide baseline survey of antimicrobial resistance in bacteria from aquaculture animals. EFSA Journal, vol. 22, art. e8928, 2024.
Falconer, Lynne and others. Insight into real-world complexities is required to enable effective response from the aquaculture sector to climate change. PLOS Climate, vol. 1, art. e0000017, 2022.
Falconer, Lynne and others.. Marine aquaculture sites have huge potential as data providers for climate change assessments. Aquaculture, vol. 595, art. 741519, 2025.
Falconer, Lynne and others. Planning and licensing for marine aquaculture. Reviews in Aquaculture, vol. 15, pp. 1374-1404, 2023.
FAO. FishStat: Global aquaculture production 1950 - 2022. In: FishStatJ. www.fao.org/fishery/en/statistics/software/fishstatj, 2024a.
FAO. The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action, Rome, FAO, 2024b.
FAO. GFCM 2030 Strategy for sustainable fisheries and aquaculture in the Mediterranean and the Black Sea. Rome, 2021.
FAO. Guidelines for Sustainable Aquaculture. Rome. FAO, 2025. https://doi.org/10.4060/cd3785en.
FAO GFCM. General Fisheries Commission of the Mediterranean – GFCM: Membership. https://www.fao.org/gfcm/about/membership/en/, 2025.
Farmery, AK and others. Food for all: designing sustainable and secure future seafood systems. Reviews in Fish Biology and Fisheries, vol. 32, pp. 101-121, 2022.
Føre, Heidi Moe and others. Technological innovations promoting sustainable salmon (Salmo salar) aquaculture in Norway. Aquaculture Reports, vol. 24, art. 101115, 2022.

Føre, Heidi Moe and Trine Thorvaldsen. Causal analysis of escape of Atlantic salmon and rainbow trout from Norwegian fish farms during 2010–2018. Aquaculture, vol. 532, art. 736002, 2021.
Føre, Martin and others. Digital Twins in intensive aquaculture — Challenges, opportunities and future prospects. Computers and Electronics in Agriculture, vol. 218, art. 108676, 2024.
Føre, Martin and others. Precision fish farming: A new framework to improve production in aquaculture. Biosystems Engineering, vol. 173, pp. 176-193, 2018.
Fry, Jillian P and others. Occupational Safety and Health in U.S. Aquaculture: A Review. Journal of Agromedicine, vol. 24, pp. 405-423, 2019.
Fuentes-Santos, Isabel and others. Modeling the impact of climate change on mussel aquaculture in a coastal upwelling system: A critical assessment. Science of The Total Environment, vol. 775, art. 145020, 2021.
Galparsoro, Ibon and others. Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. Reviews in Aquaculture, vol. 12, pp. 2061-2079, 2020.
Gentry, Rebecca R and others. Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture, vol. 12, pp. 499-512, 2020.
Georgopoulou, Dimitra G and others. Swimming behavior as a potential metric to detect satiation levels of European seabass in marine cages. Frontiers in Marine Science, vol. 11, art. 1350385, 2024.
Gephart, Jessica A and others. Environmental performance of blue foods. Nature, vol. 597, pp. 360-365, 2021.
Glencross, Brett and others. A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds. Reviews in Fisheries Science & Aquaculture, vol. 32, pp. 396-434, 2024.
Golden, Christopher D and others. Aquatic foods to nourish nations. Nature, vol. 598, pp. 315-320, 2021.
Gopal, Nikita. and others. Expanding the horizons for women in fisheries and aquaculture. Gender, Technology and Development, art. 24, pp. 1-9, 2020.
Harvey, M. and others. Ocean sprawl: The global footprint of shellfish and algae aquaculture and its implications for production, environmental impact, and biosecurity. Aquaculture, vol. 586, art. 740747, 2024.
Hodgson, S. Aquaculture Legal Assessment and Revision Tool. Legal Guide No. 6. Rome, FAO, 2023.
Human Rights At Sea. Does it do what it says on the tin? Fisheries and aquaculture certification, standards and rating ecosystem: an independent review 1.0, 2023.
IPCC. Climate Change 2023: Synthesis report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 2023.
Iversen, Audun and others. Production cost and competitiveness in major salmon farming countries 2003–2018. Aquaculture, vol. 522, art. 735089, 2020.
Jolly, Curtis M and others. Dynamics of aquaculture governance. Journal of the World Aquaculture Society, vol. 54, pp. 427-481, 2023.

Jones, Alice R and others. Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in Marine Aquaculture. BioScience, vol. 72, pp. 123-143, 2022.
Kalatzis, Panos G and others. Bacteriophage Interactions with Marine Pathogenic Vibrios: Implications for Phage Therapy. Antibiotics, vol. 7, art. 15, 2018.
Kaustell, Kim Olavi and others. Occupational injuries and diseases in fish farming in Finland 1996–2015. International Maritime Health, vol. 70, pp. 47-54, 2019.
Kebede, Endalkachew Abebe and others. Assessing and addressing the global state of food production data scarcity. Nature Reviews Earth & Environment, vol. 5, pp. 295-311.
Kelling, Ingrid and Ibrahim Lawan. Equality, diversity and inclusion: A way forward for aquaculture~~aquauclture~~ in Scotland. Frontiers in Aquaculture~~Aquauclture~~, vol. 2, art. 1151853, 2023.
Kim, Moo-Jin and others. A climate change risk assessment in aquaculture in Korea. Climatic Change, vol. 177, art. 93, 2024.
Kongsvik, TØ and others. Safety climate and compliance in the Norwegian aquaculture industry—Employees' perceptions at different company levels, In Safetyand Reliability - Safe Societies in a Changing World. Haugen S and others.eds. CRC Press, London, 2018.
Kraly, Paul and others. Understanding factors influencing social acceptability: Insights from media portrayal of salmon aquaculture in Atlantic Canada. Aquaculture, vol. 547, art. 737497, 2022.
Krause, Gesche and others. Visualizing the social in aquaculture: How social dimension components illustrate the effects of aquaculture across geographic scales. Marine Policy, vol. 118, art. 103985, 2020.
Krause, Gesche and others. Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World. Frontiers in Sustainable Food Systems, vol. 6, art. 875509, 2022.
Krause, Gesche and others. The social science of offshore aquaculture: uncertainties, challenges and solution-oriented governance needs. Frontiers in Aquaculture, vol. 3, art. 1384037, 2024.
Kruijssen, Froukje and others. Gender and aquaculture value chains: A review of key issues and implications for research. Aquaculture, vol. 493, pp. 328-337, 2018.
Li, Yanjiao and others. Risk level assessment of typhoon-induced wave fields around a large-scale suspended mussel farm. Frontiers in Marine Science, vol. 11, art. 1351316, 2024.
Lincoln, Jennifer and others. Proceedings of the Sixth International Fishing Industry Safetyand Health Conference (IFISH 6). FAO Fisheries and Aquaculture Proceedings, No. 72. Rome, FAO, 2024.
Little David C and others. Sustainable intensification of aquaculture value chains between Asia and Europe: A framework for understanding impacts and challenges. Aquaculture, vol. 493, pp. 338-354, 2018.
Liu, Yueming and others. Changes in the spatial distribution of mariculture in China over the past 20 years. Journal of Geographical Sciences, vol. 33, pp. 2377-2399, 2023.
Long, Lina and others. Offshore aquaculture in China. Reviews in Aquaculture, vol. 16, pp. 254-270, 2024.

Lulijwa, Ronald and others. Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers. Reviews in Aquaculture, vol. 12, pp. 640-663, 2020.
Luthman, Ola and others. Global overview of national regulations for antibiotic use in aquaculture production. Aquaculture International, 2024.
Machado, Patrícia. C and others. Regional communication and media analysis of aquaculture in Atlantic islands. Aquaculture International, vol. 31, pp. 2687-2704, 2023.
Mather, C. Phasing out open net-pen salmon farming in British Columbia. Science Advances, vol. 10, No. 42**,** art4568, 2024
MacLeod, Michael J and others. Quantifying greenhouse gas emissions from global aquaculture. Scientific Reports, vol. 10, art. 11679, 2020.
McClenachan, Loren and Allie Moulton. Transitions from wild-caught fisheries to shellfish and seaweed aquaculture increase gender equity in Maine. Marine Policy, vol. 146, art. 105312, 2022.
McDonald, Nicole and others. Skill Development in Current and Future Workers to Thrive in the Digital Aquaculture Industry. Aquaculture Journal, vol. 4, pp. 15-27, 2024.
McIntosh, P and others. Supersizing salmon farms in the coastal zone: A global analysis of changes in farm technology and location from 2005 to 2020. Aquaculture, vol. 553, art. 738046, 2022.
McKinley, E and others. The evolution of ocean literacy: A new framework for the United Nations Ocean Decade and beyond. Marine Pollution Bulletin, vol. 186, art. 114467, 2023.
Mikkelsen, Eirik and others. Availability and usefulness of economic data on the effects of aquaculture: a North Atlantic comparative assessment. Reviews in Aquaculture, vol. 13, pp. 601-618, 2021.
Mikkelsen, Eirik and others. Making a Web-Portal With Aquaculture Sustainability Indicators for the General Public. Frontiers in Sustainable Food Systems, vol. 5, art. 644314, 2021.
Misund, Bård. and others. Impact of rent taxation on Norwegian salmon farming companies. Aquaculture Economics & Management, 1-20, 2024.
Mitchell, Rebecca J and Lystad, RP. Occupational injury and disease in the Australian aquaculture industry. Marine Policy, vol. 99, pp. 216-222, 2019.
Mizuta, Darien D and others. The changing role and definitions of aquaculture for environmental purposes. Reviews in Aquaculture, vol. 15, pp. 130-141, 2023.
Molinet, Carlos and others. Vertical distribution patterns of larval supply and spatfall of three species of Mytilidae in a Chilean fjord used for mussel farming: Insights for mussel spatfall efficiency. Aquaculture, vol. 535, art. 736341, 2021.
Moreau, Darek TR and Barbara Neis. Occupational health and safety hazards in Atlantic Canadian aquaculture: Laying the groundwork for prevention. Marine Policy, vol. 33, pp. 401-411, 2009.
Mustapha, Umar Farouk and others. Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). Reviews in Aquaculture, vol. 13, pp. 2076-2091, 2021.
Myers, Melvin L. Review of Occupational Hazards Associated With Aquaculture. Journal of Agromedicine, vol. 15, pp. 412-426, 2010.

Nash, Kirsty L and others. Developing achievable alternate futures for key challenges during the UN Decade of Ocean Science for Sustainable Development. Reviews in Fish Biology and Fisheries, vol. 32, pp. 19-36, 2022.
Naylor, Rosamond and others. A global view of aquaculture policy. Food Policy, vol. 116, art. 102422, 2023.
Naylor, Rosamond L and others. A 20-year retrospective review of global aquaculture. Nature, vol. 591, pp. 551-563, 2021.
Ngajilo, Dorothy and Mohamed F Jeebhay. Occupational injuries and diseases in aquaculture – A review of literature. Aquaculture, vol. 507, pp. 40-55, 2019.
Nielsen, Rasmus and others. The Covid-19 impacts on the European Union aquaculture sector. Marine Policy, vol. 147, art. 105361, 2023.
Nilsen, Arve and others. A closer look at closed cages: Growth and mortality rates during production of post-smolt Atlantic salmon in marine closed confinement systems. Aquacultural Engineering, vol. 91, art. 102124, 2020.
Olsen, Marit Schei and others. Social license to operate for aquaculture – A cross-country comparison. Aquaculture, vol. 584, art. 740662, 2024.
Olsen, Marit Schei and others. Certifying the public image? Reputational gains of certification in Norwegian salmon aquaculture. Aquaculture, vol. 542, art. 736900, 2021.
Osmundsen, Tonje C. and others. The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. Global Environmental Change, vol. 60, art. 102025, 2020.
Padin, Xosé A and others. The declining availability of wild mussel seed for aquaculture in a coastal upwelling system. Frontiers in Marine Science, vol. 11, art. 1375269, 2024.
Papageorgiou, Nafsika and others. Changes of the Mediterranean fish farm sector towards a more sustainable approach: A closer look at temporal, spatial and technical shifts. Ocean & Coastal Management, vol. 214, art. 105903, 2021.
Partelow, Stefan and others. Aquaculture governance: five engagement arenas for sustainability transformation. Current Opinion in Environmental Sustainability, vol. 65, art. 101379, 2023.
Pecl, Gretta T and others. Future Seas 2030: pathways to sustainability for the UN Ocean Decade and beyond. Reviews in Fish Biology and Fisheries, vol. 32, pp. 1-7, 2022.
Pham Thai, Giang and others. Potential risks of climate change and tropical storms on ecosystem and clams culture activities in Giao Thuy, Nam Dinh, Vietnam. Human and Ecological Risk Assessment: An International Journal, vol. 29, pp. 836-858, 2023.
Rao, Nitya and others. A systematic review of the impact of post-harvest aquatic food processing technology on gender equality and social justice. Nature Food, vol. 5, pp. 731-741, 2024.
Rector, Megan E and others. The role of salmon aquaculture eco-certification in corporate social responsibility and the delivery of ecosystem services and disservices. Marine Policy, vol. 160, art. 105948, 2024.
Reverter, Miriam and others. Aquaculture at the crossroads of global warming and antimicrobial resistance. Nature Communications, vol. 11, art. 1870, 2020.

Reyden, Carrie AR and others. Impacts of seeding density on the abundance and size of juvenile mussels and biofouling accumulation in Greenshell™ mussel aquaculture. Aquaculture, vol. 592, art. 741177, 2024.

Rostan, Julie and others. Creating a social license to operate? Exploring social perceptions of seaweed farming for biofuels in Scotland, Northern Ireland and Ireland. Energy Research & Social Science, vol. 87, art. 102478, 2022.

Sánchez, Imma and Daniel Checa. iFishIENCi D4.5 Report on circularity of the iFishIENCi approach. Intelligent fish feeding through Integration of ENabling technologies and Circular principle, iFishIENCi, 2023.

Sanchez-Jerez, Pablo and others. Aquaculture's struggle for space: the need for coastal spatial planning and the potential benefits of Allocated Zones for Aquaculture (AZAs) to avoid conflict and promote sustainability. Aquaculture Environment Interactions, vol. 8, pp. 41-54, 2016.

Sanchez-Jerez, Pablo Jose. and others. *EU Bioeconomy Monitoring System indicator update Mubareka, S. editor(s), Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-61674-0, doi:10.2760/19269, JRC132405, 2023*

Sanz-Lazaro, Carlos and Pablo Sanchez-Jerez. Regional Integrated Multi-Trophic Aquaculture (RIMTA): Spatially separated, ecologically linked. Journal of Environmental Management, vol. 271, art. 110921, 2020.

Sawayama, Eitaro and others. Identification and quantification of farmed red sea bream escapees from a large aquaculture area in Japan using microsatellite DNA markers. Aquatic Living Resources, vol. 32, art. 26, 2019.

Schar, Daniel and others. Global trends in antimicrobial use in aquaculture. Scientific Reports, vol. 10, art. 21878, 2020.

Schumann, Mark and Alexander Brinker. Understanding and managing suspended solids in intensive salmonid aquaculture: a review. Reviews in Aquaculture, vol. 12, pp. 2109-2139, 2020.

Sickander, Omar and Ramón Filgueira. Factors affecting IMTA (integrated multi-trophic aquaculture) implementation on Atlantic Salmon (Salmo salar) farms. Aquaculture, vol. 561, art. 738716, 2022.

Sievers, Michael and others. Submerged cage aquaculture of marine fish: A review of the biological challenges and opportunities. Reviews in Aquaculture, vol. 14, pp. 106-119, 2022.

Skelton, Bradley M and others. 2022. Inefficiency of conversion of seed into market-ready mussels in New Zealand's Greenshell™ mussel (Perna canaliculus) industry. Aquaculture, vol. 560, art. 738584, 2022.

Soto, Doris and others. Environmental risk assessment of non-native salmonid escapes from net pens in the Chilean Patagonia. Reviews in Aquaculture, vol. 15, pp. 198-219, 2023.

Soto, Doris and others. Scientific warnings could help to reduce farmed salmon mortality due to harmful algal blooms. Marine Policy, vol. 132, art. 104705, 2021.

South, Paul M and others. The loss of seed mussels in longline aquaculture. Reviews in Aquaculture, vol. 14, pp. 440-455, 2022.

Stavrakidis-Zachou, Orestis and others. Projecting climate change impacts on Mediterranean finfish production: a case study in Greece. Climatic Change, vol. 165, art. 67, 2021.
Stenton-Dozey, Jeanette ME and others. New Zealand aquaculture industry: research, opportunities and constraints for integrative multitrophic farming. New Zealand Journal of Marine and Freshwater Research, vol. 55, pp. 265-285, 2021.
Sutherland, Jordan Francesca Jane and John Armbrecht. Media representation of aquaculture in Sweden. Aquaculture, vol. 583, art. 740578, 2024.
Thornber, Kelly and others. Evaluating antimicrobial resistance in the global shrimp industry. Reviews in Aquaculture, vol. 12, pp. 966-986, 2020.
Thorvaldsen, Trine and others. Occupational health, safety and work environments in Norwegian fish farming - employee perspective. Aquaculture, vol. 524, art. 735238, 2020.
Tigchelaar, Michelle and others. The vital roles of blue foods in the global food system. Global Food Security, vol. 33, art. 100637, 2022.
Tlusty, Michael F. Environmental improvement of seafood through certification and ecolabelling: theory and analysis. Fish and Fisheries, vol. 13, pp. 1-13, 2012.
Toledo-Guedes, Kilian and others. Domesticating the wild through escapees of two iconic mediterranean farmed fish species. Scientific Reports, vol. 14, art. 23772, 2024.
Troell, Max, and others. Perspectives on aquaculture's contribution to the Sustainable Development Goals for improved human and planetary health. Journal of the World Aquaculture Society, vol. 54, pp. 251-342, 2023.
UN General Assemby, Oceans and the law of the sea. A/RES/78/69. 5 December 2023.
UN General Assembly, *Transforming our world : the 2030 Agenda for Sustainable Development*, A/RES/70/1, 21 October 2015.
van Broekhoven, Wouter and others. Transitioning from wild seed fishery to Seed Mussel Collectors (SMCs): Reviewing the efficiency of collectors for seed provisioning in mussel bottom culture. Aquacultural Engineering, vol. 105, art. 102414, 2024.
van Riel, Anne-Jo and others. Feed-food competition in global aquaculture: Current trends and prospects. Reviews in Aquaculture, vol. 15, pp. 1142-1158, 2023.
Watson, Lauren and others. 'Offshore' salmon aquaculture and identifying the needs for environmental regulation. Aquaculture, vol. 546, art. 737342, 2022.
Watterson, Andrew and others. The neglected millions: the global state of aquaculture workers' occupational safety, health and well-being. Occupational and Environmental Medicine, vol. 77, pp. 15-18, 2020.
Weitzman, Jenny and others. Dimensions of legitimacy and trust in shaping social acceptance of marine aquaculture: An in-depth case study in Nova Scotia, Canada. Environmental Science & Policy, art. 143, pp. 1-13, 2023.
Willett, Walter and others. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. The Lancet, vol. 393, pp. 447-492, 2019.
Wurmann, Carlos and others. Regional review on status and trends in aquaculture development in Latin America and the Caribbean – 2020. FAO Fisheries and Aquaculture Circular No 123/3. Rome, FAO, 2022.
Yin, Zixu and others. Marine aquaculture spatial planning on market orientation for Pacific oyster in Shandong, China. Aquaculture, vol. 591, art. 741144, 2024.

Yuan, Jigui and others. Resource Status and Effect of Long-Term Stock Enhancement of Large Yellow Croaker in China. Frontiers in Marine Science, vol. 8, art. 743836, 2021.

Ziegler, Friederike and others. Greenhouse gas emission reduction opportunities for the Norwegian salmon farming sector - can they outweigh growth? Aquaculture, vol. 581, art. 740431, 2024.

Section 5A

Subchapter 1d: Small-scale Aquaculture

Coordinating Author: Rohana Subasinghe

Contributing Authors: Rohana Subasinghe, Antonio Garza de Yta, Blessing Mapfumo, Carlos Wurmann Gotfrit, Devin Bartley, Doris Soto, Elizabeth Cottier-Cook, Shivaun Leonard, Salin Krishna, Timothy O'Reilly

Keynotes

Small-scale aquaculture practiced in the nearshore and coastal areas play a significant role in global food security, livelihoods, nutrition, and health, despite increasing threats from anthropogenic pollutants due to accelerating coastal population growth, which compromises ecosystem integrity essential for sustainable aquaculture operations in coastal waters.

Some species and well managed practices and systems have little or no negative impacts on the ocean health (e.g., seaweeds and molluscs) and can provide significant ecosystem services by removing excess nutrients from ocean waters, thereby reducing pollution and enhancing carbon capture potential, leading to their classification as regenerative aquaculture.

There appear to be a serious lack of specific national laws governing nearshore and coastal small scale aquaculture sustainability. National laws and regulations need to be clear and promote the sector growth within scientifically determined carrying capacities.

It is timely for the states to provide greater attention, including strengthening of extension services, to nearshore and coastal small-scale aquaculture under their Blue Economy development programmes, which will collectively contribute to global food and nutrition security and improving livelihoods, whilst maintaining and improving the ocean's health.

Considering the potential negative impacts of aggregation of small-scale operations, spatial planning and addressing carrying capacity limitations should be encouraged at national and regional levels.

Best management practices, including biosecurity measures should be implemented to protect and make small scale nearshore and coastal aquaculture more sustainable with least negative impacts on the ocean health.

Improving multi-sectoral cooperation and communication between government agencies is crucial for enhancing marine aquaculture governance and ultimately improving ocean health.

Introduction

The aquaculture industry produces over 500 species of aquatic animal and plant species destined for food and non-food purposes and is practiced at an array of scales (small, medium, large, commercial, industrial) in all aquatic environments (marine, brackish and freshwater). Since there is no single, globally accepted definition of “small-scale aquaculture” currently available, in this Subchapter, “small-scale” is referred to as single or clustered (community-based) farming units operated by individual farmers, their families, and/or groups of farmers, using minimum technology, inputs, services, and resources. For the WOAIII, this Subchapter focuses on small-scale aquaculture, practiced in two environments, i.e., (a) in the nearshore marine environment (near-shore marine aquaculture - NSMA) and (b) in the coastal environment (coastal marine aquaculture - CMA), which is typically practised in constructed ponds onshore or in intertidal zones. Both NSMA and CMA play a key role by providing livelihoods and employment, contributing to food and nutrition security, and facilitating economic development among coastal communities in many countries, particularly in Asia and Latin America. In the WOAIII, other scales of aquaculture, i.e., large and medium scale, are being dealt with in the appropriate Subchapter, while culture of aquatic plants in the marine environment is discussed under the Subchapters dealing with macroalgae and microalgae. Stocking and stock enhancement in marine waters are not discussed in this Subchapter, as it is considered a fisheries activity.

World aquaculture production, at all scales, in 2022 achieved a record of 130.9 million tonnes, comprising 94.4 million tonnes (live weight equivalent; worth USD 295.7 billion) of aquatic animals and 36.5 million tonnes (wet weight; worth USD 17 billion) of algae (seaweed and micro-algae), plus a further 2,700 tonnes (worth USD 138.5 million) of shells and pearls. Of this, global production of marine and coastal (or brackish water) aquaculture accounted for 71.1 million tonnes, which included 94.4 million tonnes of aquatic animals and 36.4 million tonnes of algae - seaweed and micro-algae – (FAO, 2024). Of the top 10 farmed aquatic species groups in the world, three are seaweed, two are molluscs, three are freshwater fishes and one is a crustacean; several of the freshwater fishes can also be farmed in brackish waters. The top ten marine and brackish water species groups are shown in Table 1.

Information and disaggregated data on marine and coastal aquaculture production by scale is scarce. On a global scale, most small-scale global production of seaweed, sea cucumbers and sea molluscs originate from NSMA, whilst crustacean production, primarily takes place in onshore coastal brackish water ponds and tanks. In this case, CMA is dominated by brackish water shrimp and a few species of fish, crayfish and crabs. It is important to mention that brackishwater coastal shrimp aquaculture in Latin America is not considered as small-scale.

Cage aquaculture, raising fish in enclosed cages, is also now established successfully in the nearshore and offshore marine areas. However, offshore marine cage aquaculture should not be considered as small-scale. According to the available information, cage culture in the sea contributes around 65 percent of the total world production of finfish farmed in marine and coastal aquaculture combined (FAO, 2024). However, the largest proportion (in biomass) involves large scale offshore farming of salmonids, sea bream, seabass, tuna, cobia, etc. Most nearshore cage farms belong to NSMA (Fig. 1).

The majority of NSMA consists of species that are found at the lower trophic levels (e.g., seaweeds and molluscs). There are a few exceptions like green mud crab and prawns. However, the bulk of production comes from either non-fed (e.g., seaweed), or low-trophic-feeding species (e.g., mullets). Brackishwater aquaculture is dominated globally by penaeid shrimp (Table 1).

Table 1. Top 10 marine and brackish water production in 2022 (FAOStat 2022)

Marine Species	**Production (MT)**	**Brackish Water and Freshwater Species**	**Production (MT)**
Japanese kelp (seaweed)	10,861,335	Whiteleg shrimp	6,047,868
Eucheuma seaweeds	7,803,037	*Gracilaria* seaweeds	1,383,821
Cupped oysters	6,236,182	Milkfish	921,703
~~Japanese carpet shell~~ Ruditapse philippinarum	4,406,100	Nile tilapia	88,277
Gracilaria seaweeds	6,185,047	Giant tiger prawn	760,463
Wakame (seaweed) Undaria pinatifida	2,694,578	Freshwater fishes	279,455

Atlantic salmon	2,867,856	Mullets	35,182
Nori (seaweed)	2,176,580	Marine fishes	291,819
Scallops	1,792,323	Indo-Pacific swamp crab	96,388

Figure 1. Nearshore finfish cage farming in Ben Bao – Vietnam (Photo credit - Hien Phung)

According to FAO (2024), aquaculture provided employment for approximately 22 million people globally, (95 percent in Asia), doubling the workforce from 1995 to 2016. However, there is no global accurately disaggregated data on employment in different environments and scales. Women play a significant role in small-scale fish and shrimp aquaculture, especially in the post-harvest segment of the value chain (in seaweed culture women are involved heavily in the pre-harvest segment of the value chain), and although there are more women involved in capture fisheries, the percentage of women is higher in aquaculture (Bartley, 2022). Again, there are no disaggregated data available on women in NSMA and CMA.

Seaweed aquaculture holds significant social importance balancing environmental health, economic growth and community well-being. As global demand for sustainable food and materials increases, seaweed cultivation offers a solution that aligns with environmental stewardship and community livelihoods (Cottier-Cook *et al.*, 2021).

Socio-economically, seaweed cultivation provides job opportunities, particularly in coastal regions in developing countries ~~were~~ where, traditional industries, such as fishing may be in decline. It supports local economies by creating new markets for seaweed-based products, including food, cosmetics, biofuels and pharmaceuticals. This diversified income can help alleviate poverty and improve community resilience to the impacts of climate change (Cottier-Cook *et al.*, 2022). Seaweed cultivation also promotes food security and provides employment in many countries for women and marginalised communities (Asri *et al.*, 2022, Msuya *et al.*, 2022). The cultivation of seaweed also encourages sustainable practices in local communities, fostering environmental awareness and stewardship (Nagabhatla *et al.*, 2023). While is it true that seaweed culture is not practiced globally, the potential for its expansion and inclusion in our efforts towards increasing food security, while improving ocean health should be given due consideration.

Aquatic animal foods are rich in protein and other nutrients, in particular long-chain omega-3 fatty acids, various micronutrients and vitamins difficult to find in many other foods (e.g., vitamin A, iodine, selenium, calcium, iron and zinc). Seaweeds too are rich in nutrients and considered healthy food. As such they are considered among the healthiest foods, and their consumption is linked to improved public health outcomes (FAO, 2024). During the past decades, significant growth of the aquaculture sector contributed to the increase in global per capita consumption of aquatic animal food from 9.1 kg in 1961 to 20.6 kg in 2021 (FAO, 2024), contributing to improved health and nutrition.

The growth rate of global aquaculture production (animals and plants) exceeds that of most other food production systems and still has immense potential for expansion. However, accurately quantifying the contribution of NSMA and CMA to community nutrition is challenging, considering the species cultured. However, production of seaweed, bivalves, crustaceans and finfish from small-scale mariculture plays a significant role in local nutrition since their products are often consumed in local markets in many countries. This is different from large-scale industrial aquaculture, in which the produce is mostly processed for exports (e.g. Japan, USA, EU) and/or large national markets (e.g., China, Norway).

As in any other animal and plant production sectors, aquatic production is prone to disease. (Ward et. al., 2019). Global loss of revenue due to diseases in aquaculture is estimated to be over 10 billion US$ annually (Kumar, et. al, 2024). Consequently, the use of ~~anitimicrobials~~antimicrobials in certain types of aquacultures has increased over the years. Although regulations governing prudent use of

antimicrobials are in place, globally, there is evidence for increasing antimicrobial resistance (AMR) around the world (Schar, et. al. 2020).

Fish and shrimp aquaculture consumes significant volumes of marine resources (especially fishmeal and fish oil derived from pelagic marine fishes). As the demand for aquatic food and products is rising, it is important to expand and increase production of non-fed, low-trophic species and better manage fed species production systems to safeguard ocean health. However, harvest of marine pelagic fishes has remained constant over the last several decades while improvements in feed and feeding have allowed tremendous growth in aquaculture.

This sub-chapter discusses issues of interest to maintaining ocean health linked to NSMA and CMA and the opportunities for addressing them.

Pressures and Impacts

World fisheries and aquaculture production of aquatic species is expected to grow to 205 million tonnes (live weight equivalent) by 2032. Much of the increase will come from aquaculture, which is expected to break the 100 million tonnes threshold for the first time in 2027, reaching 111 million tonnes in 2032 (FAO, 2024). Considering the production trends during the past two decades, it is likely that NSMAs and CMAs will continue to expand in the next decade.

Extractive species of NSMA (species that obtain their feed directly from the sea and do not need external feeding), include molluscs and seaweed. These farming systems typically cover a larger area than ~~are typically covering a more area compared with~~ production systems involving fed-species and, therefore, their main interaction with the ocean is not because of the individual impact of each small-scale farm, but because of the aggregated cumulative impacts of many small-scale farms operating in one location (Harvey et al 2024). The most relevant negative impacts of bivalve filter feeders are the deterioration of the seabed due to accumulation of their pseudo feces (Marin et al 2023). Although it has been demonstrated that organic matter can accumulate on the seabed beneath mollusc farming areas, such accumulation depends largely on local hydrodynamics, inputs of nutrients from anthropogenic coastal sources and water properties such as salinity and temperature, as these parameters have been shown to be determinants of the capacity of mollusc farms to capture organic matter (Islam, et. al. 2024). Intensive bivalve farming can also lead to overharvesting of phytoplankton and changes to currents and water flow, light etc. that could affect survival of other wild species (Harvey et al 2024). Processing of farmed bivalve shells entail several environmental issues to terrestrial ecosystems around landfills) and also to marine ecosystems due to the remotion of calcium

carbonate in the shells. Burning of shells in landfills or to process shells could also contribute to CO2 emissions (Waldbusser et al 2013, Gattuso et al 2018, 2021, Hyun et al, 2024).

Some negative effects associated with seaweed farming has also been reported (Theuerkauf, 2019); mostly they relate to modifications of currents, sediments and shading, but there are still many knowledge gaps (Fricke, et. al., 2024). In general, assessments on the impacts of molluscs and seaweed at global level are lacking, although some indicator assessments and standards for management are being proposed (Troe et al 2023).

Some species under the NSMA are based on the collection of wild seed (e.g., some mussels, oysters and milkfish). These can have some negative impacts on the ocean's health (Byron et al 2023). However, there is no accurate information on the maximum sustainable levels of extraction from the sea. Wild collection of post-larvae for shrimp farming under CMA is almost non-existent.

In contrast, farming of the above species can generate important ecosystem services to humans and to the ocean ecosystem because they can filter out excess nutrients reducing human induced ocean pollution (Barret et al 2022) and increasing ocean potential to capture carbon. Chinese seaweed aquaculture, practiced as NSMA, annually removes approximately 75,000 t nitrogen and 9,500 t phosphorus and estimated that with the current growth rate of seaweed aquaculture, by 2026 seaweed farming could remove 100% of the current phosphorus inputs to Chinese coastal waters (Xiao et al 2017). Thus, bivalve and seaweed farming are often considered under the category of "regenerative aquaculture (Mizuta et al, 2023; Wong et al 2024).

Small-scale shrimp aquaculture is developed in coastal marine areas (CMA) that were often once covered by mangroves; the impact on the coastal oceans should be related to the added effects of small coastal ponds. This practice is more prominent in Asia, while coastal shrimp farming in Latin America is a large-scale aquaculture activity ~~This practice is more prominent in Asia, while coastal shrimp farming in Latin America is considered large-scale.~~ It is likely that their main impact on the ocean comes from the destruction of mangroves, which reduce their coastal carbon storage and nutrients filtering capacity and provide habitat for viable capture fisheries. Larger mangrove transformations into shrimp ponds will drain more nutrients into the sea. However, it is also evident that, at the global level, mangrove destruction is legally prohibited, and regeneration of mangroves is promoted in many countries (Lecerf, et. al. 2023). Nevertheless, mangrove friendly small-scale shrimp farming is practiced in many countries (Figure 2).

Figure 2. Small-scale shrimp farming practiced in a mangrove area in Vietnam (Photo credit – Salin Krishna)

Many NSMAs release plastic waste from floating systems, ropes, containers etc. Although it is not evaluated at a global level, NSMA can be a relevant microplastic and larger debris source to the ocean in areas where they are highly concentrated (Harvey et al 2023). Small-scale farmers often lack adequate practices regarding use and disposal of materials (Tian, et. al. 2022).

There is a need for better assessments of NSMA impacts and benefits for the nearshore areas of the ocean. To improve NSMA contribution to ocean health it is necessary to improve the spatial planning and arrangement of farms, as well as better management of individual farms. This can be done through stronger extension services and market incentives, such as area management certification. However, it is important to bring the cost of certification down so that, small-scale farmers could become partners of certification systems. This is necessary to change individual farmers' performance since the implementation of better standards is often expensive and technically cumbersome.

Disease is one of the most important threats to sustainable aquaculture production, which also has significant relevance to NSMAs and CMAs. Diseases in the marine environment affect both cultured and wild stocks and often pass undetected, undiagnosed, unreported, and/or misdiagnosed, thereby hiding their true impacts. Thus, the direct and indirect costs associated with disease outbreaks in aquaculture tend to be underestimated (Subasinghe and Shinn, 2023). Although antimicrobial use in shrimp aquaculture has been significantly reduced, there are still allegations of irresponsible use in the sector. Nevertheless, in the CMA shrimp sector, the development of specific pathogen free (SPF) shrimp, along with controlled breeding in hatcheries, has not only reduced disease impacts and antimicrobial use in shrimp aquaculture (including small-scale producers), but it has also almost diminished the wild seed and broodstock collection (Alday-Sanz, et. al., 2018).

NSMA and CMA, cannot be sustainable without addressing the impacts of climate change (CABI International, 2023). The major elements of climate change threatening NSMA and CMA production and sustainability include rising temperatures, ocean acidification, diseases, harmful algal blooms, changes in rainfall/precipitation patterns, sea level rise, uncertainty about external input supplies, changes in sea surface salinity, and severe climatic events (CABI International, 2023). The potential impact is dependent on several factors such as the season, locations, and size of the specific segment in the sector. Further, the communities engaged in NSMA and CMA are relatively poor, and with limited resources, thus, their resilience to climate change is limited in many countries.

Although some forms of aquaculture claim low GHG emissions and negative environmental impacts, the sustainability of aquaculture is widely debated. In 2000, a comprehensive review on the net contribution of aquaculture to world fish supplies was published in *Nature* (Naylor, et. al., 2000) and portrayed aquaculture in a very negative light regarding adverse environmental impacts. Later in 2021, another *Nature* article reviewed the developments in global aquaculture from 1997 to 2017, incorporating all industry sub-sectors and highlighting the integration of aquaculture in the global food system (Naylor, et. al. 2021). The review highlighted the major gains occurred in aquaculture feed efficiency and fish nutrition, lowering the fish-in–fish-out ratio for all fed species, although the dependence on marine ingredients persists and reliance on terrestrial ingredients has increased. The review further recognised mollusc and seaweed culture for its ecosystem services; however, the review admitted that the quantification, valuation, and market development of these services remain rare. They concluded that the potential for molluscs and seaweed farming, which are most relevant to NSMA, to support global nutritional security is underexploited. Pressure on the aquaculture industry to embrace comprehensive sustainability measures during this 20-year period, however, have improved the governance, technology, siting, and management in many cases.

According to the International Marine Ingredient Organization (IFFO), to sustain the global aquatic animal production in 2020 (63 million tonnes), about 46 million tonnes of feed were used (IFFO, 2024). Based on projections by FAO, global aquaculture production is predicted to more than double and reach yields of 140 M tonnes by 2050 (FAO, 2024). This also means that feed production needs to at least double to over 100 million tonnes during this time (but see below). One of the fundamental questions underpinning that projection is how to obtain the feed ingredients to sustain that growth and just as importantly, how can the sustainability of that growth be ensured (IFFO, 2024).

Fishmeal is one of the most important ingredients in livestock and aquaculture feed. About 18 million tons of fish are processed into fish oil and fishmeal for aquafeed, primarily marine pelagic fish. Although El Niño Southern Oscillation and interdecadal variability have affected anchovy and sardine populations over time (Bertrand et al., 2020 , Fang and Zhang, 2025), the production of fed-fish for aquaculture (both marine and inland) has dramatically increased. Better farming practices and feed formulation have allowed that the same amount of fish taken from the ocean is able to produce much more fish for human consumption . ~~One of the most important feed ingredients for livestock and aquaculture feeds is the fishmeal. Marine and freshwater aquaculture uses about 18 million tonnes of fish that has been processed into fish oil and fishmeal in aquafeed; most of these fish are marine pelagic fishes. Although El Nino/La Nina effects have fluctuated anchoveta populations time to time, this amount has remained constant over many decades while fed-fish production from aquaculture (both marine and inland) has dramatically increased. Better farming practices and feed formulation have allowed the same amount of fish taken from the ocean to produce much more fish for human consumption.~~

Sustainability Pathways

Aquaculture and the environment

Although the assumption is that increasing food production will inevitably result in some degradation of nature, a convincing body of evidence is now available, that challenges this assumption. In fact, it is possible to produce nutritious food and actively contribute to the recovery of ecosystems at the same time (Nature Conservancy, 2023) through 'regenerative aquaculture' (i.e., aquaculture that also provides ecosystem services, such as filtering water, sequestering carbon and providing habitat for other organisms). A recent report by the *Nature Conservancy* notes that an expansion of restorative aquaculture and improved management of wild fisheries could sustainably increase how much food we get from the ocean by 36-74% by 2050, making aquaculture a key part of transitioning toward a food system that works with nature (Bossio, et. al. 2021).

Aquaculture is recognised as one of the most environmentally efficient ways of producing food. This is especially true for bivalves and seaweed. Recent research and assessments show that shellfish and seaweed farms, with the right practices, in the right places, can help restore ocean health (Kuncoro, et. al. 2024), while supporting economic development and food production in coastal communities worldwide (Theuerkauf, et. al 2019; Brett, et. al. 2022). A major step to increase NSMA contribution to food and nutrition is to increase science and innovation efforts to increase seaweed use as direct food for humans.

Fulfilling aquaculture's growth potential requires responsible technologies and practices. Sustainable aquaculture should be ecologically efficient, product-diversified, profitable and societally beneficial with acceptable levels of risk of adverse environmental impact. Integrated multitrophic aquaculture (IMTA), has the potential to achieve these objectives by coupling non-fed NSMA farming (e.g., seaweeds and suspension and deposit-feeders) to nearby farmed fed species (e.g., finfish fed sustainable commercial diets), thus promoting the use of the inorganic and organic excess nutrients from the fed aquaculture for the growth of the non-fed species. This approach, especially practiced involving the NSMA communities, can help improve the environment, the economy, and social acceptability. This is being implemented in Chile, by farming seaweeds in industrial salmon farming sites when the intensive aquaculture is in the fallowing period.

Any production sector has an optimal environmental carrying capacity, beyond which the sector's sustainability becomes debatable. Applying cluster management approaches under the FAO's ecosystem approach to aquaculture (EAA), that considers all the components of aquatic production within a specific geographic and social boundary, aims to integrate aquaculture with other sectors and ensure that it contributes to social and economic development. ~~The EAA has been~~ integrated ~~with the ecosystem approach to fisheries (EAF) where appropriate, and promoted by responsible stakeholders of aquaculture over the past two decades with beneficial outcomes in coastal and nearshore aquaculture in many partes of the world.~~ Furthermore, as previously mentioned in Chapter 25 of WOA II, the EAA should be integrated with the Ecosystem Approach to Fisheries (EAF) to address the potential cumulative impacts of fisheries and aquaculture on coastal marine ecosystems (see Kang and Zhang, 2021), which could be promoted by responsible stakeholders of aquaculture with beneficial outcomes in coastal and nearshore aquaculture in many parts of the world.

Value chain and farming systems

Improving sustainability of NSMA and CMA and reducing any negative impacts requires a value chain approach. Strengthening the linkages between the different actors in the value chain will allow for addressing the constraints facing the actors and upgrading the value chain. Value chain analysis can

highlight the role of governance in the value chain, that is, the structure of relationships and coordination mechanisms, linkages, and trust, which exist between actors, especially among the small-scale NSMA and CMA sectors. By focusing on these linkages, it is possible to identify the mechanisms that may need to be targeted to improve capabilities in the value chain, remedy distributional distortions, and increase value-added in the sector. There are examples of improved farming systems directly contributing to reduce negative environmental impacts of coastal aquaculture, especially in the small-scale shrimp aquaculture practices in Asia.

Climate

In comparison to livestock production, seafood production has lower carbon emissions. Additionally, some species can extract carbon from aquatic environments, contributing to an extended carbon cycle. A recent review on the environmental consequences of aquaculture production and the potential effects of different aquatic products on GHG emissions suggested approaches for mitigating global climate change. They suggested improving feed efficiency, selecting suitable farmed species, and implementing sustainable farming practices and management. Holistic evaluation and strategic intervention regarding GHG emissions are fundamental and essential for achieving a sustainable, low-carbon future for aquaculture (Zhimin Zhang. 2024).

Seaweeds contribute to climate change mitigation through carbon capture via multiple pathways with varying degrees of permanence. Through photosynthesis, seaweeds absorb dissolved inorganic carbon from seawater and convert it to organic carbon compounds stored as biomass, dissolved organic carbon (DOC), and particulate organic carbon (POC) (Kim, 2024). While biomass storage is temporary unless harvested and processed, portions of DOC and POC can achieve long-term sequestration when transported to the deep ocean or buried in sediments (van den Burg et al., 2024; Kim, 2024; Fujita et al., 2022).

Current scientific evidence raises significant concerns about seaweed carbon sequestration, particularly regarding the practice of sinking seaweed biomass to the deep ocean, which could be potentially misleading (Chopin et al., 2024). The carbon stored in seaweed biomass likely represents temporary rather than permanent sequestration, with studies indicating only 6-33% of theoretical carbon dioxide removal potential is achieved when accounting for air-sea CO_2 equilibration; deep-ocean dumping risks disrupting poorly understood marine ecosystems through smothering seafloor life, altering water chemistry, and promoting deoxygenation; and the complex transport pathways make verification and

monitoring extremely difficult. While seaweeds do participate in carbon cycling through dissolved organic carbon (DOC) and particulate organic carbon (POC) pathways, the scientific consensus emphasizes that seaweeds provide greater value when utilized for food security and other product value chains that deliver multiple ecosystem services rather than being promoted primarily as carbon sequestration agents through deep-sea disposal—an approach that many scientists consider ecologically risky and potentially distracting from more effective climate solutions.

The sequestration efficiency of seaweed also varies by species, cultivation method, and environmental conditions, with estimates suggesting global potential of 61-268 TgC annually, and on average up to 173 TgC per year, which at that time was about 11% of seaweed global net C-production (Krause-Jensen and Duarte, 2016). Verification of carbon dioxide removal requires accounting for ocean-atmosphere CO_2 exchange dynamics and tracing carbon flows through marine systems (Hurd et al., 2022; 2024). The absence of rigorous carbon accounting methods precludes conclusive assertion of seaweed's sequestration potential. While uncertainties remain regarding quantification and verification, particularly concerning air-sea CO_2 equilibrium timeframes, the scientific consensus acknowledges seaweeds' role in carbon sequestration as a legitimate area of research requiring further investigation rather than outright dismissal.

Climate-Smart Aquaculture (CSA) aims to improve food security while considering the need to adapt and ways to reduce the effects of climate change (FAO, 2017). CSA tackles the difficulties of achieving synergies among the associated goals of mitigating climate change, adaptation, and increased production and income while reducing possible negative consequences. CSA is a useful strategy for reducing the potential impacts of NSMA and CMA on the ocean's health.

Genetic improvement

Genetic improvement of farmed aquatic species has been shown to improve several characteristics favourable to aquaculture (e.g., growth rate, body morphology and colour, fecundity, survivability and disease resistance). There are a range of genetic technologies available to aquaculturists (Table 2), although, several of these technologies require resources, capacity and technology which are not always available to NSMA and CMA. Domestication and genetic improvement of farmed aquatic species would reduce the negative impacts of aquaculture on the world's oceans and brackish waters. Atlantic salmon, Japanese kelp, oysters and white leg shrimp are notable examples of how genetic improvement can increase production and profits in aquaculture and reduce environmental impacts. While farming of Atlantic salmon is not included into NSMA, farming of white leg shrimp, oysters and Japanese kelp can be both intensive aquaculture and NSMA and CMA (Chen & Xiong 2018). One of the best examples of genetic improvements in CMA which has significantly reduced the pressure on the ocean is Specific

Pathogen Resistant (SPR) and Specific Pathogen Free (SPF) in shrimp. The use of locally bred SPR and SPF ~~pot-larvae~~ post-larvae by small-scale shrimp farmers under CMA has been increasing significantly over the past decade. Domesticated marine species would require less food, be more disease resistant, and have poorer survival in the wild in the event they escape. Unlike freshwater aquaculture, there are still challenges with the controlled breeding of several important farmed marine species; as such genetic improvement in marine species has not been utilized to the extent it has in freshwater species, an area of research requiring further attention. Marine species are also farmed for the ornamental pet-fish industry. However, only about 2 percent of ornamental marine species come from aquaculture (Wabnitz *et al* 2003). As most genetic improvements have been used by large-scale well financed groups and usually not by small-scale aquaculturists, the challenge of the coming decade should be to make those relevant and proven genetic technologies and improvements available, assessable and affordable to small-scale aquaculture producers in NSMA and CMA as has been done in freshwater, e.g. tilapia (ADB 2005). There is commercial potential for using DNA technologies to screen fish for diseases and make disease free fish strains for NSMA, as has been done with shrimp farming in India (Thakur et al 2013).

Table 2. *Genetic technologies. Examples of genetically improved marine and brackish water species*

Short-term	**Technology**	**Marine examples**	**Improvement**
	Hybridization	Bester sturgeon (*Huso huso x* *Acipenser ruthenus*)	Improved growth rate; No need for diadromy
	Chromosome set manipulation	Triploid Pacific oyster	Flesh quality; growth rate
Long-term			
	Selective breeding	Atlantic salmon/White leg shrimp	Growth rate; disease resistance; environmental tolerance
	Gene transfer	Atlantic salmon	Growth rate; temperature tolerance

Non-native species

Non-native aquatic species introduced into new areas for fishing or aquaculture have been shown to increase production and profits. However, they also have been shown to pose threats, such as establishment of invasive species populations, to both the ecological and economic environments (Bartly and Halwart, 2006). Over 200 species are farmed in countries where they are non-native; of the top 10 farmed aquatic species, 9 of them are farmed in more countries where they are non-native than where they are native (FAO, 2019). Although most of these are freshwater (seven out of 10) it demonstrates the economic value of non-native species in aquaculture. However, there are risks and again, using freshwater data from FAO's Database on Introductions of Aquatic Species, more negative environmental impacts than positive economic impacts were reported for farming non-native species (Bartley & Funge-Smith, 2018), thus making risk assessment and application of international guidelines necessary (ICES 2005).

Feed

Based on the current growth of aquaculture there is an urgent need to increase production of aquafeeds. A crucial point is that they should not compete with the potential to feed humans. A several options have been proposed (Glencross, et. al. 2024): *Option 1: Improve management of existing resources to increase their productivity, Option 2: Irrespective of the resources we produce, ensure we do not waste anything, and Option 3: Further develop non-competing resource production*. However, the fishing of marine pelagics for rendering into feed provides livelihood to many fishers, especially in Latin America, which would not have resources to store and process their catch for human consumption (Wijkström, 2010)

Additionally, there has been an increase in the use of by-products from fish processing plants in aquaculture feed which now is about 25-30 percent, thus reducing dependence on marine pelagic fishes. None-the-less the aquaculture industry is looking for ways to reduce dependence on marine pelagics by including plant-based and insect alternatives. Soybean is the primary alternative to fish meal, but fish oil is harder to replace (Bartley, 2022). Use of algal oils have also been reported. Since formulated feeds are heavily used in the NSMA and CMA sectors, especially in coastal shrimp and nearshore fish culture, application of better feeding practices and better management practices (BMPs) will further reduce the pressure on exploiting animal resources for aquaculture feeds from the oceans.

Disease

The need to increase aquatic food production while facing natural resource constraints will drive the intensification of aquaculture, thus inevitably enhancing disease risks in the sector. During past decades,

there have been major outbreaks of disease in NSMA and CMA. The PMP/AB (progressive management pathway – aquatic biosecurity), introduced by FAO and supported by an array of national biosecurity tools, is expected to play a major role in the systemic reduction of diseases and pests throughout the global aquaculture industry. PMP/AB could significantly contribute to improving biosecurity in aquaculture, especially in the much-needed NSMA and CMA small-scale sectors, and lead to reduced environmental impacts, improved market access, increased smallholder income, and the promotion of the 'One Health' approach (FAO, 2023).

Governance

Aquaculture governance is the set of processes by which a jurisdiction manages its resources, how its stakeholders participate in making and implementing decisions affecting the sector, how government personnel are accountable to the aquaculture community and other stakeholders, and how the respect of the rule of law is applied and enforced. Good governance will ensure the sustainability of aquaculture growth and will help reduce the sector's impacts on the ocean's health. Governance in aquaculture covers all sectors, environments and scales including small-scale NSMA and CMA.

Aquaculture activities usually occur within national authorities and the sector has traditionally been considered jointly with capture fisheries in policies and international agreements. Article 9 – Aquaculture Development in the Code of Conduct on Responsible Fisheries (CCRF) provides governance advice to stakeholders with special reference to small-scale farming sector (FAO 1995). Further guidance ~~are~~is also provided in the recent FAO Guidelines for Sustainable Aquaculture (FAO, 2025). However, growing external pressures on the industry are prompting it to improve its governance and there is evidence of good practices in some parts of the world – which translate directly into high production outputs. Achieving good governance in aquaculture is as important an objective as aquaculture development (increases in outputs) *per se* as it will ensure the achievements of sustainable aquaculture development ecologically, economically and institutionally.

Most NSMAs and CMAs and their value chains are less organized and require assistance for improvement and further development in a more sustainable manner. In fact, it is hard for small-scale producers and value chain actors to comply with all legal and governance regulations of the sector. Further, inability to comply with the laws and regulations can make the small-scale aquaculture sector environmentally less sustainable, with the potential to create more negative impacts on the production environments, and eventually on the ocean's health.

Improving governance of the small-scale aquaculture within NSMA and CMA will increase overall sector sustainability and profitability. If not, socio-economic benefits of the sector will decline, requiring government interventions and support to manage the sector's sustainability. Inability to provide state patronage to NSMA and CMA in forms of conducive policy, enforceable regulatory frameworks and affordable finance, resulting in sub-optimal sector performance, will impact negatively on the ocean's health.

Conclusions

Small-scale aquaculture under NSMA and CMA play a significant role in food security, livelihoods, nutrition, and health. Some species and well managed systems have little or no negative impacts on the ocean health (e.g., seaweeds and molluscs). However, the debate on whether the socio-economic and environmental benefits of certain species and systems (coastal shrimp and nearshore fed-fish aquaculture) currently outweigh their potential negative impacts on the ocean's health, continues.

During the WOAII aquaculture Subchapter review, unlike in the WOAIII, addressed the full spectrum of aquaculture and its benefits and threats. The review also pointed out several key knowledge gaps. The review mentioned the public debate on the increasing dependence of developed countries on farmed seafood imports from developing countries and insecurity regarding product environmental, social and safety credentials, the scientific uncertainties and conflicting information on the issues relating to seafood consumption. During the past few years, application of third-party certification systems covering the environmental, social and food safety concerns related to seafood have increased and improved addressing seafoods originating from large scale aquaculture. However, third party certification requires further efforts in addressing the impacts and concerns of the products originating from small-scale NSMA and CMA.

This review noted the lack of specific laws governing small scale NSMA and CMA impact that have been developed and enforced, especially in Latin America and Africa. Further, programs supporting aquaculture smallholder performance and sustainability are scarce worldwide. State provided aquaculture extension services are usually insufficient and NSMA and CMA actors do not have the resources to access such service from the open market. Additionally due to uncertainty ~~uncertainly~~ and lack of disaggregated data on small, medium and large-scale aquaculture, it is difficult to understand the contributions and impacts of each sub-sector. Better data would allow more effective policies and practices that could be applied more effectively. These shortfalls may cause negative impacts affecting ocean's health, if not addressed timely.

It is timely for the states to provide greater attention to NSMA and CMA under their Blue Economy development programmes, which will collectively contribute to global food and nutrition security and improving livelihoods, whilst maintaining and improving the ocean's health. National laws and regulations need to be clear and promote growth in NSMA and CMA, whilst prioritizing access to resources for vulnerable populations, directly and indirectly involved in these sectors. New business innovation models allowing accelerated permitting of lower trophic level species such as seaweeds and mussels, etc., along with other species cultures in the same locations should be considered.

Considering the potential negative impacts of aggregation of small-scale operations, spatial planning and addressing carrying capacity limitations, including integrated multitrophic production systems, should be encouraged at national and regional levels. Climate-driven technologies and practices, such as climate-smart and restorative aquaculture and economic models should be promoted and implemented. It is also important to address the capacity development on governance and entrepreneurial skills related to NSMA and CMA at all levels.

Best management practices, including biosecurity measures, such as the PMP/AB need to be implemented. The use of genetically improved farmed types and non-native species can improve production efficiency and increase profits from aquaculture; but they can also adversely impact ocean and coastal areas. Risk analysis[33], the precautionary approach[34] and the application of international codes of practice[35] are recommended to optimize the use of these farmed types and avoid negative impacts on the world's oceans and the aquaculturists that use them. Increased support for value-added product development and access to markets is needed.

References

ADB. 2005. An Impact Evaluation of the Development of the Genetically Improved Farmed Tilapia. Asian Development Bank. http://www.adb.org/Publications

[33] https://onlinelibrary.wiley.com/doi/10.1111/jwas.12968

[34] https://www.fao.org/4/V8045E/V8045E00.htm#TOC

[35] https://ices-library.figshare.com/articles/report/Codes_of_practice_and_manual_of_procedures_for_consideration_of_introductions_and_transfers_of_marine_and_freshwater_organisms/18624731?file=33403796

Alday-Sanz, V., Brock. J., Flegel, T.W., McIntosh, R., Bondad-Reantaso, M., Salazar, M., Subasinghe, R. 2018. Facts, truths and myths about SPF shrimp in aquaculture. Reviews in Aquaculture 1-9, Wiley Publishing Asia Limited.

Asri, A., Brodie, J., Cottier-Cook, E. J., Le Masson, V., Matoju, I., Montalescot, V., Nagabhatla, N., Shaxson, L. & Suyo, J. 2022. Towards a More Inclusive and Sustainable Red Seaweed Industry. Policy Brief [Online]. Available: https://cris.unu.edu/towards-more-inclusive-and-sustainable-red-seaweed-industry.

Barrett LT, Theuerkauf SJ, Rose JM, et al. Sustainable growth of nonfed aquaculture can generate valuable ecosystem benefits. Ecosyst Serv. 2022; 53:101396. doi:10.1016/j.ecoser.2021.101396

Bartley, D.M. & Halwart, M. 2006. Responsible use and control of introduced species in fisheries and aquaculture [CD-ROM]. Rome, FAO.

Bartley, D.M. and S.J. Funge-Smith. 2018. Aquatic biodiversity and inland fisheries. Pages 286309 in Funge-Smith, S.J. (ed), Review of the state of world fishery resources: inland fisheries FAO Fisheries and Aquaculture Circular No. C942 Rev.3, Rome. 397 pp.

Bartley, D.M. 2022. *World Aquaculture 2020 – A brief overview*. FAO Fisheries and Aquaculture Circular No. 1233. Rome, FAO. https://doi.org/10.4060/cb7669en

Bertrand, A., Lengaigne, M., Takahashi, K., Avadí, A., Poulain, F. & Harrod, C. 2020. El Niño Southern Oscillation (ENSO) effects on fisheries and aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 660. Rome, FAO. https://doi.org/10.4060/ca8348en

Bossio D., Obersteiner M., Wironen M., Jung M., Wood S., Folberth C., Boucher T., Alleway H., Simons R., Bucien K., Dowell L., Cleary D., Jones R. 2021. Foodscapes: Toward Food System Transition, The Nature Conservancy, International Institute for Applied Systems Analysis, and SYSTEMIQ, ISBN: 978-0-578-31122-7

Byron, C. J., Koch, S. J., Callier, M. D., Kluger, L., Angel, D. L., Vanaverbeke, J., Filgueira, R. {2024}. Indicators for ecological carrying capacity of bivalve and seaweed aquaculture. Reviews in Aquaculture, 16(4), 2010-2022.

CABI International 2023. Climate Change on Diseases and Disorders of Finfish in Cage Culture. 3rd Edition. (eds. P.T.K. Woo and R.P. Subasinghe). pp 430-461.

Chen, X. and Xiong, J. (2018). Development of the Culture of the White-Legged Shrimp, Penaeus vannamei . In Aquaculture in China (eds J. Gui, Q. Tang, Z. Li, J. Liu and S.S. De Silva). https://doi-org.proxy1.cl.msu.edu/10.1002/9781119120759.ch4_2

Chopin, T., Costa-Pierce, B.A., Troell, M., Hurd, C.L., Costello, M.J., Backman, S., Buschmann, A.H., Cuhel, R., Duarte, C.M., Gröndahl, F., Heasman, K., Haroun, R.J., Johansen, J., Jueterbock, A., Lench, M., Lindell, S., Pavia, H., Ricart, A.M., Sundell, K.S., Yarish, C. (2024). Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass, One Earth, 7(30), 359-364. https://doi.org/10.1016/j.oneear.2024.01.013.

Cottier-Cook, E. J., Nagabhatla, N., Asri, A., Beveridge, M., Bianchi, P., Bolton, J., Bondad-Reantaso, M. G., Brodie, J., Buschmann, A., Cabarubias, J., Campbell, I., Chopin, T., Critchley, A., De Lombaerde, P., Doumeizel, V., Gachon, C. M. M., Hayashi, L., Hewitt, C. L., Huang, J., Hurtado, A. Q., Kambey, C., Kim, G. H., Le Masson, V., Lim, P.-E., Liu, T., Malin, G., Matoju, I., Montalescot, V., Msuya, F. E., Potin, P., Puspita, M., Qi, Z., Shaxson, L., Sousa Pinto, I., Stentiford, G. D., Suyo, J. & Yarish, C. 2021. Ensuring the sustainable future of the rapidly expanding global seaweed aquaculture industry – a vision. Policy Brief [Online].

Cottier-Cook, E. J., Cabarubias, J. P., Brakel, J., Brodie, J., Buschmann, A. H., Campbell, I., Critchley, A. T., Hewitt, C. L., Huang, J., Hurtado, A., Kambey, C. S. B., Lim, P. E., Liu, T., Mateo, J. P., Msuya, F. E., Qi, Z., Shaxson, L., Stentiford, G. D. & Bondad-Reantaso, M. G. 2022. A new Progressive Management Pathway for improving seaweed biosecurity. Nature Communications, 13.

Fang, X. and Zhang, Y . 2025. The impact of climate change and economic development on the catches of small pelagic fisheries. Marine Policy, 175, 106631.

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome, FAO. https://openknowledge.fao.org/items/89b84fe5-1598-40f9-9e95-a050fbb730c8

FAO. 2017. Climate smart agriculture source book. https://www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b4-fisheries/b4-overview/en/?type=111

FAO. 2019. The State of the World's Aquatic Genetic Resources for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture assessments. Rome.

FAO. 2023. The progressive management pathway for aquaculture biosecurity. Rome. https://www.fao.org/3/cc6858en/cc6858en.pdf

FAO. 2024. The State of World Fisheries and Aquaculture 2024. Blue Transformation in action. Rome. https://doi.org/10.4060/cd0683en

FAO. 2025. *Guidelines for Sustainable Aquaculture*. Rome.

https://doi.org/10.4060/cd3785en

Fricke, A., Capuzzo, E., Bermejo, R., Hofmann, L.C., Hernández, I., Pereira, R., Van den Burg, S.W. K., Pereira, T., Buschmann, A.H., Cottier-Cook, E.J., (2024). Ecosystem services provided by seaweed cultivation: State of the art, knowledge gaps, constraints and future needs for achieving maximum potential in Europe. Reviews in Fisheries Science and Aquaculture. https://doi.org/10.1080/23308249.2024.2399355

Fujita, R. M., Collins, J. R., Kleisner, K. M., Rader, D. N., Mejaes, A., Augyte, S., and Brittingham, P. A., 2022. Carbon sequestration by seaweed: background paper for the Bezos Earth Fund -EDF workshop on seaweed carbon sequestration. Environmental Defense Fund, New York, NY. www.edf.org/sites/default/files/202210/Carbon%20Sequestration%20by%20Seaweed.pdf.

Glencross, B., Ling, X., Gatlin, D., Kaushik, S., Øverland, M., Newton, R., & Valente, L. M. P. (2024). A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds. *Reviews in Fisheries Science & Aquaculture*, *32*(3), 396–434. https://doi.org/10.1080/23308249.2024.2315049

Gattuso J-P, Williamson P, Duarte CM and Magnan AK (2021) The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond. Front. Clim. 2:575716. doi: 10.3389/fclim.2020.575716.

Gattuso J-P, Magnan AK, Bopp L, Cheung WWL, Duarte CM, Hinkel J, Mcleod E, Micheli F, Oschlies A, Williamson P, Billé R, Chalastani VI, Gates RD, Irisson J-O, Middelburg JJ, Pörtner H-O and Rau GH (2018) Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Front. Mar. Sci. 5:337. doi: 10.3389/fmars.2018.00337.

Harvey, M., Barrett, L.T., Morris, R.L., Swearer, S.E., Dempster, T. (2024). Ocean Sprawl: The Global Footprint of Shellfish and Algae Aquaculture and its Implications for Production, Environmental Impact, and Biosecurity. Aquaculture, Volume 586, 740747, ISSN 0044-8486, https://doi.org/10.1016/j.aquaculture.2024.740747.

Hurd, C. L., Gattuso, J.-P., & Boyd, P. W. (2024). Air-sea carbon dioxide equilibrium: Will it be possible to use seaweeds for carbon removal offsets? Journal of Phycology, 60, 4–14. https://doi.org/10.1111/jpy.13405.

Hurd CL, Law CS, Bach LT, Britton D, Hovenden M, Paine ER, Raven JA, Tamsitt V, Boyd PW. (2022) Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. Journal of Phycology, 58(3):347-363. doi: 10.1111/jpy.13249.

Hyun, C. S., Lee, J. E., Yoo, J., Park, J.H. et al 2024. Toward transformation of bivalve shell wastes into high value-added and sustainable products in South Korea: A review, Journal of Industrial and Engineering Chemistry, 129:38-52

ICES. 2005. ICES Code of Practice on the Introductions and Transfers of Marine Organisms. 30 pp. https://www.ices.dk/community/Documents/Expert%20Groups/WGITMO/ICES%20Code%20of%20Practice.pdf

IFFO. 2024. https://www.iffo.com/marine-ingredients-maintain-strategic-role-we-need-additional-bulk-nutrients-aquaculture-growth

Islam, Mazharul, et al. "Inducing mussel beds, based on an aquaculture long-line system, as nature-based solutions: effects on seabed dynamics and benthic communities." *Nature-Based Solutions* 6 (2024): 100142.

Kang, H., and Zhang, C-I. 2021. A concept and framework of the extended ecosystem-based fisheries assessment approach incorporating other driving forces. Journal of Marine Science and Engineering, 9(5), 545; https://doi.org/10.3390/jmse9050545

Kim, K.Y. (2024) Harnessing seaweed farming for climate mitigation in South Korea: evaluating carbon dioxide removal potential and future research directions. Algae. 2024;39 (4): 329-347. doi:https://doi.org/10.4490/algae.2024.39.10.28.

Kumar, A.; Middha, S.K.; Menon, S.V.; Paital, B.; Gokarn, S.; Nelli, M.; Rajanikanth, R.B.; Chandra, H.M.; Mugunthan, S.P.; Kantwa, S.M.; Usha, T.; Hati, A.K.; Venkatesan, D.; Rajendran, A.; Behera, T.R.; Venkatesamurthy, S.; Sahoo, D.K. Current Challenges of Vaccination in Fish Health Management. Animals 2024, 14, 2692.

Krause-Jensen, D., Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience, 9(10), 737–742. https://doi.org/10.1038/ngeo2790.

Kuncoro Catur Nugroho, Nimmi Zulbainarni, Zenal Asikin, Slamet Budijanto, Marimin Marimin, Toward a Sustainable Surimi Industry: Comprehensive Review and Future Research Directions of Demersal Fish Stock Assessment Techniques, Sustainability, 10.3390/su16177759, **16**, 17, (7759), (2024).

Lecerf, M., Herr D., Elverum, C., Delrieu, E. and Picourt, L., (2023), Coastal and marine ecosystems as Nature-based Solutions in new or updated Nationally Determined Contributions, Ocean & Climate Platform, Conservation International, IUCN, Rare, The Nature Conservancy, Wetlands International and WWF.

Marín, S.L., Loreto, P., Rosa, N., Daniela, F., José, L. I., Angel, B., Iñigo, M. (2023). Ecological status of benthic communities associated to mussel farms in South of Chile: Can it be predicted using AMBI? Regional Studies in Marine Science, Volume 66, 103132, ISSN 2352-4855, https://doi.org/10.1016/j.rsma.2023.103132.

Mizuta DD, Froehlich HE, Wilson JR. The changing role and definitions of aquaculture for environmental purposes. *Rev Aquac*. 2023; 15(1): 130-141. doi:10.1111/raq.12706

Msuya, F. E., Bolton, J., Pascal, F., Narrain, K., Nyonje, B. & Cottier-Cook, E. J. 2022. Seaweed farming in Africa: current status and future potential. Journal of Applied Phycology.

Nagabhatla, N., Ranasinghe, P., Koza, S. & Cottier-Cook, E. J. 2023. Seaweed Production Systems (SPSs) in Asia-Pacific Region and the SDG Agenda. In: LEAL FILHO, W., NG, T. F., IYER-RANIGA, U., NG, A. & SHARIFI, A. (eds.) SDGs in the Asia and Pacific Region. Implementing the UN Sustainable Development Goals – Regional Perspectives. Cham: Springer.

Nature Conservancy. 2023. https://www.nature.org/en-us/what-we-do/our-insights/perspectives/restorative-aquaculture-for-nature-and-communities/#:~:text=What%20is%20Restorative%20Aquaculture%3F,generate%20net%2Dpositive%20environmental%20outcomes.

Naylor, R., Goldburg, R., Primavera, J. *et al.* Effect of aquaculture on world fish supplies. *Nature* **405**, 1017–1024 (2000). https://doi.org/10.1038/35016500

Naylor, R.L., Hardy, R.W., Buschmann, A.H. *et al.* A 20-year retrospective review of global aquaculture. *Nature* **591**, 551–563 (2021). https://doi.org/10.1038/s41586-021-03308-6

Schar, D., Klein, E.Y., & Laxminarayan, R. (2020). Global trends in antimicrobial use in aquaculture. Scientific Reports 10, 21878. https://doi.org/10.1038/s41598-020- 78849-3.

Subasinghe, R.P. and Shinn, A.P. (2023). Biosecurity: Current and Future Strategies. In CABI International 2023. Climate Change on Diseases and Disorders of Finfish in Cage Culture. 3rd Edition. (eds. P.T.K. Woo and R.P. Subasinghe). pp 430-461.

Thakur, P.C., A.P. Padiyar, A.K. Sahoo, G. Subbarao, and D. Ramra. 2013. PCR-based Pathogen Detection in Shrimp Aquaculture in India. Pp 140-148 in J. Ruane, J.D. Dargie, C. Mba, P. Boettcher, H.P.S. Makkar, D.M. Bartley and A. Sonnino (eds). Biotechnologies at Work for Smallholders: Case Studies from

Developing Countries in Crops, Livestock and Fish. FAO Occasional papers on Innovation in Family Farming. Food and Agriculture Organization of the United Nations, Rome.

Theuerkauf SJ, Morris JA Jr, Waters TJ, Wickliffe LC, Alleway HK, Jones RC (2019) A global spatial analysis reveals where marine aquaculture can benefit nature and people. PLoS ONE 14(10): e0222282. https://doi.org/10.1371/journal.pone.0222282

Tian, Y., Yang, Z., Yu, X. et al. 2022. Can we quantify the aquatic environmental plastic load from aquaculture? Water Research, 219, 118551, ISSN 0043-1354, https://doi.org/10.1016/j.watres.2022.118551.

van den Burg, S. W. K., Koch, S. J. I., Poelman, M., Veraart, J., Selnes, T., Foekema, E. M., & Lansbergen, R. (2024). Seaweed as climate mitigation solution: Categorizing and reflecting on four climate mitigation pathways. WIREs Climate Change, 15(2), e868. https://doi.org/10.1002/wcc.868.

Wabnitz et al., 2003 cited in FAO. 2019. The State of the World's Aquatic Genetic Resources for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture assessments. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/ae734ce1-3f25-46b2-9e49-0bd9e2dc3605/conten

Waldbusser GG, Powell EN, Mann R. 2013. Ecosystem effects of shell aggregations and cycling in coastal waters: an example of Chesapeake Bay oyster reefs. Ecology 94:895–903

Ward, G.M., Faisan, J.P, Cottier-Cook, E.J., Gachon, C., Hurtado, A.Q., Lim, P.E., Matoju, I., Msuyu, F., Brodie, J. (2019). A Review of Reported Seaweed Diseases and Pests in Aquaculture in Asia. Journal of the World Aquaculture Society. DOI: 10.1111/jwas.12649

Wijkström, U. N. 2010. Aquaculture feeds: Is feeding fish with fish a viable practice? In FAO. Report of the Global Conference on Aquaculture 2010 – Farming the waters for people and food. Phuket, Thailand, 22–25 September 2010. FAO Fisheries and Aquaculture Report. No. 988. Rome, FAO. 2012. 84 pp. https://www.fao.org/4/i2501e/i2501e00.pdf

Wong, A., Frommel, A.Y., Sumaila, U.R. *et al.* A traits-based approach to assess aquaculture's contributions to food, climate change, and biodiversity goals. *npj Ocean Sustain* **3**, 30 (2024). https://doi.org/10.1038/s44183-024-00065-7

Xiao, X., Agusti, S., Lin, F. *et al.* Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci Rep* **7**, 46613 (2017). https://doi.org/10.1038/srep46613

Zhimin Zhang, Haokun Liu, Junyan Jin, Xiaoming Zhu, Dong Han, Shouqi Xie, 2024 Towards a low-carbon footprint: Current status and prospects for aquaculture, Water Biology and Security, Volume 3, Issue 4,2024,100290, ISSN 2772-7351

Section 5A

Sub-chapter 1e: Seafood processing

Leads: Donavan Campbell and Tymon Zielinski

Coordinating Author: Ahmed Khan

Writing Team: Hamady Diop; Ibukun Adewumi; Akintola Shehu, Ibrahim Issifu, Amadou Tall, Katrina Hilundwa; Kenneth Johnson, Cristina Pita; Colette Wabnitz, Nicole Franz, Omar Penarubia, Louise Teh, Weiwei Wang, Bernice Mclean, Eshete Dejen, Ulrich F. Kouassi; Helguile Shep, Yajie Liu; Bernedette Fregene, Josephus Mammie; Motseki Hlatshwayo; Kristen Lowitt; Kelly Harrel; Mohamed Diop; Kate Barclay, and Shakuntala H. Thilsted.

1. Highlights

- Seafood processing, marketing, and trade are a crucial dimension of the global fishing sector, with an estimated value of about 195 billion USD in 2022 and providing more than three billion people with animal protein as a primary source (FAO, 2024). Seafood broadly accounts for aquatic foods (fish, invertebrates and seaweed), sometimes also referred to as blue foods, sourced from or cultured in oceans, lakes, rivers and seas.
- Due to high perishability of fish and fishery products, and their importance in nutrition security and global trade, effective and efficient processing techniques are imperative to extend shelf life, reduce post-harvest losses, improve revenues and enhance nutritional value (Ghaly and others, 2010; FAO, 2024). This chapter focuses predominantly on wild capture fisheries and the post-harvest stages, i.e., processing, marketing, trade and consumption. It builds on World Ocean Assessment II – WOA II (United Nations, 2021), in prioritizing seafood and aquatic food systems within the UN Decade of Science as well as the UN Sustainable Development Goals- SDGs (United Nations, 2015).
- By minimizing loss and waste through best management practices and ensuring the availability of high-quality seafood, the post-harvest sector directly contributes to SDG 2 (zero hunger) SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), and SDG 12 (responsible consumption and production). It allows the processing industry an opportunity to remain lucrative in global seafood markets as well as support SDG 14 (life below water).
- However, increased mechanization and globalization have also led to challenges such as loss of employment, access to local fish products, food insecurity, and the corporate takeover of smaller local businesses. In effect, post-harvest utilization and the value chain approach have

supported management measures aligned with the SDGs and other multilateral commitments such as the African Development Bank's Feed Africa Strategy (AfDB, 2016), FAO Blue Growth initiatives, and UNIDOs Blue Industry and value chain approach.

- The chapter assesses the social drivers and impacts along the fish supply chain, suggests pathways for sustainable processing, and defines governance mechanisms that promote policy harmonization and supply chain coordination. The chapter concludes with key takeaways and future recommendations for the sustainability of the seafood processing sector. The chapter is aligned with many international governing instruments including amongst others the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines, FAO, 2015).

2. Introduction and background

The fish production chain

Seafood processing is part of the fish production chain, which spans from oceans to plates. The fish production chain consists of three main interconnected stages: pre-harvest (aquatic ecosystems), harvest (capture or culture activities), and post-harvest stages (processing and marketing) as defined by Kooiman and others, 2005. The latter stage focuses on processing, marketing, trade, including retail and wholesale, transportation, distribution, and consumption. The chapter emphasizes the importance of post-harvest and processing techniques, especially in small-scale fishing communities where community-based solutions are increasingly important to ensure food and nutrition security (Lowitt, 2013; FAO, 2024; Perez-Escamilla, 2024). Implementing effective processing techniques such as chilling, freezing, canning, smoking, drying and other value-added methods, fish value chains can be transformed to support food and nutrition security, job creation, and export earnings (FAO, 2024). Appropriate infrastructure, including landing sites, cold rooms or access to ice, improved or modern processing facilities, fish marketing outlets, and efficient distribution channels can minimize post-harvest losses (FAO, 2020; Bavinck and others 2005; Siddiqui and others 2024).

Post-harvest losses are often caused by spoilage due to improper handling or inadequate infrastructure, reduce the overall yield and result in economic losses (Thorpe and others 2005). In the case of Sub-Saharan Africa (SSA), where essential infrastructure is limited; the majority of post-harvest losses occur at the production level (39%), next to handling (36%), transportation and distribution (13%), processing (7%) and consumption at 5% (Abelti and others, 2024). This amounts to one-third of total production and financial losses of about 2 to 5 billion USD (Abelti and others 2024). Modern technology and appropriate infrastructure not only enhances food safety and security but also helps maximize economic benefits, contributing to the achievement of the SDGs.

Given this, attention to the composition of the labor force and corporate ownership models is important. Moreover, ensuring equity and social inclusion in the seafood industry determines whether local fishing communities can fully reap the benefits of their resources and these advancements (FAO and others, 2023).

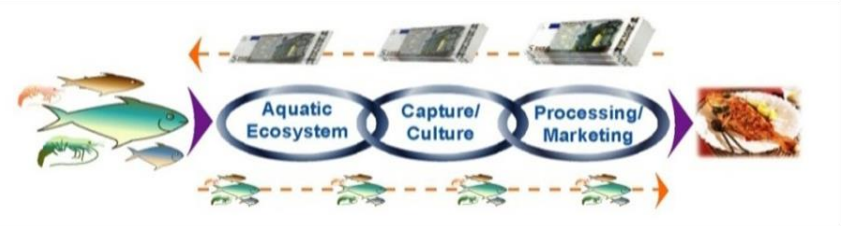


Fig 1: The fish production chain explained (source: Bavinck and others, 2005)

Although a fish production chain approach is applied focusing on supply and raw material flows and an ecosystem approach (Thorpe and others, 2005), the value chain concept is complementary as a development paradigm to increase efficiency and reduce on post-harvest loss (Gudmundsson and others, 2006). It also focuses on improving quality and price and provides better opportunities for employment and nutritional security (Khan and others, 2021).

Processing and value-addition

Processing and value-addition is the most important stage in the fish production chain. At this stage, various stakeholders transform harvested or cultured raw seafood into high-value products with a longer and more stable shelf-life, catering to diverse consumer preferences and boosting economic value (Se-Kwon, 2014; Pinfold, 2007). Processing methods and product differentiation strategies vary across communities, regions and continents. These variations are influenced by factors such as local preferences, cultural traditions, availability of resources, technology, income levels, infrastructure, as well as labor and market dynamics. Socially, processing and the 'product differentiation' stage offers lots of benefits, such as extended operational periods for processing plants, a reduction in repetitive strain injuries for workers, and allow for a greater diversity of fishery products, including repurposing of by-catch, benefiting both fishers and consumers. However, the growing reliance on migrant and forced labor on fishing vessels and processing plants, coupled with an increase in corporate mergers, raises human rights concerns as well as the fact that many of the potential benefits might not be fully realized by local fishing communities[36].

[36] https://www.humanrights.dk/promoting-human-rights-fisheries-aquaculture

Fish as superfoods

Seafood is a major source of animal-based protein, nourishing about 3 billion across the globe. It contributes directly to ending hunger (SDG 2), responsible consumption and Production (SDG 12), and enhances human well-being (SDG 5). The significance of processing and extending the shelf-life of fish is very important, given that fishery products are highly perishable and susceptible to disease and infection. As seafood is processed into various product types, its high demand and consumer buying power, makes it the most traded food commodity globally (FAO, 2024; Bellmann and others, 2016). Fish is considered a superfood, essential for overall well-being and rich in essential and highly bioavailable nutrients, including omega-3 fatty acids, vitamins (A, D and B12), and minerals, making them a critical component of a healthy diet (UN Nutrition, 2021; Issifu and others, 2022). Access to adequate infrastructure and proper processing techniques, such as freezing and canning, not only extend the shelf-life of fish but also help preserve their nutritional value, ensuring that these health benefits remain accessible to a broader population even during pandemics (Khan and others, 2021).

Circular economy and seafood processing

Applying circular economy principles to seafood processing brings additional benefits by maximizing resource efficiency and including multi-species management plans, energy use, and decarbonization (Cooney and others, 2023). Modern and improved traditional processing techniques increasingly seek to integrate economic efficiency, reduced fuel use, and environmental conservation, demonstrating the multifaceted benefits of these practices (Harrison and others., 2020a; Siddiqui and others, 2024). Recently, much of the food waste often discarded has now developed into affordable and nutritious products given their nutritional value (Penarubia and others, 2023); and the added nutrients such as iron, calcium and other micro-nutrients that can address deficiencies in human health (UN Nutrition, 2022). While advanced processing may enhance economic value through reduced losses as well as product differentiation, it may also support sustainability goals by reducing fishing pressure with higher revenues and focusing on socio-economic benefits (Fig 2).

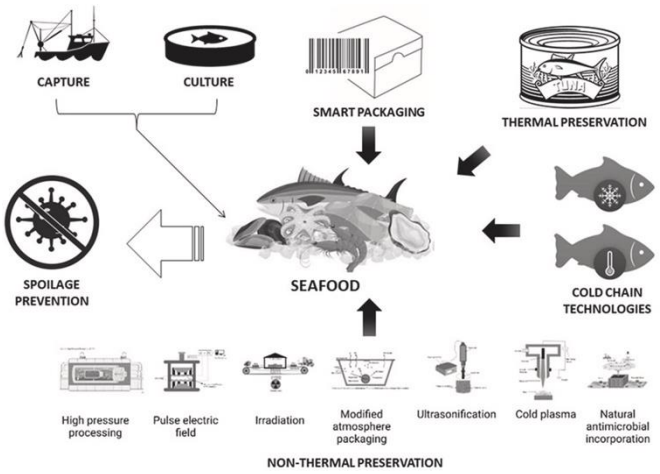


Fig 2: Value chain processing infrastructure and tools (source: Siddiqui and others, 2024)

Fish processing is often mandated under state laws and often through fisheries management policies, Bureaus of Standards, or competent agencies tasked with labeling, packaging, branding, and exports to ensure alignment and global standards (Kumar and others, 2020; UNIDO, 2024). To gain a competitive advantage across the value chain, seafood processors and stakeholders adopt strategies to differentiate and label their products according to sustainability criteria. Eco-labels such as the Marine Stewardship Council[37], ECOMARK, and traceability tools including ThisFish[38] and Vericatch[39] play a key role in appealing to consumer awareness. These tools and labels often help uphold chain of custody rules, enhance product competitiveness, extend shelf life, promote food security, and support conservation. However, this has proven complex and at times controversial compromising the integrity and intended principles (Blasiak and others, 2021; Nakamura, 2024).

Processing methods and product differentiation

Processing and product differentiation are important for two reasons: a) to increase the profit margin – by catering primarily to various markets in middle- and high-income countries; and b) to extend the shelf life, especially in low-income countries lacking improved cold chain infrastructure and purchasing power, but with large demand for nutritious and affordable seafood. Hence, three processing methods are known globally, including primary processing (in fresh or cured form without change in texture or taste), secondary processing (with some changes to taste and form), and tertiary processing (with changes in form and taste and increasing shelf life).

[37] https://www.msc.org/
[38] https://this.fish/
[39] https://vericatch.com/

The seafood processing industry employs diverse techniques to extend shelf-life and cater to local and regional preferences. For instance: freezing preserves nutritional quality and is widely used in regions with advanced cold chains, like Europe and North America; while canning ensures long-term preservation through shelf life, with canned fish being common in Asia and South America. Traditional smoking, prevalent in Northern Europe, Sub-Saharan Africa and parts of North America, imparts flavor and enhances preservation (FAO, 2022) but is associated with deforestation concerns. Smoking also risks contaminating fish with carcinogenic polycyclic aromatic hydrocarbons and other toxins (Bwala, 2023). Whilst Scandinavia excels in smoked salmon and pickled herring, the Mediterranean offers traditional salted and dried fish (e.g. bacalao) in Italy and Portugal, which is a staple ingredient in many traditional dishes such as brandade de morue, a creamy fish spread made with salt cod, as well as cured and canned fish. Traditional drying and salting methods are common in South-East Asia and Sub-Saharan Africa due to their accessibility and cultural taste, as well as their nutritional value (Johnson and others, 2023). This practice is also linked to the lack of cold room infrastructure and ice to preserve fresh fish (Bavinck and others, 2023).

Regional diversity and length of value chains

In regions where tertiary processing is common, seafood can be made into snacks and as condiments. For instance, Southeast Asia is known for producing shrimp paste and dried fish while Japan is renowned for sashimi-grade fish. In the Caribbean region, where fresh fish is invaluable to the tourism and hospitality industry, for example, in hotels; the fish value chain can be short for some commercial species such as live lobsters and longer value chains for other species such as groundfish depending on market access and price premiums (Fig 3). In Western Africa, small-scale tuna canning and large-scale transshipment contribute to national economies in coastal ports like Tema and Abidjan (Box 1), as these processing enterprises provide processed fish for exports especially regional landlocked countries as well as local nutritional needs (Ayilu and Nyiawung, 2022).

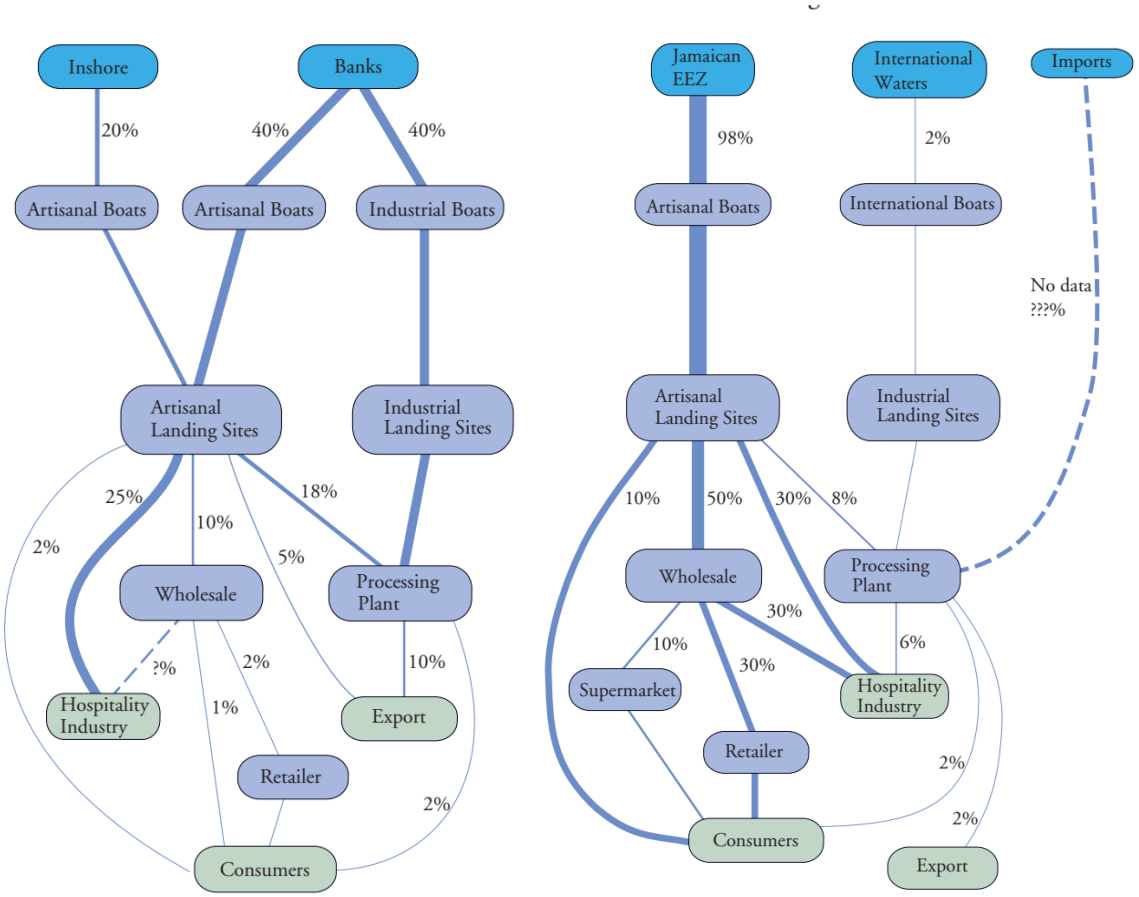


Fig 3: the dynamics of fish value chain in the Caribbean region: offshore large Pelagic fish (left) and inshore lobsters (Right). (Source: CERAMP, 2000).

Box 1: Tuna processing and transshipment in West Africa

Abidjan is West Africa's leading commercial fishing port for tuna transshipment and small-scale canning industry. The fishing port, part of the grand Port Autonome d'Abidjan economic zone, is a state-owned enterprise with capital of about 170 million USD in 2022. The fishing port handles close to a million tonnes of seafood per year, comprising of 35% of tuna. Tuna fishing is dominated by three main species: yellowfin (*Thunnus albacares)*, skipjack (*Katsuwonus pelamis)* and bigeye (*Thunnus obesus)*. These tuna stocks are mainly caught by vessels flying Spanish and French flags and national Ivorian fleet and transshipped to local canneries. In 2023, around seventy vessels transshipped to three local canneries operating in Côte d'Ivoire, producing about 60,000 tonnes of canned seafood per year, creating more than 3,000 jobs, the majority of which are dominated by women. About 15 local companies also operate at the port to facilitate a cold room seafood network with up to 70,000 tonnes of storage capacity to address seasonality and price fluctuations. The tuna industry also supports the local consumption of the popular Ivorian dish called 'Garba', made up of cured and deep-fried tuna fillet.

3. Pressures and Impacts

Demand-driven fish chains

Various pressures and drivers influence the production and productivity of aquatic foods and fish value chains. It has been argued that in regions where there is high demand for fish, in combination of sequential exploitation and mismanagement; raw material supply can be a challenge for processing; as plants closed and processing jobs are lost (Berkes and others, 2006). The earlier collapse of some stocks of Orange Roughy (*Hoplostethus atlanticus)* in Australia and New Zealand, cod stocks on the Grand Banks (*Gadus morhua*), and some groundfish stocks in New England all speak to human-induced drivers of change with processing jobs at risk (Ludwig and others, 1993; Khan and Neis, 2010). Effective governance strategies are essential to address these multifaceted challenges ensuring sustainable fisheries while safeguarding ecosystems in the face of environmental changes ((Jentoft and Chuenpagdee, 2009; Armitage and others, 2018). Collaborative approaches that involve local communities, policymakers, and scientists can foster resilience and promote long-term sustainability in fisheries resources (Neis and others, 2014).

Technological innovation

Technological innovation has had a profound impact on fishing efficiency, also influencing the supply of raw materials, fish processing measures, and product development. Recent research underscores the necessity for the implementation of policies that encourage responsible innovation, thereby ensuring that technological advancements contribute to the sustainability of fisheries and the development of premium seafood products (Siddiqui and others, 2024). While economic incentives such as subsidies can facilitate technological advancement and enhance fishing capacity (with offshore processing infrastructure and higher revenues), they can also result in overcapacity and unsustainable practices, if not properly regulated (Sumaila and others, 2021; Cisneros-Montemayor and others, 2020). For example, subsidies that promote fuel consumption may provide an incentive for increasing fishing efforts, which can undermine the health of fish stocks, especially in deep-sea environments (Foley and others, 2011; Sumaila and others, 2008). Recent estimates of global fishery subsidies suggest that subsidies provided in the preceding decades may have halted, but the bulk of harmful 'capacity-enhancing' subsidies, particularly those for fossil fuels have increased as a proportion of total subsidies (Sumaila and others, 2019). Although discussed in WOA II, the matter remains pertinent to WOA III given the evolving policy climate such as the World Trade Organization (WTO) Agreement on subsidies in 2022 and recent additional provisions during the WTO's 13th Ministerial Conference in March 2024 in Abu Dhabi. Additional provisions on overcapacity and overfishing subsidies are still being proposed and debated without reaching any consensus (Irschlinger, 2025). Moreover, subsidy research is till

topical and relevant indicating the need for better policy and practice for resource sustainability and value chain benefits (Soeparna & Taofiqurohman, 2024; Revollo-Fernández and others 2024).

Given the observed increase in fishers' incomes, a notable surge in demand for fish and seafood is expected, exerting considerable pressure on supply chains and ecosystems already operating under considerable strain (Bennett and others, 2022). As populations expand and urbanization accelerates, the demand for accessible and affordable seafood options intensifies, resulting in a complex interplay between supply constraints and consumer expectations (FAO and others, 2023). This growing demand presents a dilemma for fisheries management, as stakeholders must reconcile the imperative for economic returns with the need for sustainable fishing practices (Box 2). According to FAO (2024), maintaining the current consumption levels of aquatic animal foods until 2050 will require a huge reduction in catch and improved post-harvest utilization.

Sustainable fishing practices, bolstered by cutting-edge technologies, such as mobile applications and digital platforms are furnishing fishers with real-time market data, thereby enhancing supply chain efficiency and traceability benefits (Bennett et al., 2022). It is of paramount importance for policymakers to establish a regulatory framework that fosters sustainable post-harvest practices and technological advancements in a manner that safeguards the environment and benefits fishing communities through chain of custody, certification, and price premiums.

Box 2: Norway's Response to Pressures with an Integrated Fisheries Management Systems

Norway has implemented an integrated fisheries management system that combines scientific research, regulatory measures, and stakeholder engagement to ensure sustainable fisheries. This system includes strict quotas, real-time monitoring of fishing activities, and comprehensive data collection. By basing management decisions on robust scientific research and involving stakeholders such as fishers, scientists, and regulators, Norway's model enhances the effectiveness and sustainability of fisheries governance. Emphasis on science-based management, real-time monitoring, and collaborative governance is crucial to maintaining sustainable fisheries (Paolo and others, 2022).

Impact of non-human induced changes

Seafood products and processing methods are highly influenced by both natural and human-induced drivers of change at multiple scales. In recent years, the dynamics of commercial fish value chains have increasingly revealed a fundamental tension between demand-driven and supply-driven factors (Gudmundsson and others, 2006). The prevalence of supply-driven fish value chains frequently gives rise to considerable obstacles, including over-capacity, which can result in unsustainable fishing practices coupled with ecological shifts (Khan, 2012). Poor and inconsistent

harvest rules across different regions complicate resource management outcomes and often lead to overfishing, further destabilizing ecosystems (Berkes and others, 2009; Hilborn and others, 2020).

The sustainability of raw material supply, in the harvest stage of the fish chain, is highly important as it influences the volume and value of the catch, therefore affecting the corresponding processing methods, product types, and market viability. Other driving factors such as natural variability and El Nino and Southern Oscillation (ENSO) events can affect fisheries ecosystem, raw material supply, and seafood processing opportunities (Kumar and others, 2014). Recent studies indicate that climate change alters marine ecosystems, affecting the distribution and abundance of key commercial species, which, in turn, influences raw material supply chains (Cheung and others., 2021; Khan and others, 2020). For instance, rising sea temperatures and ocean acidification can lead to shifts in fish populations, impacting fish availability and the livelihoods of communities reliant on these resources (IPCC, 2022). In maritime regions where fisheries livelihoods are highly at stake, such as in Eastern Canada, both placed-based (at the municipal and district level governance) and sector-based interventions (at provincial and federal management levels) are jointly needed to address sedentary species such as lobster fisheries (Khan and others, 2018). In many parts of the developing world, climate finance has been sought though multilateral banks to support nature-based solutions and other institutional capacity to be resilient[40].

To address these challenges, a multifaceted governance approach is required, encompassing improvements in resource management, investment in environmentally sustainable practices, and the promotion of responsible production and consumption. Moreover, to develop effective strategies that support economic viability, it is essential to comprehend the interplay between drivers of production capacity, labor and corporate ownership practices, environmental impacts, and integrated responses to stressors (Khan and Cundil, 2018).

4. Socio-economic considerations

Ethical issues during seafood processing

Social and ethical considerations in seafood processing are important as they support human rights values (for details see chapter S5B.C5 on Equity, justice, and human rights in the ocean). Ensuring safe working conditions, fair wages, and prohibiting forced and child labor are essential for protecting workers' rights within the fish processing sector. Yet migrant and forced labor exist in fisheries around the world, especially seafood processing (ILO, 2016). The International Labor Organization (ILO) Work on Fishing Convention (ILO C188) establishes international standards for

[40] https://www.thegef.org/what-we-do/topics/country-engagement-strategy

labor conditions, highlighting the importance of its adoption and enforcement to promote ethical labor practices (Gonçalves, 2024). However, the list of countries that have not ratified C188 remains extensive,[41] and much work remains to be done to secure the basic human rights of fishers and workers across the global seafood supply chain.

This convention is crucial to ensure that all workers in the fishing sector enjoy decent working conditions (SDG 8), thereby fostering a more responsible seafood sector.

Safe and well-paying employment opportunities are crucial equity to seafood processing licensing agreements, especially for international companies relocating to areas with weaker labor rights and regulations (Knott and Marschke, 2020). Ethical and social best practices should ensure that the economic benefits of the seafood sector contribute positively to coastal communities, including fair compensation for local fishers and support for community development initiatives (Marschke and others, 2018). Integrating these social considerations benefit workers and living aquatic resources and enhances the overall integrity of social-ecological systems (Box 3).

Box 3: Alaska's Responsible Fisheries Management Certification

Alaska's Responsible Fisheries Management (RFM) certification is a voluntary third-party program that verifies the sustainability of fisheries based on internationally recognized standards. RFM certification emphasizes local management and stakeholder involvement while aligning with global sustainability benchmarks. A key feature of RFM certification is its transparency with publicly available assessment reports and stakeholder consultations. This model illustrates the significance of local involvement, alignment with global standards, and transparency in certification processes for effective fisheries governance (Packer et al., 2019; Lue et al., 2022).

As consumer demand for ethically sourced seafood increases, the seafood processing sector must prioritize labor, animal rights, transparency and traceability in its supply chains to meet these expectations (Österblom and others, 2015).

[41] List of countries that have not ratified ILO C188: https://normlex.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:11310:0::NO:11310:P11310_INSTRUMENT_ID:312333:NO

Gender equity and social inclusion

Promoting gender equity and social inclusion in seafood processing is essential for ensuring that everyone benefits from the fisheries sector (Neis and others, 2014). As discussed fully in Chapter S5B.C5 on Equity, justice, and human rights, increasing attention has been paid to the crucial role that women play in the fishing industry, particularly in processing, marketing, distribution, and retail (Harper and others, 2013; Kleiber and others, 2017; Pedroza-Gutiérrez and Hapke, 2022). The Illuminating Hidden Harvests study estimated 45 million women worldwide participate in small-scale fisheries value chains or engage in subsistence activities, which translates into 40% of the total people active in the subsector. Women represent 15% of total employment in the pre-harvest segment of the small-scale fisheries value chain (e.g. gear fabrication and repair, bait and ice provisioning, boat-building), 18.7 percent in the harvesting segment (including vessel-based and non-vessel-based activities), 50% in the post-harvest segment (e.g. processing, transporting, trading, selling) and 45% of the total actors engaged in small-scale fisheries subsistence activities (FAO and others, 2023).

Yet, they often face barriers such as gender bias, traditional caregiving responsibilities, and limited access to resources and decision-making opportunities. In many coastal communities, women are deeply involved in various fisheries-related activities, including seaweed farming, fish selling, and invertebrate marketing. Their specialized knowledge of marine resources, especially in shallow waters, is vital for local economies and food security (FAO, 2022; Harper and others, 2020). Unfortunately, the contributions of women are frequently undervalued due to a focus on commercial fisheries, which are typically male dominated (Barclay and others, 2021). In addition, to attain SDG 5, it is further crucial to ensure women are coached into leadership and managerial positions in the fisheries sector given their impact to society (Keliber and others, 2017).

Broader understandings of fishing communities' social and cultural dynamics are needed to understand social and ecological equity issues in fisheries (Knott and others, 2022). Also, the issue faced by lack of soft skills which removes most women from benefiting from financial support shapes who can access and benefit equally from the fishing industry, including processing. Additionally, class, race, disability and citizenship are significant factors in shaping seafood labor (Griffith, 2012; Knott, 2016; Knott, 2020; Knott and Marschke, 2020; Sangaramoorthy, 2019).

While scholars have argued that gender inequality can be achieved through the implementation of gender-sensitive policies, and targeted programs; this needs to be broadened to include other social realities including partnerships and governing frameworks (Mangubhai and others, 2022). By acknowledging that social inequalities exist between and among diverse groups of people that include but are not limited to gender and drawing on intersectional frameworks; more robust recognition of contributions to the fishery could be achieved (Crenshaw, 1991). Such an approach not only meets the most basic criteria of sustainability but also empowers and strengthens the

resilience and productivity of the entire fisheries sector and value chain actors (Barclay and others, 2021).

Stakeholder interactions - winners and losers

Stakeholders are broadly defined along the fish production chain referring to those that govern (e.g. fisheries managers, maritime observers, custom officers, NGOs), and those that are being governed including fishers, processors, traders, and cooperatives (Bavinck and others 2005; Khan and Chuenpagdee, 2012). Fisheries management and governance practices are influenced by these social relations that involves power and authority, especially legislative and regulatory norms. When properly diagnosed and understood, power analyses could support cooperation among stakeholders, improve compliance with rules, foster equitable distribution of benefits, and mitigate conflicts (Khan and Neis, 2010). In this context, power and political economy are essential social issues in governance and governing interactions. Often, these stakeholder interactions and social relations are hidden, and are invisible. Or often, they are intangible or translucent, until conflicts or dissension arise or agreements are signed and announced.

Groups and their productive bargaining power including labor unions, fisher cooperatives, processor associations, and trade hubs are all mechanisms to leverage resources and advocate for fair gains and access to resources. Given the importance of stakeholders across the fish chain and the sustainability of the resource, procedural and equitable distribution of benefits are important. This will take shape differently whether within small-scale fisheries (SSF), industrial commercial fisheries, or distant-water fisheries (DWF). Small-scale fisheries, which provide essential nutrition and income to millions globally, often encounter obstacles such as restricted access to markets, insufficient post-harvest infrastructure, and food waste. Conversely, distant-water fisheries play a significant role in the global seafood supply, yet they can contribute to overfishing and ecological degradation in the absence of offshore monitoring and control mechanisms, raising concerns about resource sustainability and equitable distribution to local communities (Daw and others, 2021; Torreblanca and others, 2022).

Moreover, collaboration among stakeholders, including government agencies, NGOs, and the private sector, is crucial for developing comprehensive policies that address the multifaceted issues (Jentoft & Chuenpagdee, 2007). Such inclusive policies can foster a sustainable and equitable fisheries sector, ensuring that the needs of stakeholders are met adequately.

5. Sector-relevant governance

Governing fish processing activities

The seafood processing sector, which is integral to global food security and economic growth, necessitates robust governance to ensure product safety, quality, and adherence to international standards. Policy harmonization, which aligns regulations across jurisdictions, is a critical factor in this process. It facilitates product design and standards and also ensures quality control and safety. Adherence to the international best practices and policies set by the WTO, FAO, and ILO are crucial for global market access, strengthening competitiveness, upholding ethical standards, and fostering sustainable growth. This alignment increases processing efficiency, reduces trade barriers, enhances market access, and increases consumer confidence.

Harmonized policies eliminate regulatory discrepancies that function as non-tariff barriers and facilitate international trade (Jouffray and others, 2019). Alignment of standards across countries ensures that seafood products meet uniform safety and quality requirements, thereby improving market access. Electronic sanitary certificates have further streamlined trade processes, enhancing transparency and risk management (Lee, 2024; Stetkiewicz and others, 2022). For instance, harmonizing Sanitary and Phytosanitary (SPS) measures established by the WTO are crucial for protecting health and maintaining the integrity of the seafood supply chain (Sumaila and others, 2020; Tickler and others, 2018).

As the most traded agri-commodities (Smith and others., 2010); seafood processing are highly linked with regional markets and export revenues (see Chapter S5A. C1f on Trade). For instance, experience gathered in the Southern Africa Development Community (SADC) showed that integrating fishery commodities into the One Stop Border Post (OSBP) initiative is the most practical trade facilitation approach through standardization and policy harmonization. This approach is often seen as ‘market exports’, whereby high value commodities are processed for foreign exchange and regional benefits (Crona and others, 2016). The OSBP involves placing officials of two countries in each other’s border offices so that outward and inward clearance is carried out in one place sequentially (NEPAD, 2022), thus providing an opportunity for joint, harmonized controls between each side of the border. The concept of a sanitary compliance and conformity assessment implementation framework through OSBPs should potentially address checks at borders and also the application of the process control model for fisheries product quality and safety within the various fish value chains, see Fig 4 (UNIDO, 2024).

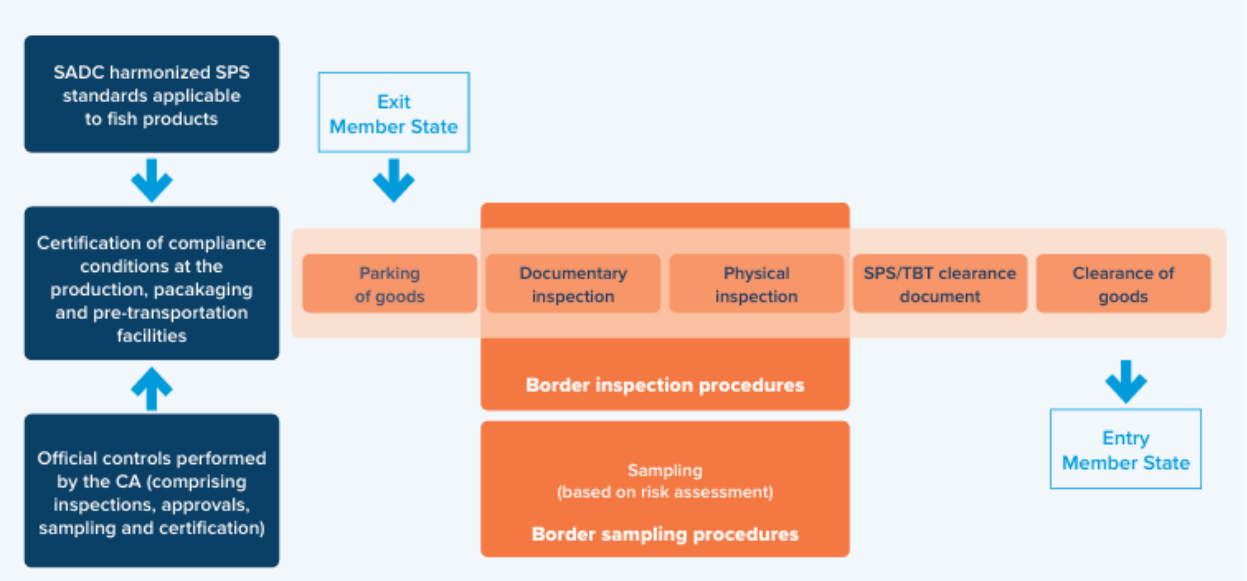


Fig 4: *The OSBP approach for harmonized standards, processing requirements, and cross border trade (source: UNIDO, 2024)*

Instruments of governance

Effective governance of seafood processing requires a comprehensive approach that integrates a variety of regulatory instruments across the local, regional, and international levels from harvesting, processing, to marketing. These governing frameworks are crucial for addressing the multifaceted challenges of the seafood industry and for promoting practices that enhance economic sustainability and environmental stewardship (Khan and Chuenpagdee, 2014). The industry operates within a complex network of regulations to ensure food safety, protect labor rights, and preserve the marine environment. These instruments include legal frameworks, international agreements, voluntary measures, and organizational mandates that collectively oversee the management of value chains and conservation of aquatic resources. Some key ones include:

- **The United Nations Convention on the Law of the Sea (UNCLOS**) and the **FAO's Code of Conduct for Responsible Fisheries**, establish global standards for marine resource governance.
- **United nations Fish Stock Agreement** focuses on conserving and managing straddling and highly migratory fish stocks, emphasizing international cooperation to ensure sustainable fisheries.

- The **International Labor Organization's Work in Fishing Convention (C188)** sets forth international labor standards to ensure safe working conditions, fair wages, and prohibition of forced and child labor within the seafood industry.

- The United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of **Areas beyond National Jurisdiction (ABNJ)** aims to protect marine biodiversity in areas beyond national jurisdiction, recognizing the importance of conserving marine ecosystems for the sustainability of fisheries and aquatic food systems.

- Similarly, the **Kunming-Montreal Global Biodiversity Framework**, established during the 15th Conference of the Parties to the Convention on Biological Diversity, emphasizes the need for integrated approaches to biodiversity conservation and sustainable resource use.

- **The World Trade Organization (WTO)** Fisheries Subsidies Agreement represents another critical element in global fisheries governance useful to curb harmful subsidies that contribute to overfishing and IUU, thereby promoting cooperation, fairness, and sustainable fishing practices.

- **Port State Measures Agreement** (PSMA) is legally binding and empowers port States to deny foreign vessels suspected of having engaged in IUU fishing from using their ports to land catches.

- **Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines)** are a negotiated international instrument endorsed by the FAO Committee on Fisheries and include a dedicated chapter on value chain, post-harvest and trade.

- The **Fisheries Transparency Initiative (FiTI)** strengthens governance by promoting transparency and accountability within the seafood processing industry.

In addition to international and regional frameworks, **regional fisheries management organizations (RFMOs) and regional fisheries bodies (RFBs)** play a pivotal role in the governance of shared fish stocks that spans across national boundaries. National regulations further complement international and regional frameworks by addressing specific local needs and conditions. For instance, the USA Food Safety Modernization Act and the European Union's General Food Law Regulation impose stringent food safety and traceability requirements on seafood processing facilities.

6. Sustainability Pathways

Management controls

Fisheries management controls influence access rights, raw material supply, and the profitability of fish commodity chains. Often, sustainability parameters such as catch per unit effort (CPUE) are

used to address stock abundance and the viability of fish value chains. This is a useful policy instrument that controls fishing efforts, and the question is how best to optimize or 'satisfice' fisheries management goals (Miller and Shelton, 2010). A combination of input and output control measures may be appropriate in some instances, whether total allowable catch, vessel or individual quotas, seasonal closures, community quotas, gear restrictions, permits, and licenses. The choice(s) of measure could be a function of objectives, cost, and national priorities. These management controls help to maintain fish production chains, especially in the small-scale sector, and to ensure full benefits to society (see Fig 5).

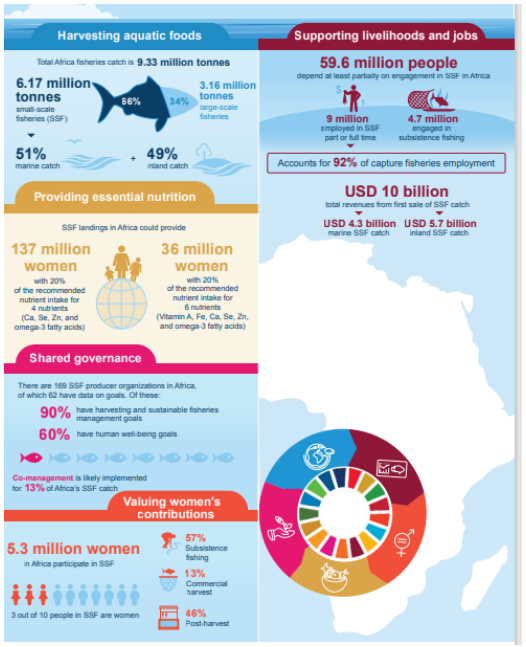


Fig 5: the contributions of SSF to processing and value addition benefits in Africa (Source: FAO and others, 2023)

In addition to management control measures that are designed to support an ecosystem approach, there are market-based incentives aimed at the sustainability of the seafood industry towards ensuring fair trade, ensuring stewardship, and addressing concerns relating to overfishing (Box 4).

Box 4: Iceland's Comprehensive Fisheries Management System (OECD, 2017)

Iceland developed a comprehensive fisheries management system that integrates sustainability, traceability, and quality assurance. Central to this system is a quota management system (QMS) that allocates fishing rights to individual vessels, ensures sustainable harvest levels, and prevents overfishing. Advanced traceability systems track seafood products from catching to consumers, ensuring compliance with regulatory standards and enhancing consumer confidence. The active involvement of stakeholders, including fishers, processors, and regulators, fosters a collaborative approach to fisheries management, highlighting the significance of quota management, transparency, and stakeholder engagement for effective governance.

These market-based tools have ensured that each player in the seafood industry is held accountable for the course of sustainability practices in the complex international seafood trade especially regarding mislabeling (Jacquet and Pauly 2008). The adoption of eco-certification processes, for instance, strives to improve awareness and information sharing, which may be empowering for the seafood industry.

Quality infrastructure and standardization

Quality and safety are crucial drivers of sustainable seafood trade and processing methods. Consumers must be convinced that seafood is safe from foodborne pathogens, mycotoxins, and other production hazards. Similarly, seafood buyers must meet increasingly robust food safety and quality control standards. The difficulty of establishing cause and effect along value chains demands an urgency to invest in mycotoxin prevention and other hazards (Akintola and others, 2022). In tropical settings, where microbial activities are predominant due to high temperatures and humidity, postharvest activities might be compromised with the growth of fungi molds and bacterial infection. Understanding postharvest best practices is imperative for social and economic reasons in the context of safety and seafood quality.

A prime example is the implementation of hazard analysis and critical control point (HACCP) systems, which are globally recognized approaches for improving food safety in seafood processing (Alqattan and others, 2020; Okeke-Ogbuafor & Gray, 2021). The HACCP systems are designed to proactively identify and control potential hazards and prevent food safety issues before they occur. Adopting these systems is often a prerequisite for accessing major international markets such as the EU and the United States, where strict quality and safety standards are enforced (Kurnia and others, 2020; Naabi & Bose, 2020). Consequently, operators implementing HACCP and pre-requisite programmes such as GMP, and food safety management

systems are better positioned to compete globally, thus enhancing their market access, competitiveness, and consumer confidence. Therefore, policies must be designed to maximize the economic benefits while simultaneously enabling the prosperity of local markets and communities. As presented in Fig 1, processing activities within the fish production chain is influenced by a continuum of management measures in the pre-harvest and harvest/culture stages and impacts post-harvest measures as well as retail trade and consumption patterns. These consumption patterns and dietary preferences within agri-food systems and commodity chains has implications for consumer preferences and human well-being, see Fig 6.

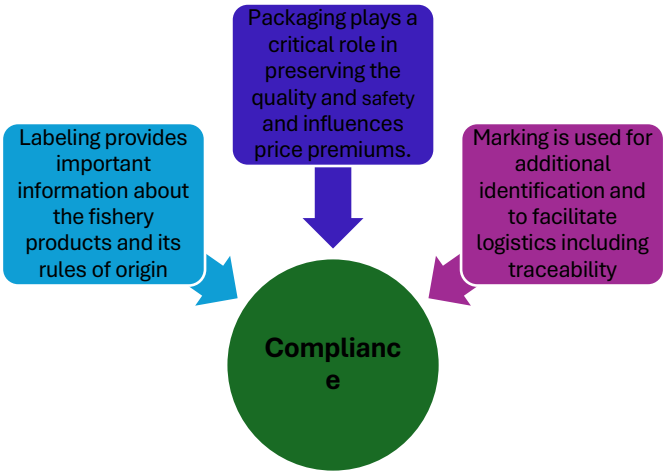


Fig 6: Processing activities that is influences by management measures and consumer preference including traceability, rules of origin, and branding (source: UNIDO, 2025).

Social disconnects, fragility and global change

As discussed in Chapter, S5B.C7 Covid-19 affected fish harvesting and seafood processing, especially with social distancing, lockdowns, and border closures to contain infection (Bennett and others, 2020). Various strategies were deployed to address the nutritional needs of communities in the absence of active fishing and processing but also to address short-term health protocols and social safety nets (Khan et al., 2021). As shown in Box 5, Covid 19 also impacted fisheries distribution and trade, as import bans has implications for trade and shorter value chains to ensure food security (Song and others, 2024).

Box 5: China's fish supply chains during COVID-19

China is the largest seafood trading partner in the world. From 2015 to 2019 China overhauled its Food Safety Law as part of a wider campaign to improve the governance of food safety and quality of domestically produced and imported foods. Chinese exports, for instance, include a wide array of fish products (both local and imported), that include frozen whole fish, frozen fillets, and canned fish products such as cuttlefish (FAO, 2024). Hence disruption in global supply chains owing to COVID-19 will affect import and export and value chain dynamics. During the COVID-19 pandemic, China imposed bans on some cold chain imports, including seafood. Some of the import bans also appear to have trade implications, with disruption of fish supply chains, and market access. ~~Although the intended purpose was necessary for safety and health compliance issues, yet issues around non-tariff barriers became evident.~~ Post COVID-19, also saw a boost in surge of imports of various seafood including frozen shrimps, fresh rock lobster, frozen Alaska pollack and fresh salmon (FAO, 2024), demonstrating China's policy ~~eclecticism~~flexibility in negotiating trade as well as addressing phyto-sanitary conditions~~.~~ ~~Contemporary Chinese food safety policy, therefore, is best understood as an integrated part of general food policy and diplomacy and reflects China's geopolitical relations as~~

Policy innovation and sustainability entry points

Five key take aways are provided as tenets for seafood processing to complement and to align with other WOA III chapters on food systems, trade, SSF, gender, industrial fisheries, and well-being:

- **SDGs:** The seafood industry has made significant progress in aligning with global objectives like SDG 14 and SDG 2, contributing to sustainable marine governance and food and nutritional security. Processing methods such as freezing and canning adverse seafood's nutritional value and reduce post-harvest losses, thus supporting food security, livelihoods and economic prosperity. It also addresses gender, wellbeing, decent work, responsible consumption and production and climate action (SDGs 5, 8, 10, 12 & 13).

- **Efficiency and Value Addition:** The fish production chain consists of interconnected stages where effective post-harvest techniques reduce spoilage and add value. Processing methods like chilling, freezing, and curing are crucial in transforming raw seafood into more shelf-life stable and marketable products contributing to food and nutrition security.

- **Technological Advancements:** Advances in technology and modern infrastructure, including automation, digital platforms, and precision tools, have improved fish supply chain efficiency (Siddique and others, 2024). This is achieved by inactivating spoilage microorganisms and enzymes that contribute to the deterioration of the product over time (Russo and others., 2023). Technologies such as high-pressure processing, cold plasma, and pulsed electric field are particularly effective in this regard (Russo and others, 2023). However, they also present challenges which require regulatory frameworks to ensure long-term viability and sustainability.

- **Environmental and Social Pressures:** Factors like adverse incentives and subsidies towards overfishing, climate change, and pollution pose risks to marine ecosystems, raw material supply, and seafood production. Moreover, social issues such as labor rights, gender equity and social inclusion further challenge the industry's governance and demands policy reforms.

- **Governance and Regulatory Frameworks:** Effective governance of the seafood industry is essential for maintaining sustainability. International frameworks like the UNCLOS and the WTO's Fisheries Subsidies Agreement emphasize cooperation and regulatory harmonization to curb overfishing and ensure compliance with environmental and labor standards.

Summary and conclusion

In 2022, out of the 165 million tonnes of fish destined for human consumption: live, fresh or chilled accounted for about 43 percent (FAO, 2024). This was followed by frozen (35 percent), prepared and preserved (12 percent) and cured (10 percent). Moreover, freezing is the main method of preserving aquatic foods, accounting for 62 percent of the 93 million tonnes of processed aquatic animal production for human consumption. This represents about 89% for direct human consumption, with the remaining 11% for non-food purposes such as fish meal in aquaculture and biofuel. Recently, much of the food waste often discarded has now developed into affordable and nutritious products given their nutritional value (Penarubia and others, 2023); and the added nutrients such as iron, calcium and other micro-nutrients that can address deficiencies in human health (UN Nutrition, 2021).

-By addressing the social and economic issues in coastal communities, the seafood processing industry can play a central role in promoting gender inclusion, fair wages, and decent work conditions for all (SDG 5, 8, 10 and 12). To achieve a more sustainable and equitable future for seafood processing, stakeholders are encouraged on some key policy recommendation:

1. **Invest in Public Goods and Fisheries Governance**: Seafoods systems are governed by public institutions because of the common benefits to global citizens. Hence governments and industry leaders should invest in natural capital assets and fisheries conservation as well as appropriate technologies and modern infrastructure to ensure compliance with management best practices. These investments will drive compliance, reduce perverse incentives to overfish, and cater to evolving consumer preferences and community benefits.

2. **Promote Ethical Labor Practices and Social Equity**: Advanced processing techniques especially towards traceability and rules of origin will play a pivotal role in compliance and meeting the diverse needs of stakeholders. However, technological innovation should not come at the expense of social exclusion and community resilience. Through prioritization and promotion of social inclusion, it is important to ensure safe working conditions, fair wages, and gender equity across all levels of the seafood processing in the value chain.

Thus, governments and industry actors could ensure that the ratification and enforcement of global labor standards to protect workers' rights and foster ethical consumption and production practices are sustained (ILO, 2016).

3. **Strengthen Governance and Policy Harmonization**: As global demand for seafood increases, integrated policy frameworks and value-chain enhancements must be aligned to foster a more inclusive and resilient sector. Policymakers must prioritize harmonizing regulations across jurisdictions to facilitate fair trade, uphold environmental standards, and ensure labor rights are met (Harrison and others, 2020b). Collaborative efforts between regional and global bodies will be essential to curbing overfishing, improving traceability, and promoting sustainable fishing practices and processing methods.

4. **Upgrade Infrastructure and Build Capacity**: embracing circular economy best practices, such as renewable energy in processing plants and biodegradable packaging, will ensure that the industry remains aligned with sustainability principles and environmental stewardship. Developing nations and coastal communities require investments in cold storage facilities, modern processing plants, and transportation networks. Capacity-building programs targeted at women and small-scale fishers will empower local communities, increase revenues, and create more equitable opportunities within seafood value chains and the processing industry.

5. **Foster Consumer Awareness and Demand for Sustainable Food Products**: Consumer awareness and education campaigns in eco-labelling and sustainability certifications should be a priority for all economic sectors (businesses) and governments to boost demand and enable more informed and sustainable purchasing decisions of seafood (Osterblom and others, 2015).

By taking these sustainable pathways, the seafood processing industry can meet global challenges in the future, by safeguarding marine ecosystems and ensuring the well-being of millions of people who rely on seafood as a vital source of nutrition, jobs, and export earnings.

References

Abelti, A.L., and Teka, T.A. (2024). Intervening fish post-harvest losses to narrow the gap between demand and supply: a review on magnitude of fish post-harvest losses in some sub-Saharan African countries. Aquaculture, Fish and Fisheries, 4, e168.

African Development Bank. (2022). Southern Africa regional integration strategy paper 2020-2026. AfDB.

African Development Bank (AfDB). (2016). Annual Report. African Development Bank https://www.afdb.org/en/documents/southern-africa-regional-integration-strategy-paper-2020-2026

African Development Bank (AfDB). (2016). Annual Report. African Development Bank

Akintola S.L., Fakoya K.A., Elegbede I.O., Odunsi E., Jolaosho T. (2022) In: Sustainable Fish Production and Processing. Galanakis C., editor. Academic Press; Cambridge, Massachusetts: Postharvest practices in small-scale fisheries; pp. 79–110

Al-Maamari, R., Al-Haddad, M., & Al-Rumaihi, K. (2022). Marine pollution in Kuwait and its impacts on fish-stock decline in Kuwaiti waters: Reviewing the Kuwaiti government's policies and practices. *Marine Pollution Bulletin*, *175*, 113247. https://doi.org/10.1016/j.marpolbul.2021.113247

Bavinck, M. (ed.); Ahern, M. (ed.); Hapke, H.M. (ed.); Johnson, D.S. (ed.); Kjellevold, M. (ed.); Kolding, J. (ed.); Overå, R. (ed.); Schut, T. (ed.); Franz, N. (ed.). 2023. Small fish for food security and nutrition. FAO Fisheries and Aquaculture Technical Papers. No. 694. Rome.

Bellmann, C., Tipping, A. & Sumaila, U. R. (2016). Global trade in fish and fishery products: an overview. *Mar. Policy* 69, 181–188.

Bennett, E.M., Peterson, G.D., & Gordon, L.J. (2022). Understanding the role of fish in food systems: A global perspective. Food Security, 14(1), 1-12. https://www.tandfonline.com/doi/full/10.1080/08920753.2020.1766937#abstract

Bwala, M. N., (2023). Effect of smoking methods on polycyclic aromatic hydrocarbons (PAHs) contamination. National Environmental Standards and Regulations Enforcement Agency (NESREA). Ecotoxicol Environmental Contamination., volume 18, n.2, 2023, 18 - 25

Charles, A., Macnaughton, A. and Hicks, S. 2024. Environmental stewardship by small-scale fisheries. FAO, Rome.

Cheung, W.W.L., Watson, R., & Pauly, D. (2021). Climate change and the oceans: Impacts on fisheries. Marine Policy, 123, 104320.

Cisneros-Montemayor, A.M., Ota, Y., Bailey, M., Hicks, C.C., Khan, A., Rogers, A., Sumaila, U.R. Virdin, J., He, K.K. 2020. Changing the narrative on fisheries subsidies reform: Enabling transitions to achieve SDG 14.6 and beyond. *Marine Policy*, Vol. 117.

Cooney, R., Bennun, L., & Haseeb, M. (2023). Integrated approaches to biodiversity and ecosystem services management. Journal of Cleaner Production, 416, 136541. - https://www.sciencedirect.com/science/article/pii/S0959652623004419

Crenshaw, K. W. (1999). Mapping the margins: Intersectionality, identity politics, and violence against women of color. In Critical race theory: The key writings that formed the movement (pp. 357-383). New York: The New Press.

Daw, T., Brown, K., & Rosendo, S. (2021). The role of distant-water fishing fleets in global fish supply: Implications for fisheries management. Marine Policy, 130, 104525.

Food and Agriculture Organisation (FAO). 2024. The State of World Fisheries and Aquaculture 2024 – Blue Transformation in Action. Rome

FAO, Duke University & WorldFish. 2023. Illuminating Hidden Harvests – The contributions of small-scale fisheries to sustainable development. Rome.

FAO. (2022). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation. Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization (FAO). (2022). Post-harvest fish loss assessment: A guide to conducting a desk and field studies. FAO

FAO. (2020). The State of World Fisheries and Aquaculture 2020. FAO.

FAO. (2015). Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication. FAO, Rome

Ghaly, A. E., Ramakrishnan, V. V., Brooks, M. S., Budge, S. M., & Dave, D. (2010). Fish processing wastes as a potential source of proteins, amino acids and oils: A critical review. Journal of Microbial & Biochemical Technology, 5(4), 107-129.

Gudmundsson, E.; Asche, F.; Nielsen, M. 2006. Revenue distribution through the seafood value chain. *FAO Fisheries Circular.* No. 1019. Rome, FAO. 2006. 42p.

Harper, S., Zeller, D., Hauzer, M., Pauly, D., & Sumaila, U. R. (2013). Women and fisheries: Contribution to food security and local economies. Marine Policy, 39, 56–63.

Harrison, J., & Houghton R. (2020) (a). The role of policy in promoting fair trade and environmental standards in fisheries. Journal of Environmental Management, 260, 110189.

Harrison, J., & Houghton R. (2020)(b). Sustainable seafood processing: Innovations in efficiency and environmental conservation. Marine Policy, 113, 104801.

Hilborn, R., Branch, T.A., & Ernst, B. (2020). The management of fisheries: A retrospective and prospective view. Fish and Fisheries, 21(1), 1-26.

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Intergovernmental Panel on Climate Change.

Irschlinger, T. (2024). World Trade Organization Talks on Subsidies That Contribute to Overcapacity and Overfishing: What's on the Table? International Institute for Sustainable Development (IISD) Report. IISD.org

Issifu, I., Deffor, EW., Deyshappriya, NPR., Dahmouni, I., Sumaila, UR. (2022). Drivers of Seafood Consumption at Different Geographical Scales. J Sustain Res.4(3): e220012.ILO. 2016. Fishers first - Good practices to end labour exploitation at sea / International Labour Office, Fundamental Principles and Rights at Work Branch, Sectoral Policies Department. IlO, Geneva.

Jacquet, J., & Pauly, D. (2008). Trade secrets: Renaming and mislabeling of seafood. Marine Policy, 32(3), 309-318; https://www.sciencedirect.com/science/article/abs/pii/S0308597X07000760

Jentoft, S., & Chuenpagdee, R. (2022). The importance of stakeholder participation in fisheries governance. Marine Policy, 130, 104593.

Jentoft, S., & Chuenpagdee, R. (2009). Fisheries and coastal governance as a wicked problem. Marine Policy, 33(4), 553–560.

Jentoft, S., & Chuenpagdee, R. (2007). Fisheries and coastal governance as a wicked problem.

Jouffray, J. B., Blasiak, R., Norström, A. V., Österblom, H., & Nyström, M. (2019). The Blue Acceleration: The trajectory of human expansion into the ocean. One Earth, 2(1), 43–54

Kleiber, D., Harris, L. M., & Vincent, A. C. J. (2017). Gender and small-scale fisheries: A case for counting women and beyond. Fish and Fisheries, 18(5), 958–972.

Khan, A., Ahmed, S.M., Sarr, C. et al. 2021. Nourishing nations during pandemics: why prioritize fish diets and aquatic foods in Africa. Maritime Studies. doi.org/10.1007/s40152-021-00236-z https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8382667/

Khan, A.S. and G. Cundill. 2019. Hotspots 2.0: Towards an integrated understanding of stressors and response options. Ambio, 48: 639-648.

Khan, A. S., & Cundill, G. (2018). Integrated approaches to coastal management: A critical review of the literature. Coastal Management, 46(4), 328–343

Khan, A.S. 2012. Understanding global supply chains and seafood markets for the rebuilding prospects of Northern Gulf Cod Fisheries. Sustainability, 4(11): 2946-2969.

Khan, A.S., and B. Neis. 2010. The rebuilding imperative in fisheries: Clumsy solutions for wicked problems? Progress in Oceanography, 87(1-4): 347-356.

Knott et al. (2022): Knott, C. D., Marschke, M. J., & Van Aken, H. (2022). "The Blue Economy in a Time of Climate Change: A Rapid Review of the Evidence." Marine Policy, 136, 104932. DOI: 10.1016/j.marpol.2021.104932.

Knott (2020): Knott, C. D. (2020). "The Blue Economy: The Promise of Sustainable Development for the Ocean." In M. A. H. N. W. L. N. Lejano (Ed.), Sustainable Development and the Blue Economy: A Systems Perspective (pp. 53-68). Springer.

Knott and Marschke (2020): Knott, C. D., & Marschke, M. J. (2020). "Governance and Management for the Blue Economy." Ocean & Coastal Management, 182, 104958. DOI: 10.1016/j.ocecoaman.2019.104958.

Knott (2016): Knott, C. D. (2016). "Exploring the Potential for a Blue Economy in the Western Indian Ocean." African Journal of Marine Science, 38(1), 1-8. DOI: 10.2989/1814232X.2016.1143654.

Kooiman et al. (2005): Kooiman, J., Bavinck, M., Jentoft, S., & Pullin, R. (2005). Fish for Life: Interactive Governance for Fisheries. MARE Publication Series, Vol. 2. Amsterdam University Press.

Kumar, S., Gupta, S., & Jha, A. (2021). Post-harvest losses in fisheries: A review of the challenges and solutions. Aquaculture Reports, 19, 100588.

Kumar, S., & Tiwari, B. (2020). Sustainable practices in seafood processing: Innovations and challenges. Journal of Cleaner Production, 258, 120618.

Kumolu-Johnson, C. A., & Ndimele, P. E. (2011). A review on post-harvest losses in artisanal fisheries of some African countries. Journal of Fisheries and Aquatic Science, 6(4), 365-378.

Kurnia, S., Triana, I. A., & Sultoni, R. (2020). "The Concept of Blue Economy: A Literature Review." International Journal of Innovation, Creativity and Change, 13(1), 347-365

Lee, S. (2024). "A Blue Economy for Sustainable Development: Policy Recommendations." Ocean & Coastal Management, 236, 105874

Lowitt, K. (2013). "The Blue Economy: The Role of Coastal Communities in Sustainable Development." Coastal Management, 41(3), 226-241.

Ludwig, D., R. Hilborn, and C. Walters.1993. Uncertainty, resource exploitation and conservation: Lessons from history. Science 260:36–37.

Lue, M.; Makino, M.; Asari, M. (2022) Seafood Sustainability Supply Chain Trends and Challenges in Japan: Marine Stewardship Council Fisheries and Chain of Custody Certificates. Sustainability, 14,13523. https://doi.org/10.3390/su142013523

Mangubhai, L., Cowley, S., Mangubhai, J.P., and Williams, M.J. 2022. Progressing gender equality in fisheries by building strategic partnerships with development organisations. World Development,158: 105922.

Mangubhai, S., & Lawless, S. (2021). The role of blue carbon in climate change mitigation: The case of coral reef ecosystems in the Coral Triangle. Ocean & Coastal Management, 210, 105677.

Marschke, M., O'Leary, B. C., & Salomon, A. (2018). The blue economy: The next phase of sustainable development. Sustainability, 10(10), 3464. https://doi.org/10.3390/su10103464

Miller, K. A., & Shelton, S. C. (2010). The role of the ocean in global warming: Is it still a dirty word? Marine Policy, 34(4), 829–836.

Naabi, M. R., & Bose, S. (2020). Blue economy in the context of sustainable development goals: Marschke et al (2018)

Naylor, L., Sumaila U.R., Issifu, I., et al. (2021). Blue food demand across geographic and temporal scales. *Nature Communications,* 12, 5413.

Neis, B., Gollner, S., & Thiel, H. (2013). Towards an integrated approach for the assessment of ecosystem services in the marine environment: The example of the blue economy. Ecosystem Services, 5, 1–11

NEPAD. (2022). Accelerating the Blue Economy: Policy and Action Plan. African Union.

Okeke-Ogbuafor, N., & Gray, T. (2021). Assessing the blue economy potential in Nigeria: Challenges and opportunities. Sustainability, 13(9), 4921.

Österblom, H., Jouffray, J.-B., & Folke, C. (2015). The blue economy and the role of the ocean in sustainable development. Global Sustainability, 2, e2.

Packer, M., Stoll, J. S., & Smith, R. C. (2019). Marine biodiversity and the blue economy: Opportunities and challenges. Ocean & Coastal Management, 170, 1–8.

Paolo, B., Mariani, S., & Sgorbati, S. (2022). Blue economy and marine spatial planning: Lessons from the Mediterranean Sea. Ocean & Coastal Management, 219, 106061.

Pedroza-Gutiérrez, C., & Hapke, H. M. (2022). Developing a blue economy in Mexico: Opportunities and challenges for sustainable growth. Sustainability, 14(4), 2072.Pérez-Escamilla R. 2024. Food and nutrition security definitions, constructs, frameworks, measurements, and applications: global lessons. Frontiers In Public Health 12: 1340149.

Pinfold G. (2007). Nova Scotia seafood processing sector: state of the industry and competitiveness assessment. https://novascotia.ca/fish/documents/seafoodreport.pdf

Russo, G.L., Langellotti, A.L., Torrieri, E., & Masi, P. (2023). Emerging technologies in seafood processing: An overview of innovations reshaping the aquatic food industry. Comprehensive Review in Food Science and Food Safety.

Sangaramoorthy, T. (2019). The blue economy: The impacts of marine pollution on economic growth and sustainable development. ResearchGate.

Se-Kwon Kim (2014). Seafood processing by-product: trends and application. Springer New York.

Siddiqui SA, Singh S, Bahmid NA, Sasidharan A. Applying innovative technological interventions in the preservation and packaging of fresh seafood products to minimize spoilage - A systematic review and meta-analysis. Heliyon. 2024 Apr 4;10(8):e29066. doi: 10.1016/j.heliyon.2024.e29066. PMID: 38655319; PMCID: PMC11035943.

Soeparna, I. I., & Taofiqurohman, A. (2024). Transversal policy between the protection of marine fishery resources and fisheries subsidies to address overfishing in Indonesia. *Marine Policy*, *163*, Article 106112. https://doi.org/10.1016/j.marpol.2024.106112~~2~~

Song, A. Fabinyi, M., Barclay, K. 2024. China and seafood trade after coronavirus: the role of state actors.
Marine Policy, 160, 105992.

Sumaila et al. (296 co-authors). 2021. WTO must ban harmful fisheries subsidies. *Science*, 374: 6567

Sumaila, U.R., Zeller, D., & Pauly, D. (2021). The impact of subsidies on fisheries: A global perspective. Global Environmental Change, 68, 102229.

Sumaila, U.R., Cheung, W., Dyck, A., Gueye, K., Huang, L., et al. (2012). Benefits of rebuilding global marine fisheries outweigh costs. PLoS ONE, 7(7), e40542. Here

~~Sumaila, U. R., Tse, W. K., & Watson, R. (2008). Fishing for a living: The impact of fisheries on the economy of coastal countries. Fisheries Research, 94(1), 44-56.~~

Sumaila, U.R., Ebrahim, N., Schuhbauer, A., Skerritt, D., Li, Y., Kim, H.S., Mallory, T.G., Lam, V., and Pauly, D. (2019). Updated estimates and analysis of global fisheries subsidies. Marine Policy, 109, 103695.

Tickler D., SIMMONDS, E.J and McPhee, D (2018). The role of fisheries in the blue economy. Nature sustainability, 1(5), 261-272

Thilsted, J. P., Van Houtte, A., & Reddy, R. (2023). Aquatic foods and the blue economy: Opportunities for enhancing food and nutrition security. Global Food Security, 38, 100152

Thorpe, A., & A. J. L. (2005). The economic value of coastal and marine ecosystem services. Environmental Science & Policy, 8(5), 1-12

Torreblanca, S., Gutiérrez, A., & Rojas, M. (2022). Strengthening international regulations for sustainable distant-water fisheries: A global perspective. Ocean & Coastal Management, 218, 105645.

Revollo-Fernández, D. A., Fulton, S., & Chávez Sánchez, S. (2024). Value and economic impact of fuel subsidies on the Mexican fishing industry. Applied Economics, 1–13. https://doi.org/10.1080/00036846.2024.2399814

UN Nutrition. 2021.The role of aquatic foods in sustainable healthy diets - https://www.unnutrition.org/wp-content/uploads/FINAL-UN-Nutrition-Aquatic-foods-Paper_EN_.pdf

UNIDO 2024. Improving Blue Economy Trade Corridors in the SADC Region: Towards the Adoption of a Regional Strategy for OSBP on Fisheries Products under ProFishBlue Project. UNIDO, Vienna, Austria.

UNIDO 2025. Strategic and Operational Guide to Assess the Conformity of Fishery Products: Improving Trade under the One Stop Border Post in the SADC Region. UNIDO, Vienna, Austria.

Venugopal, V. (2006). Marine pollution in Kuwait and its impacts on fish-stock decline in Kuwaiti waters: Reviewing the Kuwaiti government's policies and practices.

Section 5A

Sub-chapter 1f: (seafood) Trade

Jessica A. Gephart, Frank Asche, Carlos Chavez, Bolanle Erinosho, Anna Farmery, Senia Febrica, Cheol-Kyu Maeng, Carmen Pedroza-Gutiérrez, Cristina Pita, Cathy Roheim, U. Rashid Sumaila

Key findings

- The uneven distribution of aquatic resources has driven trade at local to global levels for millennia, but the share of marine production exported has increased in recent decades. Specific trade patterns are mediated by differences in production and transport infrastructure, governance, economic factors, and geopolitical relationships.
- Seafood trade can result in positive or negative impacts on local environments, economies, and communities and what impacts occur depend upon the institutional and governance context.
- Trade regulations, certifications, and traceability tools are emerging to support sustainable seafood trade, but their impacts and effectiveness require further analysis~~but unknowns remain regarding aspects of their impacts and effectiveness~~.

Overview

Aquatic resources are unevenly distributed around the world and human population centers are often ~~geographically removed~~ distant from areas of high abundance. As a result, fish and other aquatic organisms (i.e., aquatic foods) have been traded for millennia with some communities specializing in producing and trading it to obtain other goods that are often not available locally. Aquatic food continues to be caught and farmed for subsistence, gifting, bartering, and trade within communities, sub nationally and internationally. Here, we consider trade to include all exchanges of aquatic food for monetary or non-monetary benefit but focus most heavily on international trade. Additionally, we focus primarily on trade of marine fisheries and aquaculture~~farmed and wild~~ products (which we refer to as "seafood"), but it is often not possible to fully separate marine products from inland products in reported trade statistics. Therefore, at times we refer to the collective group of all farmed and wild caught foods from marine and inland habitats as "aquatic foods". At the international level, aquatic food is among the most highly traded foods with around a third of all production traded, and higher export orientation for marine wild caught and farmed products compared to inland products (Asche et al., 2015; Gephart et al., 2024).

While economic theory indicates that society as a whole benefits from trade, there are important distributional effects, along with potential social and environmental impacts. The specific effects of trade are shaped by the social, economic, and institutional context in which it operates and impacts often represent opposite sides of the same coin. For instance, sellers are willing to export products to obtain a higher price, but removing products from the local market increases local prices and

reduces local seafood availability. Conversely, buyers usually purchase less expensive seafood from distant sources, which increases seafood availability and reduces prices for consumers, but cheaper imported products then compete with local products (Asche et al., 2015). However, the net effect on affordability and broader food and nutrition security is not known.

Trade can also provide consumers with a wider set of species than what is available locally and allow producers with abundant resources and limited local markets to find buyers. Seafood is a highly heterogeneous resource, including over 1990 wild and farmed marine species, which are used in diverse products, including fresh and frozen filets, smoked fish, shelf stable canned and pouch products, which are offered at a wide range of price points (FAO, 2024). Production of high-value marine species further incentivizes export to wealthy consumers and correspondingly, many of the top traded species groups such as salmon, shrimp, and tuna, are also high value species (Gephart et al., 2024). High value seafood exports can be particularly important for some national economies, with fisheries representing up to 80% of all exports for some island nations (Gillett, 2009). However, the distribution of economic benefits across society is context dependent and evidence of the impact of seafood exports on food security is mixed (Béné et al., 2010). Recent work has demonstrated that the majority (63%) of countries gain nutrient supply from trade in marine fishery products, however, of the 36% of countries that experience net nutrient losses, over half are small island developing states or African nations (Nash et al., 2022).

Global seafood trade has evolved in recent decades along with shifts in global production patterns and practices. Although marine wild fish landings leveled off in the mid-90s, total aquatic food exports nearly doubled from 1996-2020, with aquaculture responsible for the majority of that increase (Gephart et al., 2024). Over this period, interregional trade remained dominant for many regions, but Asia became increasingly important as a destination market for all regions. Correspondingly, there have been shifts in the top importers and exporters of marine products. For example, between 1996 and 2020, China and Russia emerged as the top two exporters of marine wild fish products (Gephart et al., 2024). However, a significant share of China's exports represent products imported for processing and re-exported, with China re-exporting an estimated 75% of its total aquatic food imports (Asche, Yang, et al., 2022). This pattern represents another important change in aquatic food trade – the commodification of aquatic foods and regional specialization in processing.

In this chapter, we focus first on the drivers underlying increased trade. We then overview the risks to trade from both slow-moving pressures and sudden disruptions. Next, we review the environmental impacts associated with trade, followed by key social and economic considerations. Finally, we cover key governance aspects related to trade before describing sustainability pathways for marine resource trade.

Pressures and impacts

Drivers of increasing trade

The uneven distribution of fisheries resources and suitable production environments underpin trade, but there are a number of economic, logistic, and governance factors driving increased trade in recent decades. Population and economic growth have increased demand for all types of food products.

Aquatic foods plays an important role in meeting this demand as global aquatic food production has increased more rapidly than the human population (FAO, 2024), with aquaculture (dominated by inland production) playing a crucial role in meeting recent and projected future demand as the scope for increasing supply from wild fisheries is low (Costello et al., 2019; Naylor et al., 2021).

Whether and where seafood is exported depends on consumers' willingness and ability to pay, along with the presence of infrastructure to support transport to those markets. The globalization of seafood markets has been facilitated by improved logistics that reduce transportation costs, thereby increasing the competitiveness of distant producers or distant markets (Anderson et al., 2018). Lower logistics costs and improved supply chains, such as cold chains, enhances producer and consumer access to seafood markets, but such improvements have disproportionately been realized in wealthier countries. However, in recent years logistics have improved globally and correspondingly the share of the seafood traded to the wealthiest countries has diminished (Asche et al., 2015). Relatedly, a lack of local processing facilities, wage differentials, and differences in regulatory stringency across nations have likely contributed to increased exports for processing and re-exports.

International governance systems have also accelerated trade. The introduction of 200 nautical miles Exclusive Economic Zones in the 1970s, with broader adoption in 1982 under the Law of the Sea Convention, excluded distant water fishing activities from fishery access without a formal access agreement and in many cases, the domestic fishers who assumed control continued supplying to the same markets through exports. For instance, this drove Japan's transition from a distant water fishing nation to a major seafood importer (Swartz et al., 2010). Finally, the Word Trade Organization Agreement, and its predecessor GATT, regards seafood as an industrial product rather than an agricultural product. This contributes to increased trade as tariffs are generally lower for industrial products, and there have been several general reductions in the maximum tariff rate in this category (Bellmann et al. 2016). There are also numerous agreements giving some countries preferential treatment in the form of lower tariffs, sometimes to zero or tariff free export quotas that impact trade-flows and market access (Roheim, 2004).

Slow moving pressures on seafood trade

Although seafood trade has continued to grow in recent decades, evolving economic, regulatory, and geopolitical conditions, along with changing environmental conditions, serve as pressures that inhibit and reshape trade.

Although aquatic foods are generally subject to low tariffs, many countries seek to protect domestic processing industries by escalating tariffs on products that are more processed. ~~Consequently,~~ ~~a~~Aquatic food has also appeared in numerous anti-dumping cases, particularly in the EU and USA. While there may be legitimate reasons for this, there has been a significant increase in such cases in general, as well as for seafood specifically, and following the establishment of the WTO countries have limited possibilities for increasing tariffs (Asche et al., 2015). A similar situation exists for so-called non-tariff barriers. These come in a number of forms such as heightened food safety regulations, which are legitimate within the WTO agreement as long as they are not discriminatory (Bellmann et al., 2016).

However, such regulations have been increasingly used with some indication they serve as a substitute for tariffs, sometimes as short-term measures that slow imports until a broader agreement is reached (Asche et al., 2015).

It has also become legal to implement trade measures to prevent seafood produced with what the importing country considers environmentally unacceptable production practices, as long as these are not discriminatory (Roheim & Sutinen, 2006). For instance, the U.S. has import restrictions on tuna with high bycatch of swordfish, as well as shrimp with high bycatch of turtles. More recently, a Seafood Import Monitoring Program was implemented by the U.S. to combat Illegal, Unreported and Unregulated (IUU) fishing. Similarly, the EU has had a program using import restrictions to combat IUU fishing since 2008 (Sumaila, 2019).

Environmental change is simultaneously shifting production, with the potential to reshape global trade. Climate change is modifying ocean biophysics and thus generating diverse ecological, economic, nutritional, and social impacts (Cheung et al., 2010; Golden et al., 2016; Lam et al., 2016). Fisheries productivity is also projected to shift, with large decreases around the equator, and increases in Arctic waters (Cheung et al., 2010) (for more on climate impacts on fisheries, see S4.C4d, S5A.C1a, and S5A.C1b). Climate impacts can compound existing challenges to marine fishery production, which already have stagnated global catches and an estimated 28–33% of all stocks are overexploited and 7–13% of stocks are collapsed (Branch et al., 2011). Changes in local fish abundance can also incentivize trade as local consumption may be maintained by increased imports and increases in fish abundance may incentivize exports. The higher degree of control in the aquaculture production process can allow it to be more climate resilient (Asche, Eggert, et al., 2022), though the impacts of climate change on marine aquaculture (i.e., mariculture) production potential are projected to be heterogeneous (Froehlich et al., 2018).

Disruptions to seafood trade

Sudden disruptions, or shocks, to seafood trade can occur due to a range of environmental, policy, economic, and logistic events (Davis et al., 2020). Production shocks represent drops in landings or mariculture harvest which can potentially reduce exports, creating a risk of the shock propagating to other countries. Theoretical work suggests net importers, low-income nations, and countries with low food stocks tend to be more exposed to the effects of such shocks, but there is limited empirical evidence on this risk (Gephart et al., 2016; Marchand et al., 2016; Tamea et al., 2016). Industrial scale producers also have better access to more diversified markets, enabling them to avoid the impact of many shocks by re-allocating their exports to alternative markets (Asche, Sogn-Grundvåg, et al., 2022; Straume et al., 2022). Conversely, trade also allows countries to buffer drops in their own production through increased imports. Analysis of past aquatic food production shocks suggests that exports decrease about as often as imports increase, though the exact combination is highly context dependent (Gephart et al., 2017).

Disruptions can also occur at other points along the supply chain, including events that specifically impact trade such as those affecting transportation logistics and the implementation of trade

barriers (Davis et al., 2020). As an ocean-based resource, seafood production is exposed to natural hazards that impact associated infrastructure such as tropical storms, tsunamis, and flooding that impacts fishing vessels, coastal aquaculture farms, and coastal ports. Disturbances create uncertainty in landings, prices, and incomes that can impact actors along the supply chain from fishers to processors to wholesalers and retailers (Rice et al., 2024). Meanwhile, shipping bottlenecks and long waiting times in ports pose a risk to highly perishable products. Trade barriers, such as tariffs or import bans, which can arise from geopolitical disputes, can also restrict trade (see Section 5A, Chapter 6 for more on shipping). Changes to import standards can serve as an important shock for exporters, as occurred with the 1997 import ban by the European Union on shrimp from Bangladesh based on the claim that the shrimp did not meet the Hazard Analysis Critical Control Point regulations resulting in 14.7 million USD of lost revenues in the processing sector (Cato & Dos Santos, 1998; Yunus, 2009).

However, trade networks have also shown to be relatively adaptive. For example, following sanctions on Russia related to the annexation of Crimea in 2014, Russia imposed import restrictions on sanctioning countries and imports from these countries declined nearly 60% but the import volume was offset by increased imports from non-sanctioning countries (Gephart et al. 2025) Products previously destined for Russia, such as farmed Atlantic salmon (*Salmo salar*) from Norway, experienced short-term price declines and their trade network shifted toward Europe (Graziano et al., 2018). ~~Other disruptions have indirect impacts on trade. The Russian-Ukraine war, for example, has increased prices for energy and raw materials that fed directly to the high operating costs for fishers, aquaculture farmers and fish-processing companies in the European Union (Frederik, 2022).~~

As a notable, but potentially unique shock, the COVID-19 pandemic disrupted all stages of aquatic food supply chains, but also highlighted many forms of adaptiveness (Love et al., 2021; Nyiawung et al., 2024). For international trade, the earliest impacts were related to China's ban on live animal imports, which, for example, halted live lobster exports to China, and increased congestion at ports due to quarantine closures (Love et al., 2021). Canceled passenger flights also restricted trade of fresh products air freighted in their cargo (Love et al., 2021). The closure of hotels, restaurants and cafes and decreases in tourism was also a major cause of disruption to seafood supplies in many locations (Nyiawung et al., 2024). However, in some cases, suppliers were able to adapt within the global trade network. For example, in the early months of the pandemic, frozen Ecuadorian shrimp destined for China was shifted to the U.S. and European market and Norwegian salmon destined for China was shifted to the U.S. and Brazil (Love et al., 2021). In other cases, suppliers provided local markets through direct selling, as was the case in many locations across the world, with small-scale fisheries producers often stepping-up to provide seafood to their communities (Bassett et al., 2022; Belton et al., 2021; Campbell et al., 2021). For more on COVID-19 impacts, see Chapter 7 of Section 5B.

Environmental impacts stemming from trade

The specific impact of trade on the environment depends upon the environmental, socioeconomic, and regulatory contexts. Trade can theoretically reduce environmental pressures generated by food by shifting production to regions that are more efficient, either due to superior technology or environmental conditions (Yang et al., 2006). By shifting processing to countries with more

efficient processing, trade can reduce environmental footprints by increasing product yields (see Section 5A - Sub Chapter 1e for more on seafood processing). Centralized processing and access to larger markets also creates opportunities for trade to support a more circular economy by supplying byproducts to markets where there are existing alternate uses (e.g., fish heads). Trade can also create opportunities for product substitution that can reduce pressure on poorly managed fisheries, as has been demonstrated for some aquaculture production (Asche, Oglend, et al., 2022).

However, trade can also increase environmental impacts through three mechanisms: 1) increased global demand, 2) shifting sourcing to countries with weaker regulations, and 3) transport-related emissions. Under an open access situation for fishery resources, increased global demand coupled with trade liberalization increases fish prices, motivating increased harvesting effort by exporters. In the absence of entry restrictions or when regulations are weak, this could reduce stocks and catch in the long run, which implies negative environmental impacts from trade (Brander & Taylor, 1998). However, as a corollary, imports into a country with weak management would likely reduce prices and thereby fishing pressure. The net welfare effect will depend on the comparison between the short-run gains and the long-run losses from reduced stocks (Brander & Taylor, 1998). Recent empirical research on the impact of trade on stock status shows mixed evidence. Consistent with theoretical predictions, (Eisenbarth, 2022) shows that exports significantly increase fishery resource depletion. Meanwhile, ~~(~~Erhardt~~,~~ (2018) found that trade liberalization may decrease the likelihood of fishery collapse in countries with lax governance. Trade liberalization may also reshape local governance. For example, a price increase of marine resources in a given exporting country due to demand increase from trade, could affect common-pool resource management (Dietz et al., 2017).

Trade liberalization has also fueled increases in aquaculture production. Because aquaculture requires resource inputs, especially feed, and relies on natural environments, there are different externalities of concern: water pollution from nutrient load and use of antibiotics, escaped fish that could produce genetic contamination, fish disease spread, and pressure on other natural resources because of input demands like feed (Asche, Eggert, et al., 2022; Gephart et al., 2021). Although there is currently no clear evidence as to whether trade is driving increases in aquaculture-related environmental impacts, ~~it is important to consider them~~ any incurred impacts must be weighed in the context of ~~within~~ the broader food system (i.e., how they compare to foods that would be eaten instead) and their nutrient contribution (Gephart & Golden, 2022).

Finally, since diet-related greenhouse gas emissions are dominated by the production stage, which foods are consumed is generally more important than where the food is produced (Halpern et al., 2022; Poore & Nemecek, 2018). Aquatic foods generally result in lower greenhouse emissions than terrestrial animal source foods, meaning that improved seafood availability can reduce dietary emissions when they substitute for higher emission foods (Gephart et al., 2021; Poore & Nemecek, 2018). Yet, transport itself results in greenhouse gas emissions, as transport is responsible for around 10% of life cycle emissions for food (Poore & Nemecek, 2018). Air freighted products, including some high value seafood products, typically have much higher transport emissions. However, the breakdown of transport emissions along the supply chain is not sufficiently well established to compare product emissions for internationally versus more regionally traded products. Nevertheless, transitioning transportation to

renewable sources of energy would reduce the overall life cycle emissions of seafood. Notably, reduced transportation costs that facilitate trade over large distances are partly due lack of internalization of the environmental impacts.

Socio-economic considerations

Seafood trade results in a diverse set of social and economic changes, which depend upon the production and institutional context. Potential impacts stemming from seafood trade generally differ for the industrial and small-scale sectors due to the larger scale and capacity of industrial aquaculture and fisheries supply chains.

Industrial fishing and mariculture production and trade can support income and livelihoods in coastal communities. Empirical evidence on the impact of export-oriented fisheries and aquaculture on local economies suggests that the effect could be significant but depends on local conditions. For example, a recent study of Alaska's fisheries indicates that positive direct effects include an increase in local employment for the fishing crew, more value-added from processed catch, and spillover effect from commercial fishing to non-fishing sectors (Watson et al., 2021). However, industrial scale seafood production also creates many of the most significant challenges associated with seafood production when governance is weak, for example, large-scale distant water fleets have been associated with severe overfishing and forced labor (Decker Sparks & Hasche, 2019; Nakamura et al., 2018).

Mariculture can also represent an important source of revenue, ~~but~~ with the potential to transform coastal communities in a myriad of ways. An example is the salmon farming industry in Chile, currently representing around 6% of the country's total exports of goods. The rise of this industry has transformed the regions where it has developed, resulting in heterogenous impacts across local coastal communities traditionally devoted to small-scale agriculture and artisanal fisheries (Barrett et al., 2002). Developing an export-oriented seafood industry has also been important for employment and settlement along Norway's coast (Johansen et al., 2019). Although the empirical evidence is limited, large-scale aquaculture appears to have contributed to poverty alleviation and reduced income inequality in some remote coastal communities. For example, ~~(~~Ceballos et al.~~,~~ (2018) found that industrial salmon aquaculture reduced poverty in remote coastal areas of southern Chile, while Cárdenas-Retamal et al. (2021) found evidence that this industry also reduced income inequality where it operates.

In the context of small-scale fisheries, the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, the United Nations Declaration on the Rights of Peasants, and Sustainable Development Goal 14.b.1 call for ensuring small-scale fishers' security of tenure and access to resources and markets (FAO, 2022a, 2022b). Small-scale fisheries account for at least 40 percent of global fish landings and although most small-scale fishery landings are marketed domestically, a substantial share of marine small-scale fisheries enters international trade (FAO, 2023). Small-scale fishers, farmers and their communities around the world, however, face barriers to access market for their harvests, as they often lack sufficient marketing facilities, appropriate logistics infrastructure and technology, and access to financial services (e.g. bank account, credit and loan schemes) (Golo & Erinosho, 2023; Kanyimba &

Jonas, 2023). Financial institutions, for example, are hesitant to finance small-scale fishers because the majority of them do not have collateral and bank accounts (Kanyimba & Jonas, 2023). Small-scale producers can also face barriers certification, which can limit access to potential price premiums for exported products (Stratoudakis et al., 2016; Wakamatsu & Wakamatsu, 2017). For more on small-scale fisheries, see S5A.C1b.

Gender dimensions of trade

Forty percent of the labor force in small-scale fisheries-related activities are women (FAO, 2023) and they play an essential role in all aspects of the fisheries value chain (Harper et al., 2013; Pedroza-Gutiérrez & Hapke, 2022). Women are particularly engaged in processing and trade, as trading fish is considered a suitable activity for women in many societies (Overå, 2007; Pedroza-Gutiérrez & Hapke, 2022). However, gender norms and rules vary and while women dominate trade in some places, such as in Ghana, women might not engage in fish trade, or only in certain regions, in other countries, such is the case of India and Mexico (Pedroza-Gutiérrez & Hapke, 2022).

Despite women often playing a central role in fish trade and markets, their labor is largely informal and therefore 'invisible,' underscoring the persistent need for gender-disaggregated statistics. Moreover, women's double burden - considered responsible to manage household and childcare (Kleiber et al., 2017; Weeratunge et al., 2010), limits the possibility of childbearing aged women to spend more hours in the marketplace or to travel to fish markets affecting their income. Therefore, the gendered institutions in fish markets shape trading dynamics, limiting women's participation.

The gendered nature of the fisheries sector results in women often concentrating in local small-retail trade, relegated as helpers, with limited access to wholesale fish markets where higher income fisheries take place. Men often dominate larger scale trade and benefit from a larger economic income obtained from these activities. However, despite the disadvantages for women in securing access to fish, the economic income generated by this activity represents a livelihood strategy that benefits household and local economies. Therefore, to transform existing gendered fish trade dynamics that limit women's participation, it is imperative to give voice to women in fish market governance and improve access rights to resources and training (Oloko et al., 2024).

Role in food security

Aquatic foods are highly nutritious and play a central role in food and nutrition security for billions of people (FAO, 2024; Tigchelaar et al., 2022). In many coastal countries, the majority of landings from small-scale fisheries is consumed in the household, or gifted or bartered with kin and community, thereby directly contributing to local food and nutrition security (March & Failler, 2022; Seto et al., 2024). Aquaculture production may also contribute to local and national food security (Garlock et al., 2022), though there is limited work distinguishing inland and marine aquaculture impacts on food security.

Seafood caught or farmed for sale in local or international markets can directly and indirectly contribute to food and nutrition security. Trade can directly help meet seafood demand in many

countries (Gephart et al., 2024) and imports can be highly important for aquatic food availability (Marin et al., 2024) and provide more affordable nutrients from aquatic foods (Liu et al., 2025). Seafood can also indirectly contribute to food and nutrition security by generating income, which can be used to buy other food (Béné et al., 2015). However, at the same time, seafood trade can have negative food and nutrition securing impacts when highly nutritious products are exported and less nutritious food is imported (e.g., Liverpool-Tasie et al., 2021), or when commercial fishers compete with artisanal and subsistence fishers (Belhabib et al., 2020). This may happen when farmed or wild seafood is only seen for its export value and contribution to the national economy, undervaluing its importance as a source of nutrition (Farmery et al., 2021).

Interactions and competition with other ocean-based economy sectors

In response to increased recognition of the ocean as an economic frontier, industrial scale development has accelerated in the world's ocean over the past two decades (Jouffray et al., 2020). Growth in ocean-based economy sectors such as shipping and port development have created opportunities to further trade. For example, investments in the development of seaports stimulate foreign trade growth in port areas and neighboring regions (Fedorenko et al., 2021). However, the growth of these sectors alongside other ocean-based economy sectors such as mining, energy production, tourism, and marine conservation, has created competition for ocean space and resources, which may constrain seafood landings and impact the livelihoods of fishers (Germond-Duret, 2022; Germond-Duret et al., 2023). Referred to as the 'spatial squeeze', the conflict potential between fisheries and mariculture with these other ocean-based sectors is expected to increase (Stelzenmüller et al., 2022) as fisheries and aquaculture are rarely prioritized in blue economy narratives or related marine spatial planning exercises (Farmery et al., 2021).

Tourism, particularly ecotourism, contributes substantially to GDP growth and total employment in many countries (Cisneros-Montemayor & Sumaila, 2010). Increased tourism can lead to greater domestic seafood trade to meet restaurant demand. For example, deep-bottom fish species account for a substantial component of commercial fishing income in Vanuatu, and this fishery is driven by tourist demand (Vanuatu Fisheries Department, 2016). Tourism can be an important driver of food systems, particularly in developing countries where fisheries play a key role in food and nutrition security of local communities (Degarege & Lovelock, 2020). At the same time, international trade could also supply foreign seafood products to meet tourist demand.

Without appropriate guardrails, f~~F~~urther coastal development is likely to result in impacts on ocean ecosystems, such as physical damage to habitats, waste discharge, oil spills, and noise pollution (e.g. ~~(~~Simpson et al., 2016), leading to degradation of wild-capture fisheries that could reduce the yield of capture fisheries. These environmental changes, coupled with climate change, are projected to negatively impact the food and nutrition security of millions of coastal people as well as affecting trade (Golden et al., 2016; Hicks et al., 2019; Srinivasan et al., 2010). However, if done well, ocean-based economy development can produce synergies~~, though these are not well documented~~. For example, potential fishing opportunities can arise from the development of offshore wind farms (Thatcher et al.,

2024) and programs like the Blue Ports Initiative aim to transform marine ports to promote social, environmental, and economic sustainability.

Sector-relevant governance

The impacts of seafood trade, positive or negative, on local environments, economies, and communities are shaped by the institutional and governance context. Each fishery, small-scale or industrial, can operate in very different forms with a range of governance structures. These governance entities can be seen as the formal and informal rules and norms governing fishing interactions and behavior (Pellowe & Leslie, 2020) and shaping how benefits and externalities accrue along value chains. They create fishery management institutions, which are highly influenced by the fisheries context, and at the same time shape and are shaped by national and global market demands (Eriksson et al., 2015). Formal institutions that depend on human action, related to the State and government regulations, and informal such as self-imposed codes of conduct (Van Assche et al., 2020), all govern marine fisheries around the world (Pellowe & Leslie, 2020). Depending on the context, i~~I~~nformal institutions can promote sustainable fisheries management (~~might have positive impacts on fisheries management and promote sustainability~~ e.g., ~~(~~Pedroza-Gutiérrez & López-Rocha, 2021), or undermine it ~~on the other hand they can also increase IUU fishing activities~~ because they can determine norms of operation that can allow unstainable practices and illegal fishing activities (Etiegni et al., 2017). While trade can create incentives that exacerbate positive or negative features of governance, this section focuses on governance and management structures directly related to trade, namely trade measures aimed at ensuring the sustainability of traded seafood and trade measures focused on ensuring positive health and social benefits.

Trade measures for ensuring sustainability of traded seafood

Rigorous traceability and other verification systems have become increasingly important to reinforce and support sustainable aquaculture practices and fisheries management in the context of globalization. A range of bilateral and international agreements, national import regulations, and private certifications have become prevalent for regulating seafood trade and supporting seafood traceability (Lewis & Boyle, 2017).

The earliest sustainability-focused trade measures for seafood targeted restricting trade in endangered species. National governments have passed laws banning or restricting trade in endangered species, including aquatic species. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international treaty under which all parties subject species listed species in CITES Appendices to to additional trade controls, in compliance with CITES provisions~~, while the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international treaty under which all parties subject listed species to additional trade controls~~. However, relatively few marine species fall within CITES (Vincent et al., 2014), though the set of shark and ray species included was expanded in 2023 (*History of CITES Listing of Sharks (Elasmobranchii) | CITES*, n.d.). Bilateral and regional trade agreements can also include sustainability standards for fisheries and aquaculture products.

Import regulations aimed at restricting markets for IUU-sourced products are becoming increasingly common. IUU practices have been estimated to account for 18% of global fisheries, equating to losses in value worth US$10-23.5 billion annually (Agnew et al., 2009) and reduced economic benefits of roughly US$50 billion a year (Roheim & Sutinen, 2006). As a first layer to reduce market access for IUU-sourced products, the Agreement on Port State Measures, introduced in 2016, was the first binding international agreement to prevent vessels engaged in IUU fishing from using ports and landing their catches. In this way, the PSMA limits the ability of IUU-sourced products from entering national and international markets. As another layer, individual countries or groups of countries have created import regulations that require reporting on seafood sourcing and/or documentation, such as the EU catch certification program and the US Seafood Import Monitoring Program.

Outside national and international regulation, a suite of private labeling and certification schemes rely on traceability and chain of custody systems to ensure seafood from certified sustainable fisheries are accurately identified and sold in the international market (Roheim et al., 2018). Early approaches to promoting sustainable seafood supply chains focused on single-species eco-labels, such as dolphin-safe tuna, and seafood ranking guides, such as the Monterey Bay Aquarium's Seafood Watch program and Ocean Wise. Sustainability and conservation-related certification tools such as the Marine Stewardship Council and the Aquaculture Stewardship Council have expanded and evolved to influence relationships between the actors within the supply chain, as well as buyers and consumers (Bush & Roheim, 2019).

Trade measures to promoting positive health and social outcomes

Trade can benefit human health, through provision of employment opportunities, improved living conditions and improved access to nutritious food, however, it can also result in harm to health and health equity (Hawkes et al., 2009). Yet, clear benefits can be gained by aligning trade policy so that it contributes explicitly to the goal of improving diets and nutrition. Countries such as Ghana and Samoa have attempted to do so, with mixed results (Thow et al., 2014, 2017).

Food products, including seafood, are governed by a variety of national, regional and international food safety rules, guidance and codes of practice aimed at protecting consumers from health hazards. These protections cover such issues as food hygiene, chemical contaminants, and diseases and their compliance with national food standards. International standards, such as those produced through the *Codex Alimentarius* Commission, a joint body of the FAO and the World Health Organization, also aim to improve the safety, quality and fairness of the international food trade. Global improvements in food and nutrition security under an open and inclusive trade regime have contributed to falling levels of undernourishment, better nutrition and greater dietary diversity, and overall economic development (IFPRI, 2018).

Trade can also provide greater income security and improved labor standards that can promote positive health and social outcomes within appropriate governance structures. However, opening trade in countries without appropriate guardrails can create social risks including those stemming from increased in inequality and negative impacts on health (IFPRI, 2018). Significant incidence of debt

entrapment, human rights abuses, forced labor, child labor, or forced child labor in the main seafood hub countries has led to legislative changes making food companies liable for the working conditions behind the goods they sell (Decker Sparks & Hasche, 2019; Nakamura et al., 2018). Multi-level governance approaches are needed to deal with the potential negative effects of market integration on local livelihood options and fishery health (Crona et al., 2015).

Sustainability pathways

The production of seafood ~~remains~~ is unevenly distributed around the world due to differences in environmental conditions, comparative advantages and governance institutions (Smith et al., 2010) and~~,~~ c~~C~~limate change is ~~also~~ already reshaping the distribution of seafood globally (Cheung et al., 2010). Therefore, by 2050 trade ~~must~~ will need play an even more important role in supporting sustainable production and equitably distributing the nutritional and economic benefits stemming from seafood production. Positive outcomes related to trade will need to ~~occur~~ be expanded in food systems spanning from those oriented toward local to global sourcing reflecting local resource endowments and capacities.

Sustainable wild fish and mariculture production is the foundation for sustainable trade of marine foods. Appropriate management must first be in place to enable trade of sustainable products. Trade can also serve as a tool to incentivize better social and environmental performance by limiting markets for illegally caught products that create an unfair playing field, creating opportunities for higher prices for sustainably sourced products, and raising the global standard for products.

However, to realize this opportunity, it is key to strengthen sustainability standards for all seafood and improve traceability systems. Under this scenario, countries ~~have~~ need to adopt~~ed~~ strong import regulations that are inclusive of social and environmental sustainability standards~~,~~ and ~~have~~ coordinate~~d~~ these standards to align reporting criteria and to create interoperable systems ~~to~~ that reduce the burden on industry. To ensure that higher trade standards do not ~~reduce~~ impede market access for lower income countries, countries must coordinate to support these producers in meeting the import standards. This includes equitable investments in processing technology and infrastructure.

To support implementation of trade standards, countries c~~s~~hould invest in tools related to traceability and environmental forensics. For example, b~~B~~lockchain technology provides a distributed recordkeeping system to track claimed seafood product origins and movements (Blaha & Katafono, 2020). The claims include a record of actors and other information can be used to verify the claims and connect trade flows to bad actors. A key area of development are environmental forensic tools. DNA analysis, genomics and biogeochemistry allow identification of species, in some cases allowing subpopulations to be distinguished, testing for wild versus farmed origin, and improved estimation of geographic origin (Boultby et al., 2024; Cusa et al., 2022). ~~Connection to~~Identifying the actors involved allows trade flows to be connected back to vessel information, which can subsequently be linked to production stage activities using remote sensing, satellite imagery, and machine learning that detects destructive and illegal fishing activities, such as dynamite fishing and the presence of IUU fishing vessels and support systems, including bunker ships, transshipment ships, and offshore infrastructure.

While these technologies are rapidly improving, they still require significant investments

(Sumaila et al., 2021) and key knowledge gaps remain with respect to their broad application. The initial phase of adoption has generally involveds industrial, high value fisheries, but as technology systems improve and costs decline, broader adoption is possible. Yet, knowledge gaps remain on equitable expansion to small-scale fisheries and research on strategies for market development that is inclusive of small-scale fisheries remains a priority.

While ensuring the sustainability of traded seafood is important, it does not guarantee on its own that trade positively contributes to human wellbeing. Eliminating existing injustices related to aquatic food trade requires incorporating three interdependent dimensions of justice: distributional (economic structures enable people to have the resources necessary to fully participate), recognitional (social and cultural structures recognize all identities, allowing participation), and representational (political structures ensure voices count in decision making) (Hicks et al., 2022; Schlosberg, 2007). There is no single tool for eliminating injustices related to trade; however, countries can take several steps toward this. First, they can develop meaningfully inclusive processes for crafting trade policies and agreements. Second, they can ensure transparency in decision making processes of trade agreements and policies, and in monitoring of adherence to, and impacts of, adopted trade agreements and policies. As an element of improved transparency, countries support the democratization of information, which requires clear identification of the data and its maintenance with complete metadata and following best practices for open data. Third, if communities choose to export products, they may also aim to capture more economic value in their communities, which could require processing and trade infrastructure and training to ensure products meet safety and sustainability standards.

To arm communities and countries with the information needed to make decisions about trade policies, there is a need for a better understanding and recognition of diverse benefits of aquatic foods. Aquatic foods represent an economically valuable resource, but theyand are increasingly recognized for their high nutrient content and longstanding importance for livelihoods and cultural practices. Clearer pathways are needed to support the inclusion of fisheries and aquaculture in food systems planning, where the focus has been on terrestrial agricultural activities (Farmery et al., 2024). Better understanding of seafoods' diverse values, combined with inclusive decision-making processes, will enable seafood trade to better contribute toward the range of social, environmental, and health goals.

References

Agnew, D. J., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J. R., & Pitcher, T. J. (2009). Estimating the Worldwide Extent of Illegal Fishing. *PLoS ONE*, *4*(2), e4570. https://doi.org/10.1371/journal.pone.0004570

Anderson, J. L., Asche, F., & Garlock, T. (2018). Globalization and commoditization: The transformation of the seafood market. *Journal of Commodity Markets*, *12*, 2–8.

Asche, F., Bellemare, M. F., Roheim, C., Smith, M. D., & Tveteras, S. (2015). Fair Enough? Food Security and the International Trade of Seafood. *World Development*, *67*, 151–160. https://doi.org/10.1016/j.worlddev.2014.10.013

Asche, F., Eggert, H., Oglend, A., Roheim, C. A., & Smith, M. D. (2022). Aquaculture: Externalities and Policy Options. *Review of Environmental Economics and Policy*, *16*(2), 282–305. https://doi.org/10.1086/721055

Asche, F., Oglend, A., & Smith, M. D. (2022). Global markets and the commons: The role of imports in the US wild-caught shrimp market. *Environmental Research Letters*, *17*(4), 045023. https://doi.org/10.1088/1748-9326/ac5b3e

Asche, F., Sogn-Grundvåg, G., & Zhang, D. (2022). Large-scale fisheries during the COVID-19 pandemic: The case of the oceangoing groundfish fleet in Norway. *Marine Policy*, *144*, 105223. https://doi.org/10.1016/j.marpol.2022.105223

Asche, F., Yang, B., Gephart, J. A., Smith, M. D., Anderson, J. L., Camp, E. V., Garlock, T. M., Love, D. C., Oglend, A., & Straume, H.-M. (2022). China's seafood imports—Not for domestic consumption? *Science*, *375*(6579), 386–388. https://doi.org/10.1126/science.abl4756

Barrett, G., Caniggia, M. I., & Read, L. (2002). "There are More Vets than Doctors in Chiloé": Social and Community Impact of the Globalization of Aquaculture in Chile. *World Development*, *30*(11), 1951–1965. https://doi.org/10.1016/S0305-750X(02)00112-2

Bassett, H. R., Sharan, S., Suri, S. K., Advani, S., & Giordano, C. (2022). A comparative study of small-scale fishery supply chains' vulnerability and resilience to COVID-19. *Maritime Studies*, *21*(2), 173–192. https://doi.org/10.1007/s40152-021-00231-4

Belhabib, D., Cheung, W. W. L., Kroodsma, D., Lam, V. W. Y., Underwood, P. J., & Virdin, J. (2020). Catching industrial fishing incursions into inshore waters of Africa from space. *Fish and Fisheries*, *21*(2), 379–392. https://doi.org/10.1111/faf.12436

Bellmann, C., Tipping, A., & Sumaila, U. R. (2016). Global trade in fish and fishery products: An overview. *Marine Policy*, *69*, 181–188. https://doi.org/10.1016/j.marpol.2015.12.019

Belton, B., Rosen, L., Middleton, L., Ghazali, S., Mamun, A.-A., Shieh, J., Noronha, H. S., Dhar, G., Ilyas, M., Price, C., Nasr-Allah, A., Elsira, I., Baliarsingh, B. K., Padiyar, A., Rajendran, S., Mohan, A. B. C., Babu, R., Akester, M. J., Phyo, E. E., … Thilsted, S. H. (2021). COVID-19 impacts and adaptations in Asia and Africa's aquatic food value chains. *Marine Policy*, *129*, 104523. https://doi.org/10.1016/j.marpol.2021.104523

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., & Williams, M. (2015). Feeding 9 billion by 2050 – Putting fish back on the menu. *Food Security*, *7*(2), 261–274. https://doi.org/10.1007/s12571-015-0427-z

Béné, C., Lawton, R., & Allison, E. H. (2010). "Trade Matters in the Fight Against Poverty": Narratives, Perceptions, and (Lack of) Evidence in the Case of Fish Trade in Africa. *World Development*, *38*(7), 933–954. https://doi.org/10.1016/j.worlddev.2009.12.010

Blaha, F., & Katafono, K. (2020). *Blockchain application in seafood value chains*. FAO. https://doi.org/10.4060/ca8751en

Boultby, E. N., Martino, J. C., Baring, R., & Doubleday, Z. A. (2024). Using isotopic fingerprints in gastropod shells to validate commercial production pathway and geographic provenance. *Royal Society Open Science*, *11*(5), 231673. https://doi.org/10.1098/rsos.231673

Branch, T. A., Jensen, O. P., Ricard, D., Ye, Y., & Hilborn, R. (2011). Contrasting Global Trends in Marine Fishery Status Obtained from Catches and from Stock Assessments: Global Trends in Marine Fishery Status. *Conservation Biology*, *25*(4), 777–786. https://doi.org/10.1111/j.1523-1739.2011.01687.x

Brander, J. A., & Taylor, M. S. (1998). Open access renewable resources: Trade and trade policy in a two-country model. *Journal of International Economics*, *44*, 181–209.

Bush, S. R., & Roheim, C. A. (2019). *The shifting politics of sustainable seafood consumerism: Vol. Oxford handbook of political consumerism*. Oxford University Press.

Campbell, S. J., Jakub, R., Valdivia, A., Setiawan, H., Setiawan, A., Cox, C., Kiyo, A., Darman, Djafar, L. F., Rosa, E. D. L., Suherfian, W., Yuliani, A., Kushardanto, H., Muawanah, U., Rukma, A., Alimi, T., & Box, S. (2021). Immediate impact of COVID-19 across tropical small-scale fishing communities. *Ocean & Coastal Management*, *200*, 105485. https://doi.org/10.1016/j.ocecoaman.2020.105485

Cárdenas-Retamal, R., Dresdner-Cid, J., & Ceballos-Concha, A. (2021). Impact assessment of salmon farming on income distribution in remote coastal areas: The Chilean case. *Food Policy*, *101*, 102078. https://doi.org/10.1016/j.foodpol.2021.102078

Cato, J. C., & Dos Santos, C. A. L. (1998). European Union 1997 Seafood-Safety Ban: The Economic Impact on Bangladesh Shrimp Processing. *Marine Resource Economics*, *13*(3), 215–227. https://doi.org/10.1086/mre.13.3.42629235

Ceballos, A., Dresdner-Cid, J. D., & Quiroga-Suazo, M. Á. (2018). Does the location of salmon farms contribute to the reduction of poverty in remote coastal areas? An impact assessment using a Chilean case study. *Food Policy*, *75*, 68–79. https://doi.org/10.1016/j.foodpol.2018.01.009

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, *16*(1), 24–35. https://doi.org/10.1111/j.1365-2486.2009.01995.x

Cisneros-Montemayor, A. M., & Sumaila, U. R. (2010). A global estimate of benefits from ecosystem-based marine recreation: Potential impacts and implications for management. *Journal of Bioeconomics*, *12*(3), 245–268. https://doi.org/10.1007/s10818-010-9092-7

Costello, C., Cao, L., & Gelcich, S. (2019). The future of food from the Sea. *World Resources Institute: Washington, DC, USA*, 2019–11.

Crona, B. I., Van Holt, T., Petersson, M., Daw, T. M., & Buchary, E. (2015). Using social–ecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Global Environmental Change*, *35*, 162–175. https://doi.org/10.1016/j.gloenvcha.2015.07.006

Cusa, M., St John Glew, K., Trueman, C., Mariani, S., Buckley, L., Neat, F., & Longo, C. (2022). A future for seafood point-of-origin testing using DNA and stable isotope signatures. *Reviews in Fish Biology and Fisheries*, *32*(2), 597–621. https://doi.org/10.1007/s11160-021-09680-w

Davis, K. F., Downs, S., & Gephart, J. A. (2020). Towards food supply chain resilience to environmental shocks. *Nature Food*, *2*(1), 54–65. https://doi.org/10.1038/s43016-020-00196-3

Decker Sparks, J. L., & Hasche, L. K. (2019). Complex linkages between forced labor slavery and environmental decline in marine fisheries. *Journal of Human Rights*, *18*(2), 230–245. https://doi.org/10.1080/14754835.2019.1602824

Degarege, G. A., & Lovelock, B. (2020). *Sustainable tourism development and food security in Ethiopia: Policy-making and planning*. Routledge.

Dietz, T., Ostrom, E., & Stern, P. C. (2017). *The struggle to govern the commons*. Routledge.

Eisenbarth, S. (2022). Do exports of renewable resources lead to resource depletion? Evidence from fisheries. *Journal of Environmental Economics and Management*, *112*, 102603. https://doi.org/10.1016/j.jeem.2021.102603

Erhardt, T. (2018). Does International Trade Cause Overfishing? *Journal of the Association of Environmental and Resource Economists*, *5*(4), 695–711. https://doi.org/10.1086/698362

Eriksson, H., Österblom, H., Crona, B., Troell, M., Andrew, N., Wilen, J., & Folke, C. (2015). Contagious exploitation of marine resources. *Frontiers in Ecology and the Environment*, *13*(8), 435–440. https://doi.org/10.1890/140312

Etiegni, C. A., Irvine, K., & Kooy, M. (2017). Playing by whose rules? Community norms and fisheries rules in selected beaches within Lake Victoria (Kenya) co-management. *Environment, Development and Sustainability*, *19*(4), 1557–1575. https://doi.org/10.1007/s10668-016-9799-2

FAO. (2022a). *A policy and legal diagnostic tool for sustainable small-scale fisheries*. FAO. https://doi.org/10.4060/cb8234en

FAO. (2022b). *Applying coherently the human rights framework to small-scale fisheries for achieving multiple Sustainable Development Goals*. FAO. https://doi.org/10.4060/cc3251en

FAO. (2023). *Illuminating Hidden Harvests*. FAO; Duke University; WorldFish ; https://doi.org/10.4060/cc4576en

FAO. (2024). *The State of World Fisheries and Aquaculture 2024*. FAO. https://doi.org/10.4060/cd0683en

Farmery, A. K., Allison, E. H., Andrew, N. L., Troell, M., Voyer, M., Campbell, B., Eriksson, H., Fabinyi, M., Song, A. M., & Steenbergen, D. (2021). Blind spots in visions of a "blue economy" could undermine the ocean's contribution to eliminating hunger and malnutrition. *One Earth*, *4*(1), 28–38. https://doi.org/10.1016/j.oneear.2020.12.002

Farmery, A. K., Delisle, A., & Tioti, R. (2024). Clearer pathways needed to engage small-scale fisheries in food system planning: Lessons from the Pacific experience. *One Earth*, *7*(10), 1660–1664. https://doi.org/10.1016/j.oneear.2024.09.012

Fedorenko, R., Yakhneeva, I., Zaychikova, N., & Lipinsky, D. (2021). Evaluating the Socio-Economic Factors Impacting Foreign Trade Development in Port Areas. *Sustainability*, *13*(15), 8447. https://doi.org/10.3390/su13158447

Frederik, S. (2022). *Russia's war on Ukraine: Support for the fishing, aquaculture and fish-processing sectors*. EPRS: European Parliamentary Research Service. https://coilink.org/20.500.12592/rp378s

Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2018). Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution*, *2*(11), Article 11. https://doi.org/10.1038/s41559-018-0669-1

Garlock, T., Asche, F., Anderson, J., Ceballos-Concha, A., Love, D. C., Osmundsen, T. C., & Pincinato, R. B. M. (2022). Aquaculture: The missing contributor in the food security agenda. *Global Food Security*, *32*, 100620. https://doi.org/10.1016/j.gfs.2022.100620

Gephart, J. A., Agrawal Bejarano, R., Gorospe, K., Godwin, A., Golden, C. D., Naylor, R. L., Nash, K. L., Pace, M. L., & Troell, M. (2024). Globalization of wild capture and farmed aquatic foods. *Nature Communications*, *15*(1), 8026. https://doi.org/10.1038/s41467-024-51965-8

Gephart, J. A., Deutsch, L., Pace, M. L., Troell, M., & Seekell, D. A. (2017). Shocks to fish production: Identification, trends, and consequences. *Global Environmental Change*, *42*, 24–32. https://doi.org/10.1016/j.gloenvcha.2016.11.003

Gephart, J. A., & Golden, C. D. (2022). Environmental and nutritional double bottom lines in aquaculture. *One Earth*, *5*(4), 324–328. https://doi.org/10.1016/j.oneear.2022.03.018

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature*, *597*(7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L., & Brännström, Å. (2016). Vulnerability to shocks in the global seafood trade network. *Environmental Research Letters*, *11*(3), 035008. https://doi.org/10.1088/1748-9326/11/3/035008

Gephart, J. A., Maxson, P., Simeone, J., Agrawal Bejarano, R., Anderson, C. M., Asche, F., Barnes, J., Hauser, L., Love, D. C., Mallory, T., & Smith, M. D. (2025). Existing seafood traceability tools are insufficient for enforcing import restrictions. Npj Ocean Sustainability, 4(1), 6. https://doi.org/10.1038/s44183-025-00103-y

Germond-Duret, C. (2022). Framing the Blue Economy: Placelessness, Development and Sustainability. *Development and Change*, *53*(2), 308–334. https://doi.org/10.1111/dech.12703

Germond-Duret, C., Heidkamp, C. P., & Morrissey, J. (2023). (In)justice and the blue economy. *The Geographical Journal*, *189*(2), 184–192. https://doi.org/10.1111/geoj.12483

Gillett, R. (2009). *Fisheries in the economies of the Pacific island countries and territories*. Asian Development Bank.

Golden, C. D., Allison, E. H., Cheung, W. W. L., Dey, M. M., Halpern, B. S., McCauley, D. J., Smith, M., Vaitla, B., Zeller, D., & Myers, S. S. (2016). Nutrition: Fall in fish catch threatens human health. *Nature News*, *534*(7607), 317. https://doi.org/10.1038/534317a

Golo, H. K., & Erinosho, B. (2023). Tackling the challenges confronting women in the Elmina fishing community of Ghana: A human rights framework. *Marine Policy*, *147*, 105349. https://doi.org/10.1016/j.marpol.2022.105349

Graziano, M., Fox, C. J., Alexander, K., Pita, C., Heymans, J. J., Crumlish, M., Hughes, A., Ghanawi, J., & Cannella, L. (2018). Environmental and socio-political shocks to the seafood sector: What does this mean for resilience? Lessons from two UK case studies, 1945–2016. *Marine Policy*, *87*, 301–313. https://doi.org/10.1016/j.marpol.2017.10.014

Halpern, B. S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J. L., Cottrell, R. S., Froehlich, H. E., Gephart, J. A., Jacobsen, N. S., Kuempel, C. D., McIntyre, P. B., Metian, M., Moran, D., Nash, K. L., Többen, J., & Williams, D. R. (2022). The environmental footprint of global food

production. *Nature Sustainability*, *5*(12), 1027–1039. https://doi.org/10.1038/s41893-022-00965-x

Harper, S., Zeller, D., Hauzer, M., Pauly, D., & Sumaila, U. R. (2013). Women and fisheries: Contribution to food security and local economies. *Marine Policy*, *39*, 56–63. https://doi.org/10.1016/j.marpol.2012.10.018

Hawkes, C., Chopra, M., & Friel, S. (2009). Globalization, Trade, and the Nutrition Transition. In *Globalization and Health*. Routledge.

Hicks, C. C., Cohen, P. J., Graham, N. A. J., Nash, K. L., Allison, E. H., D'Lima, C., Mills, D. J., Roscher, M., Thilsted, S. H., Thorne-Lyman, A. L., & MacNeil, M. A. (2019). Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, *574*(7776), 95–98. https://doi.org/10.1038/s41586-019-1592-6

Hicks, C. C., Gephart, J. A., Koehn, J. Z., Nakayama, S., Payne, H. J., Allison, E. H., Belhbib, D., Cao, L., Cohen, P. J., Fanzo, J., Fluet-Chouinard, E., Gelcich, S., Golden, C. D., Gorospe, K. D., Isaacs, M., Kuempel, Caitlin. D., Lee, K. N., MacNeil, M. A., Maire, E., … Naylor, R. L. (2022). Rights and representation support justice across aquatic food systems. *Nature Food*, *3*(10), 851–861. https://doi.org/10.1038/s43016-022-00618-4

History of CITES listing of sharks (Elasmobranchii) | CITES. (n.d.). Retrieved March 16, 2025, from https://cites.org/eng/prog/shark/history.php

IFPRI. (2018). *Trade: The free flow of goods and food security and nutrition* (0 ed.). International Food Policy Research Institute. https://doi.org/10.2499/9780896292970_03

Johansen, U., Bull-Berg, H., Vik, L. H., Stokka, A. M., Richardsen, R., & Winther, U. (2019). The Norwegian seafood industry – Importance for the national economy. *Marine Policy*, *110*, 103561. https://doi.org/10.1016/j.marpol.2019.103561

Jouffray, J.-B., Blasiak, R., Norström, A. V., Österblom, H., & Nyström, M. (2020). The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. *One Earth*, *2*(1), 43–54. https://doi.org/10.1016/j.oneear.2019.12.016

Kanyimba, A. T., & Jonas, M. N. (2023). Barriers to Integrating Financial Inclusion for Coastal Small-Scale Fishermen into Namibian Fisheries Policies and Regulatory Frameworks. In H. Chitimira & T. V. Warikandwa (Eds.), *Financial Inclusion and Digital Transformation Regulatory Practices in Selected SADC Countries* (Vol. 106, pp. 323–350). Springer International Publishing. https://doi.org/10.1007/978-3-031-23863-5_15

Kleiber, D., Frangoudes, K., Snyder, H. T., Choudhury, A., Cole, S. M., Soejima, K., Pita, C., Santos, A., McDougall, C., Petrics, H., & Porter, M. (2017). Promoting Gender Equity and Equality Through the Small-Scale Fisheries Guidelines: Experiences from Multiple Case Studies. In S. Jentoft, R. Chuenpagdee, M. J. Barragán-Paladines, & N. Franz (Eds.), *The Small-Scale Fisheries Guidelines* (Vol. 14, pp. 737–759). Springer International Publishing. https://doi.org/10.1007/978-3-319-55074-9_35

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., & Sumaila, U. R. (2016). Projected change in global fisheries revenues under climate change. *Scientific Reports*, *6*(1), Article 1. https://doi.org/10.1038/srep32607

Lewis, S. G., & Boyle, M. (2017). The Expanding Role of Traceability in Seafood: Tools and Key Initiatives. *Journal of Food Science*, *82*(S1). https://doi.org/10.1111/1750-3841.13743

Liu, Y., Smith, M. D., Abbott, J. K., Dietz, D., Colson Leaning, D., Smyth, A., & Yamashita, T. (2025). The global seafood trade, embodied nutrients, and nutritional affordability. *Nature Communications*, *16*(1). https://doi.org/10.1038/s41467-025-61012-9

Liverpool-Tasie, L. S. O., Sanou, A., Reardon, T., & Belton, B. (2021). Demand for Imported versus Domestic Fish in Nigeria. *Journal of Agricultural Economics*, *72*(3), 782–804. https://doi.org/10.1111/1477-9552.12423

Love, D. C., Allison, E. H., Asche, F., Belton, B., Cottrell, R. S., Froehlich, H. E., Gephart, J. A., Hicks, C. C., Little, D. C., Nussbaumer, E. M., Pinto da Silva, P., Poulain, F., Rubio, A., Stoll, J. S., Tlusty, M. F., Thorne-Lyman, A. L., Troell, M., & Zhang, W. (2021). Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Global Food Security*, *28*, 100494. https://doi.org/10.1016/j.gfs.2021.100494

March, A., & Failler, P. (2022). Small-scale fisheries development in Africa: Lessons learned and best practices for enhancing food security and livelihoods. *Marine Policy*, *136*, 104925. https://doi.org/10.1016/j.marpol.2021.104925

Marchand, P., Carr, J. A., Dell'Angelo, J., Fader, M., Gephart, J. A., Kummu, M., Magliocca, N. R., Porkka, M., Puma, M. J., Ratajczak, Z., Rulli, M. C., Seekell, D. A., Suweis, S., Tavoni, A., & D'Odorico, P. (2016). Reserves and trade jointly determine exposure to food supply shocks. *Environmental Research Letters*, *11*(9), 095009. https://doi.org/10.1088/1748-9326/11/9/095009

Marin, C., Adewumi, O. M., Asche, F., Garlock, T. M., Kristofersson, D. M., Lorenzen, K., & Yang, B. (2024). Does seafood trade enhance seafood availability in developing countries? The case of Nigeria. *Marine Policy*, *161*, 106030. https://doi.org/10.1016/j.marpol.2024.106030

Nakamura, K., Bishop, L., Ward, T., Pramod, G., Thomson, D. C., Tungpuchayakul, P., & Srakaew, S. (2018). Seeing slavery in seafood supply chains. *Science Advances*, *4*(7), e1701833. https://doi.org/10.1126/sciadv.1701833

Nash, K. L., MacNeil, M. A., Blanchard, J. L., Cohen, P. J., Farmery, A. K., Graham, N. A. J., Thorne-Lyman, A. L., Watson, R. A., & Hicks, C. C. (2022). Trade and foreign fishing mediate global marine nutrient

supply. *Proceedings of the National Academy of Sciences*, *119*(22), e2120817119. https://doi.org/10.1073/pnas.2120817119

Naylor, R. L., Kishore, A., Sumaila, U. R., Issifu, I., Hunter, B. P., Belton, B., Bush, S. R., Cao, L., Gelcich, S., Gephart, J. A., Golden, C. D., Jonell, M., Koehn, J. Z., Little, D. C., Thilsted, S. H., Tigchelaar, M., & Crona, B. (2021). Blue food demand across geographic and temporal scales. *Nature Communications*, *12*(1), 5413. https://doi.org/10.1038/s41467-021-25516-4

Nyiawung, R. A., Ehrlick, T., Bennett, N. J., Brunet, N. D., Matos, F., Pita, C., Stoll, J. S., & Loring, P. A. (2024). Fisheries and the COVID-19 pandemic: A global scoping review of the early pressures, impacts, and responses in least developed, emerging, and developed countries. *Regional Studies in Marine Science*, *74*, 103501. https://doi.org/10.1016/j.rsma.2024.103501

Oloko, A., Harper, S., Fakoya, K., & Sumaila, U. R. (2024). The multi-dimensional perspectives of taboos on gender roles of fisherfolk in the Global South. *Maritime Studies*, *23*(1), 1. https://doi.org/10.1007/s40152-023-00340-2

Overå, R. (2007). When men do women's work: Structural adjustment, unemployment and changing gender relations in the informal economy of Accra, Ghana. *The Journal of Modern African Studies*, *45*(4), 539–563. https://doi.org/10.1017/S0022278X0700287X

Pedroza-Gutiérrez, C., & Hapke, H. M. (2022). Women's work in small-scale fisheries: A framework for accounting its value. *Gender, Place & Culture*, *29*(12), 1733–1750. https://doi.org/10.1080/0966369X.2021.1997936

Pedroza-Gutiérrez, C., & López-Rocha, J. A. (2021). Ungovernable systems: The strength of informal institutions in the sea cucumber fishery in Yucatan, Mexico. *PLOS ONE*, *16*(3), e0249132. https://doi.org/10.1371/journal.pone.0249132

Pellowe, K. E., & Leslie, H. M. (2020). The interplay between formal and informal institutions and the potential for co-management in a Mexican small-scale fishery. *Marine Policy*, *121*, 104179. https://doi.org/10.1016/j.marpol.2020.104179

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987–992. https://doi.org/10.1126/science.aaq0216

Rice, E., Bennett, A., Smith, M., Liverpool-Tasie, L. S., Katengeza, S., Infante, D., & Tschirley, D. (2024). Price volatility in fish food systems: Spatial arbitrage as an adaptive strategy for small-scale fish traders. *Ecology and Society*, *29*(2), art13. https://doi.org/10.5751/ES-15076-290213

Roheim, C. A., Bush, S. R., Asche, F., Sanchirico, J. N., & Uchida, H. (2018). Evolution and future of the sustainable seafood market. *Nature Sustainability*, *1*(8), 392–398. https://doi.org/10.1038/s41893-018-0115-z

Roheim, C. A., & Sutinen, J. (2006). *Trade and Market-Related Instruments to Reinforce Fisheries Management Measures to Promote Sustainable Fishing Practices* (Report for the International Centre for Trade and Sustainable Development, Geneva, Switzerland, and the Organization for Economic Cooperation and Development – High Seas Task Force).

Schlosberg, D. (2007). *Defining Environmental Justice: Theories, Movements, and Nature*. OUP Oxford.

Seto, K. L., Friedman, W. R., Eurich, J. G., Gephart, J. A., Zamborain-Mason, J., Sharp, M., Aram, E., Tekaieti, A., Tekiau, A., & Golden, C. D. (2024). Characterizing pathways of seafood access in small island developing states. *Proceedings of the National Academy of Sciences*, *121*(7), e2305424121. https://doi.org/10.1073/pnas.2305424121

Simpson, S. D., Radford, A. N., Nedelec, S. L., Ferrari, M. C. O., Chivers, D. P., McCormick, M. I., & Meekan, M. G. (2016). Anthropogenic noise increases fish mortality by predation. *Nature Communications*, *7*(1), 10544. https://doi.org/10.1038/ncomms10544

Smith, M. D., Roheim, C. A., Crowder, L. B., Halpern, B. S., Turnipseed, M., Anderson, J. L., Asche, F., Bourillón, L., Guttormsen, A. G., Khan, A., Liguori, L. A., McNevin, A., O'Connor, M. I., Squires, D., Tyedmers, P., Brownstein, C., Carden, K., Klinger, D. H., Sagarin, R., & Selkoe, K. A. (2010). Sustainability and Global Seafood. *Science*, *327*(5967), 784–786. https://doi.org/10.1126/science.1185345

Srinivasan, U. T., Cheung, W. W. L., Watson, R., & Sumaila, U. R. (2010). Food security implications of global marine catch losses due to overfishing. *Journal of Bioeconomics*, *12*(3), 183–200. https://doi.org/10.1007/s10818-010-9090-9

Stelzenmüller, V., Letschert, J., Gimpel, A., Kraan, C., Probst, W. N., Degraer, S., & Döring, R. (2022). From plate to plug: The impact of offshore renewables on European fisheries and the role of marine spatial planning. *Renewable and Sustainable Energy Reviews*, *158*, 112108. https://doi.org/10.1016/j.rser.2022.112108

Stratoudakis, Y., McConney, P., Duncan, J., Ghofar, A., Gitonga, N., Mohamed, K. S., Samoilys, M., Symington, K., & Bourillon, L. (2016). Fisheries certification in the developing world: Locks and keys or square pegs in round holes? *Fisheries Research*, *182*, 39–49. https://doi.org/10.1016/j.fishres.2015.08.021

Straume, H.-M., Asche, F., Oglend, A., Abrahamsen, E. B., Birkenbach, A. M., Langguth, J., Lanquepin, G., & Roll, K. H. (2022). Impacts of Covid-19 on Norwegian salmon exports: A firm-level analysis. *Aquaculture*, *561*, 738678. https://doi.org/10.1016/j.aquaculture.2022.738678

Sumaila, U. R. (2019). A Carding System as an Approach to Increasing the Economic Risk of Engaging in IUU Fishing? *Frontiers in Marine Science*, *6*, 34. https://doi.org/10.3389/fmars.2019.00034

Sumaila, U. R., Walsh, M., Hoareau, K., Cox, A., Teh, L., Abdallah, P., Akpalu, W., Anna, Z., Benzaken, D., Crona, B., Fitzgerald, T., Heaps, L., Issifu, I., Karousakis, K., Lange, G. M., Leland, A., Miller, D.,

Sack, K., Shahnaz, D., … Zhang, J. (2021). Financing a sustainable ocean economy. *Nature Communications*, *12*(1), 3259. https://doi.org/10.1038/s41467-021-23168-y

Swartz, W., Rashid Sumaila, U., Watson, R., & Pauly, D. (2010). Sourcing seafood for the three major markets: The EU, Japan and the USA. *Marine Policy*, *34*(6), 1366–1373. https://doi.org/10.1016/j.marpol.2010.06.011

Tamea, S., Laio, F., & Ridolfi, L. (2016). Global effects of local food-production crises: A virtual water perspective. *Scientific Reports*, *6*(1), 18803. https://doi.org/10.1038/srep18803

Thatcher, H., Stamp, T., Moore, P. J., & Wilcockson, D. (2024). Using fisheries-dependent data to investigate landings of European lobster (*Homarus gammarus*) within an offshore wind farm. *ICES Journal of Marine Science*, fsad207. https://doi.org/10.1093/icesjms/fsad207

Thow, A. M., Annan, R., Mensah, L., & Chowdhury, S. N. (2014). Development, implementation and outcome of standards to restrict fatty meat in the food supply and prevent NCDs: Learning from an innovative trade/food policy in Ghana. *BMC Public Health*, *14*(1), 249. https://doi.org/10.1186/1471-2458-14-249

Thow, A. M., Reeve, E., Naseri, T., Martyn, T., & Bollars, C. (2017). Food supply, nutrition and trade policy: Reversal of an import ban on turkey tails. *Bulletin of the World Health Organization*, *95*(10), 723–725. https://doi.org/10.2471/BLT.17.192468

Tigchelaar, M., Leape, J., Micheli, F., Allison, E. H., Basurto, X., Bennett, A., Bush, S. R., Cao, L., Cheung, W. W. L., Crona, B., DeClerck, F., Fanzo, J., Gelcich, S., Gephart, J. A., Golden, C. D., Halpern, B. S., Hicks, C. C., Jonell, M., Kishore, A., … Wabnitz, C. C. C. (2022). The vital roles of blue foods in the global food system. *Global Food Security*, *33*, 100637. https://doi.org/10.1016/j.gfs.2022.100637

Van Assche, K., Hornidge, A.-K., Schlüter, A., & Vaidianu, N. (2020). Governance and the coastal condition: Towards new modes of observation, adaptation and integration. *Marine Policy*, *112*, 103413. https://doi.org/10.1016/j.marpol.2019.01.002

Vanuatu Fisheries Department. (2016). *Vanuatu National Deep-Bottom Fish Fishery Management Plan*. The Pacific Community.

Vincent, A. C. J., Sadovy De Mitcheson, Y. J., Fowler, S. L., & Lieberman, S. (2014). The role of CITES in the conservation of marine fishes subject to international trade. *Fish and Fisheries*, *15*(4), 563–592. https://doi.org/10.1111/faf.12035

Wakamatsu, M., & Wakamatsu, H. (2017). The certification of small-scale fisheries. *Marine Policy*, *77*, 97–103. https://doi.org/10.1016/j.marpol.2016.12.016

Watson, B., Reimer, M. N., Guettabi, M., & Haynie, A. (2021). Commercial fisheries & local economies. *Journal of Environmental Economics and Management*, *106*, 102419. https://doi.org/10.1016/j.jeem.2021.102419

Weeratunge, N., Snyder, K. A., & Sze, C. P. (2010). Gleaner, fisher, trader, processor: Understanding gendered employment in fisheries and aquaculture. *Fish and Fisheries*, *11*(4), 405–420. https://doi.org/10.1111/j.1467-2979.2010.00368.x

Yang, H., Wang, L., Abbaspour, K. C., & Zehnder, A. J. B. (2006). Virtual water trade: An assessment of water use efficiency in the international food trade. *Hydrology and Earth System Sciences*, *10*(3), 443–454. https://doi.org/10.5194/hess-10-443-2006

Yunus, M. (2009). EU Ban, HACCP Compliance and Shrimp Exports from Bangladesh. *The Bangladesh Development Studies*, *32*(3), 41–57.

Section 5A
Chapter 2: Recreational fishing

Coordinating Author: Sean Tracey
Writing Team: Sean Tracey, Robert Arlinghaus, Asta Audzjionyte, Steven J. Cooke, Kátia Meirelles Felizola Freire, Dong-Hun Go, Meaghan Guckian, Kieran Hyder, Warren Potts, Pedro Pintassilgo, Karina Ryan, Alicia Bugeja Said
GOE Lead/Co-Lead: Chang-Ik Zhang/Eric Okuku

Key findings

- Marine recreational fishing is a widely practiced activity with substantial economic and ecological impacts, especially in coastal ecosystems. ~~Marine recreational fishing is a globally popular activity with significant economic and ecological implications, particularly in coastal ecosystems.~~
- Marine recreational fisheries generate billions of dollars annually, particularly in developed nations. ~~Globally, marine recreational fisheries contribute billions annually, especially in developed countries.~~
- Many marine recreational fisheries remain informally recognized, creating governance challenges for sustainability.~~Many Marine Recreational Fisheries lack formal recognition, posing challenges for sustainable governance~~.
- Effective management requires addressing data gaps for data-driven management including integration of socio-economic factors, fostering stakeholder collaboration and implementing equity-focused management frameworks and integrated governance, and promoting stewardship and compliance through education.

Introduction

Defined as fishing of aquatic animals (mainly fish) that do not constitute the individual's primary resource to meet basic nutritional needs and are not generally sold or otherwise traded on export, domestic or black markets (FAO, 2012), recreational fishing takes place in about three-quarters of the world's Exclusive Economic Zones (EEZs) (Mora and others, 2009). Globally, an estimated 300 million people participate in recreational fishing each year, generating at least US$47 billion in expenditure (Arlinghaus and others, 2019; Cisneros-Montemayor and Sumaila, 2010). Many recreational fishers engage in both freshwater and marine recreational fisheries (MRF), which makes it challenging to estimate the number of marine recreational fishers. One global estimate suggests that 121 million people worldwide participate in marine based recreational fishing (Cisneros-Montemayor and Sumaila, 2010).

In countries with reliable statistics, participation rates in recreational fishing average around 10% of the total population, translating to approximately 140 million anglers in North America, Europe, and Oceania alone (Arlinghaus and others, 2015). Participation rates vary significantly by country. For example, more than 40% of Norwegians (Arlinghaus

and others, 2015) and 21% of Australians (Moore and others, 2023) engage in recreational fishing, primarily marine fishing. Other countries, such as Brazil, report lower participation rates (about 1%) (Freire and others, 2016), but these lower numbers are likely to be influenced by data gaps on recreational fisheries (FAO, 2012). In China, recreational fishing is the fastest growing fishing sector (Ding and others, 2021) and similar trends are also observed in other developing countries in Asia and Africa (Kadagi and Wambiji, 2021), encouraged by changing social norms, economic development and tourism (Coleman and others, 2004; Cooke and Cowx, 2004).

The focus of this chapter is on MRFs rather than freshwater recreational fisheries. The importance of integrating recreational fisheries into marine fisheries conservation and management extends beyond the ecological impacts of excessive recreational harvest (Altieri and others, 2012; Lewin and others, 2006; Lewin and others, 2019). Marine recreational fisheries provide significant social and economic benefits to communities and participants (Hyder and others, 2018). For example, it supports employment in retail, boating, tourism, and related sectors, and offers public health benefits by encouraging outdoor activities and supporting nutritional security (Cooke and others, 2018; Henry and Lyle, 2003). In ~~many~~ some coastal areas, the economic value of recreational fisheries exceeds that of small-scale commercial fisheries (Strehlow and others, 2023). For individual participants, the value of recreational fisheries lies in the generation of psycho-social benefits, relaxation and access to self-caught fish (Parkkila and others, 2010) . Furthermore, MRF fosters conservation awareness, strengthening the connection between fishers and marine ecosystems (Barnett and others, 2016) and promoting broader stewardship efforts (Shephard and others, 2023; Shephard and others, 2024). The socio-economic and ecological significance of recreational fishing underscores the need for sustainable, scientifically informed management practices in marine environments, addressing the needs, impacts, and socio-economic importance of MRF (Cowx and others, 2010; Hyder and others, 2018; Hyder and others, 2020).

Certain marine and coastal aquatic species are either solely exploited by recreational fishers or co-exploited alongside commercial and customary fisheries (Arlinghaus and others, 2019; Arlinghaus and others, 2023; Hyder and others, 2018; Ihde and others, 2011; Mora and others, 2009). Given the large number of people engaged in MRF, the impacts are diverse and include: 1) potentially high harvest rates of fish and other animals, which can reduce population abundance; 2) selective removal of specific species, sizes, and genotypes, leading to truncated age and size structures, and potential trophic cascades that may affect ecosystem stability, ecological interactions, genetic diversity, and adaptive potential; 3) habitat modification and disturbance from trampling, boating, anchoring, and bait collection; 4) pollution from lost or discarded fishing gear; and 5) the introduction of invasive species via bait transfer - reviewed in (Lewin and others, 2006) and (Lewin and others, 2019). These impacts vary by location and fishery, underscoring the need for local evidence to better understand the relative importance and consequences of these pressures.

Recreational fisheries are by no means the only source of impact on coastal fish populations, and, while comprehensive global assessments are limited, marine fish

populations are generally more heavily affected by industrial commercial fisheries than by coastal recreational fisheries. However, in cases where recreational fishing focuses on specific coastal species that are easily targeted, these fish populations may be predominantly harvested by recreational fishers (Altieri and others, 2012; Kleiven and others, 2016). In some cases, recreational fisheries contribute up to 100% of the harvest for specific coastal fish populations in places like Australia, and the USA (Coleman and others, 2004; Tracey and Stark, 2024).

As the economic situation improves in many countries, motivations for recreational fishing are shifting from food provision to leisure and experience (Kleiven and others, 2020). These non-catch benefits (e.g., enjoying nature) mean recreational fishing effort often remains steady despite declining fish populations, unlike commercial fisheries, where fishing effort often correlates with stock levels and expected gains (Kleiven and others, 2020; Post and others, 2002). Recreational fishing effort also surged in many regions during the COVID-19 pandemic, though the long-term sustainability of this increase is uncertain (Audzijonyte and others, 2023; Britton and others, 2023; Kaz and others, 2024).

Despite its popularity, most countries do not require reporting of marine recreational catch, except for specific species or regions (Coleman and others, 2004). For example, in Brazil, only tournament catches must be reported, but compliance remains low. The European Union (EU) recently mandated MRF catch reporting, though implementation across member states will take years. Consequently, estimates of total MRF catches and harvests are highly uncertain. The Global Sea Around Us Project (Freire and others, 2020) estimates global marine recreational landings at over 900,000 tonnes annually in 2014. Independent estimates suggest annual removals of around 200,000-300,000 tonnes in the USA (Andrews and others, 2018; Cooke and Cowx, 2004), 350,000 tonnes in the EU (Hyder and others, 2018), and 25,000-30,000 tonnes in Australia (Henry and Lyle, 2003) and New Zealand (Southwick and others, 2018). The actual catch from recreational fishing is likely to be much higher when considering fish that are caught and released (Coggins Jr and others, 2007), and the impacts of post-release stress and mortality likely contribute a significant source of unaccounted mortality in some fisheries (Cooke and Suski, 2005).

Catch-and-release (C&R) is widely practiced, with an estimated 60% of recreational catches released globally (Cooke and Cowx, 2004), with estimates ranging widely based on country, fishery and species (Ferter and others, 2013; Lennox and others, 2017). The practice occurs to comply with management regulations (e.g., bag limits, size limits) or voluntarily where a fisher chooses to release a fish that could be legally harvested (Ferter and others, 2013). The impact of C&R practices is complex, and post-release mortality varies across species depending on factors such as depth, gear used, fisher behaviour, fish handling times, water temperatures, and species biology (Brownscombe and others, 2017). In addition to direct post-release mortality and barotrauma injuries—which are particularly relevant in deep marine environments—other potential negative impacts of C&R include hook-related injuries, effects on growth and reproduction, increased predation risk after release, and reduced reproductive success if fish are caught and released during

reproductive activities (Arlinghaus and others, 2007). In some cases, such as fishing at great depths or in areas with high predation pressure, post-release mortality rates can be extremely high, raising ethical concerns about whether releasing fish could be considered "wasting" fish (Coggins Jr and others, 2007).

As management of recreational fisheries and social norms may shift towards lower reliance on fishing for food in more developed nations, release rates are likely to further rise in some cultures, especially when the release is perceived as a conservation measure that reduces mortality. Alternatively, in some countries (e.g., Germany and Switzerland), release rates may decrease because C&R is viewed as an unethical practice—playing with animals without a purpose—a perspective held in certain individuals and cultures (Arlinghaus and others, 2012). In these countries only fishing for food is considered morally acceptable, and indeed the primary motivation for catching fish is for food (e.g., Atlantic cod, *Gadus morhua*, (Bronnmann and others, 2023) in many countries.

Beyond the direct impacts of harvesting and C&R fishing, recreational fishers are often highly selective, targeting the largest individuals and predatory fish (Flink and others, 2024; Lewin and others, 2006). Recreational fishing also disproportionately removes more active and bolder fish (Biro and Post, 2008; Klefoth and others, 2017; Sbragaglia and others, 2024), which may have higher reproductive success and adaptive potential (Sutter and others, 2012). Size and otherwise trait-selective removal of predatory species can affect ecosystem trophic structure by altering and changing natural species composition and reducing predatory control (Lewin and others, 2019).

Pressures

Over the past decade, changes in the impacts of MRF on ecosystems and fish populations have been driven primarily by: 1) a growing human population, especially in coastal areas, where currently about 15% of the global population lives within 10 km of the coast (Cosby and others, 2024); 2) rapid advances in gear and technology, allowing recreational fishers to detect and target specific species, access previously unreachable areas, and use increasingly effective lures and baits (Cooke and others, 2021); and 3) the rise of communication technologies, which facilitate rapid information exchange and shift societal norms, with both positive and negative effects on marine ecosystems (Cooke and others, 2021). While the total global estimated MRF harvest constitutes only about 1% of total commercial landings, recreational removals are generally concentrated in the narrow band of coastal area and its impacts are most intense in localised areas (Coleman and others, 2004). Given its potential intensity and environmental impact, the sustainability of recreational fisheries is a growing concern (Lewin and others, 2006; Lewin and others, 2019), which involves both ecological but also social and governance related issues (Coleman and others, 2004; Cooke and Cowx, 2004; Grati and others, 2024).

The cumulative impacts of recreational fishers on marine habitats extends beyond fish harvest and include disturbances from boating, anchoring, and shore-based activities. In Australia, for example, there are 0.9 million recreational vessels, which is 50 times the

number of artisanal and industrial vessels combined[42], and this level of boat ownership is not uncommon in developed countries. Boating activity can locally impact habitats like reef systems and seagrass beds when anchors are deployed or propellor wash disturbing habitat in shallow areas, though global impacts remain relatively low (Lewin and others, 2019). Shore-based fishing and bait collection can also degrade fragile habitats, particularly in high-use areas (Lewin and others, 2006).

Like all fishing, some recreational fishing gear is lost, contributing to the abandoned, lost or otherwise discarded fishing gear (ALDFG) problem (Watson and others, 2022a). Overall, the ALDFG impacts from MRF are considered relatively small, when compared with commercial fishing activities, given that gears themselves are generally small, and are not regularly lost (Bornt and others, 2023; Lewin and others, 2019).

As recreational fishing remains largely unreported and, in many cases, unregulated it is often overlooked as a component of global fisheries (Arlinghaus and others, 2019). Common regulations include licensing, gear restrictions, spatial and temporal closures, daily catch limits, and size limits. However, total effort and catches are rarely restricted at the population level, and less popular species often lack size or catch limits. Compliance monitoring is often challenging, especially in remote areas or when recreational fishing effort is relatively low and dispersed, and many recreational fishers may not be even aware of regulatory requirements (Freire and others, 2012; Ryan and others, In Press; Venerus and Cedrola, 2017).

To summarize: key sustainability challenges in recreational fisheries include declines in biomass, truncations in fish size and age through harvest, and intensified local fishing efforts that can threaten biodiversity, fish populations, and, in extreme cases, lead to trophic cascades (Altieri and others, 2012), Other challenges include the introduction of non-native species via recreational gear, the lack of consideration of recreational fisheries in marine spatial planning and fisheries management (Arlinghaus and others, 2023; Hyder and others, 2018; Ihde and others, 2011), and the difficulties of obtaining data such as recreational catch and discards required for sustainable management (Cowx and others, 2010; Garibaldi, 2012; Karachle and others, 2020).

Perhaps one of the greatest overarching pressures on MRF, which incorporates all factors identified above, is shared utilisation of coastal regions and the ecosystems and resources they encompass (Barbier and others, 2011; Navarro and others, 2022; Noble and others, 2019). This theme is consistent with the findings of several other chapters in this assessment. From an MRF perspective, this is explored further below in the sustainability pathways section.

Socio-economic considerations

[42] https://bia.org.au/wp-content/uploads/State-of-Industry-Report-2024.pdf

Recreational fishing generates extensive social and economic benefits on multiple scales, from individual participants to communities, regions, and nations (Parkkila et al., 2004). The concept of value is interpreted variably across disciplines, with Parkkila et al. (2004) identifying the psychological, social, and economic impacts of fishing, distinguishing between individual benefits (e.g., angler satisfaction or health) and broader economic effects (e.g., regional tourism expenditure). In microeconomic terms, the value of recreational fishing for individuals is often measured as willingness-to-pay (WTP) to participate. Meta-analyses have revealed high individual WTP in MRF, such as thousands of USD generated from a single charter trip (Johnston and others, 2006; Whitehead and others, 2013). Recent estimates suggest a total WTP of $11.4 billion for European recreational fisheries alone (Gren and Marbua, 2024). While WTP can quantify some of these benefits, many psychological and social values are difficult to measure (Parkkila and others, 2010). Recreational fishers often engage in environmental stewardship (e.g., coastal cleanups, habitat restoration), participate in management councils, or contribute tournament catches to charity. Valuing these societal contributions is not straightforward and is rarely done quantitatively.

A macroeconomic perspective focuses on the economic impact, specifically jobs created through recreational fisher expenditures, particularly valuable in coastal regions reliant on tourism. In Europe, MRF contribute €10.5 billion and 100,000 jobs, while in the U.S., they support $138 billion in sales and 692,000 jobs (Hyder and others, 2018; NMFS, 2024). In Brazil, during 2011-2014, marine recreational fishers spent $524 million annually (Freire and Sumaila, 2019). These benefits support local and national economies, especially in rural and coastal areas, through job creation in boat and vehicle manufacturing, fishing tackle, outfitting, and tourism industries. The magnitude of the financial benefits generated by recreational fishers can be significant, at times exceeding commercial fishing revenues for certain stocks (Oinonen and others, 2016; Scheufele and Pascoe, 2022; Strehlow and others, 2023).

However, comparisons between the recreational and commercial fisheries contributions are difficult and require examining producer and consumer surplus rather than changes in macroeconomic variables (Scheufele and Pascoe, 2022). Much of recreational fishing's value is classified as non-market, derived from the fishing experience itself that is not reflected in a market price. Some of this value can be estimated or inferred through travel cost methods, contingent valuation or choice experiments. Long-standing and well-managed recreational fisheries help preserve local cultures and traditions, support regional economies or support fishers transitioning from non-profitable commercial fisheries. At the same time, in some countries, recreational fisheries that attract tourist trade often face foreign ownership, limiting local economic benefits to local communities (Potts and others, 2022).

For effective consideration of socioeconomics in recreational fisheries policies studies must consider how the recreational fishery provides economic benefits to communities where the activity is taking place (Potts and others, 2020). Traditionally, particularly in underdeveloped communities, most of the money spent by recreational fishers is not

retained as required services are unavailable. For example, Butler et al (2020) found that the local community retained less than 10% of the money foreign recreational fishing tourists spent at a lodge in Angola. When this economic leakage was considered, it was found that the community obtained greater economic benefits if the fish was captured in the artisanal fishery. Similarly, Potts et al. (2023) found that less than 10% of the money generated by recreational fishing was retained in low-income households in the South African recreational fishery. They suggested that a whole-of-government approach, which included the identification of recreational fisheries tourism hotspots, the development of local education and skills, and investment in appropriate infrastructure through public-private partnerships, would be necessary to realise the potential of recreational fisheries to drive social development.

In addition to the limited economic benefits, tourist-based recreational fishing ventures can create conflict with local communities and small-scale and subsistence fisheries. In such scenarios it is important to consider the cultural, spiritual, economic, and nutritional benefit of fisheries to local communities. In the case of Indigenous Ppeoples that engage in ceremonial or subsistence fishing, they must be viewed as rights holders with priority access to fisheries resources. The boundary between recreational and subsistence fishing can, however, be fuzzy (Nyboer and others, 2022). Given the need to manage fisheries in a cohesive and comprehensive manner, it is essential that fisheries planning extends across sectors and considers not just fish populations and fishery dynamics but also cultural traditions and values as well as sovereign rights to fish, involving fishers as active participants in decision making (e.g., via co-management) (Arlinghaus and others, 2016; Cooke and others, 2023).

From the social perspective, recreational fishing is often male dominated, of limited ethnic diversity, and generally has a higher proportion of older participants (Arlinghaus and others, 2021; Moore and others, 2023). The reasons for that disparity are unclear and may include barriers related to socialization (Arlinghaus, 2024). Some recreational fisheries tend to be limited to those with high disposable income given high entry costs, (e.g., boat, fuel). For example, fisheries targeting large pelagic species, such as tuna or billfish, are one of the most expensive ventures. Lower-cost shore-based coastal fisheries attract participants from lower socioeconomic backgrounds, often relying on catch to supplement protein consumption (Cooke and others, 2018). Disability inclusion in MRF is less understood (Lindsay and others, 2022). There are also programmes that support recovery from mental health issues and rehabilitation of offenders (Bennett and others, 2017). Ensuring equitable participation remains an opportunity to enhance diversity within the sector.

There is increasing recognition that recreational fisheries must be studied and managed as coupled social-ecological systems (Arlinghaus and others, 2017; Kleisner and others, 2022; Solomon and others, 2020). For example, increasing societal concerns about animal welfare resulted in bans of voluntary C&R practices in places like Germany and Switzerland. Recreational fishing must therefore foster its social license by meeting ethical standards, respecting animal welfare, adopting high sustainability and welfare standards

(Brownscombe and others, 2017), and demonstrating environmental responsibility (Arlinghaus and others, 2012; Arlinghaus and others, 2021).

Community concerns about recreational fishing may also arise from conflicts with other water users, e.g., swimmers at a beach, lack of adherence to no vessel wake zones. There is a growing consideration of increased traffic and overall space utilization of the oceans, which must be resolved with adequate spatial planning. Marine spatial planning (MSP) is a process that aims to reduce conflict and manage the ocean space based on economic, social and environmental objectives, and in some instances, zoning frameworks support this goal, for example, ~~is an approach that often designates zones for specific uses, as seen in~~ Australia's Great Barrier Reef Marine Park, ~~aiming~~ with zonation aimed at ~~to balance~~ balancing recreational fishing with commercial activities, diving, and research (Stephenson and others, 2023). Such zonation can mitigate user conflicts but may restrict recreational fisher access, creating further conflict. This is accentuated in nearshore coastal environments where there are various forms of recreation, shipping/boat traffic, and coastal development. Managing relationships with other users and addressing conflicts over shared water resources will be critical as coastal populations grow and development increases (Ramadhan and others, 2022).

A young recreational fisher in Australia. Photo: Sean Tracey

Sector-relevant governance

The recreational fishing sector's lack of formal recognition is a fundamental concern in fisheries resource governance (Arlinghaus and others, 2019; Grati and others, 2024; Hyder and others, 2020; Potts and others, 2020), contributing to overexploitation (Cooke and Cowx, 2004), conflicts with commercial and subsistence fishers (Gómez and others, 2021; Kadagi and others, 2021; Said and others, 2018), and reduced societal benefits from recreational fisheries (Grati and others, 2024). Despite its importance, only about two-thirds of countries mention marine recreational fishing in primary fisheries legislation (Potts and others, 2020). Barriers to recognition include limited data on recreational fishing participation, catches, biological impacts, and socio-economic importance, as well as a historical bias favouring commercial fisheries (e.g., the EU's Common Fisheries Policy)

(Grati and others, 2024). Where economic value and impact data exist, efforts to compare these metrics with other fisheries often face stakeholder resistance, complicating resource allocation. Even among countries recognizing recreational fisheries, definitions are often unclear or insufficient for legal and management purposes, making it difficult to distinguish between recreational and other small-scale fisheries. Recreational fishers range from affluent, specialized touristic fishers to poorer individuals dependent on fishing for basic nutrition (Cooke and others, 2018; Nyboer and others, 2022), underscoring the need for locally adapted definitions. In some cases, there is a blurred boundary between 'recreational' and 'traditional' fishers given that the former could be representing remnants of what was before a commercial small-scale sector. A case in point is the Mediterranean where a number of individuals hailing from fishing families have kept the tradition through a recreational license because of fishing capacity regulations that pushed small enterprises out of business (Said and others, 2018).

The lack of data on MRF catch and effort, and the misalignment of existing data with monitoring and reporting scales across jurisdictions, make it difficult to integrate recreational fisheries data into stock assessments and management frameworks (ICES, 2024), although, there are some emerging examples of integration at various scales (Carruthers and others, 2014; Punt and others, 2020). This challenge is particularly pressing for stocks where recreational fishing significantly contributes to mortality (Griffiths and Fay, 2015).

Assessment methods are chosen based on data availability, from data-poor (catch, effort, or length data) to data-rich (catch, abundance index, age/length composition) (Hoyle and others, 2024; Kokkalis and others, 2024; Rudd and others, 2021). Methods for MRF data integration include catch-only models for species like Baltic northern pike (*Esox lucius*) and Norway lobster (van Gemert and others, 2022; Zimmermann and others, 2021), integrated models for snapper-grouper stocks (Williams and Shertzer, 2024) and European sea bass (Walker and others, 2020), with some models factoring in environmental variability (Watson and others, 2022b).

Incorporating MRF data into stock assessments helps refine the determination of the Total Allowable Catch (TAC) , which guide sustainable harvest strategies (Fowler and others, 2023; Harford and others, 2021) and allocation among sectors (National Academies of Sciences and Medicine, 2024). Additionally, management strategy evaluation (MSE) can be used to explore how regulatory changes, such as hook size, minimum-length or harvest slot limits, affect recreational harvests, as applied to red snapper in the Gulf of Mexico (Bohaboy and others, 2022; Garner and others, 2020). In some jurisdictions, fisheries legislation considers biological, social, and economic factors, prioritizing sustainable yields, equitable catch allocation, and socioeconomic benefits (Tidbury and others, 2021), exemplified by European Sea Bass management (Cevenini and others, 2023).

At the EU level, the data collection framework now requires some MRF data, with specific quota allocations (e.g., for bluefin tuna) and bag limits (e.g., for dolphinfish). However, the

Common Fisheries Policy's focus on commercial objectives, such as maximum sustainable yield (MSY), does not align well with recreational fisheries (Grati and others, 2024), where the aim is often maximum fisher satisfaction and may require maintaining biomass levels above those typically associated with MSY (Birdsong and others, 2021; Johnston and others, 2010). Therefore, harmonized objectives that recognize the social and experiential goals of recreational fisheries are essential for effective management (Grati and others, 2024).

In fisheries that are targeted by both the recreational and commercial sectors tensions are common, especially in cases where stocks are declining. In some regions (e.g., Australia, New Zealand, USA), "explicit allocation" of catch shares—assigning fixed portions of TAC based on historical data— can mitigate conflicts, however the use of historical data may also create conflict if either sector is in a growth phase or historical representation of recreational catch share is inaccurate (Bess and Rallapudi, 2007; McShane and others, 2021). In other areas, allocation is implicit, with management measures indirectly influencing catch distribution. This lack of transparency can hinder balanced societal benefits, as seen with European species like sea bass and western Baltic cod (Hyder and others, 2020). A transparent and consistent approach to explicitly allocating catches between recreational and commercial fisheries, taking into account both social and economic objectives and benefits, is necessary (Hyder and others, 2020), but currently not in place in most countries. Social-ecological systems perspectives and economic valuation provide one potential approach to achieve this and have been applied to some recreational fisheries (Arlinghaus and others, 2017). The approaches are flexible and adaptive rather than command and control, but there are challenges in including feedback, and external drivers of changes in state and social and ecological diversity (Arlinghaus and others, 2017). The key constraints involve defining clear objectives that account for both social and economic factors, as well as implementing multi-objective systems that incorporate a broader range of metrics beyond traditional ones like MSY or fisheries reference points. For example, if objectives would focus on maximizing economic values of all sectors of fisheries, the target fishing mortality rates would likely be much smaller than those aiming for MSY but establishing such a system places even greater demands on data. It also involves difficult negotiations about objectives and performance criteria, which are well-beyond the comfort zone of most fisheries governance systems.

Only about one-third of national fisheries policies support co-management in recreational fisheries, which is essential for stakeholder collaboration, sustainable resource use, compliance, and local knowledge integration (Ehrlich and others, 2023; Potts and others, 2020). Co-management is challenging in recreational fisheries due to the diversity and fragmented organization of recreational fishers. Angler Management Organizations (AMOs) can facilitate stakeholder integration in management processes by sharing management responsibilities and fostering outreach (Arlinghaus and others, 2019), especially if they are broadly representative and independently funded.

Whatever mechanism is applied to manage recreational fisheries, success depends on minimizing non-compliance (Battista and others, 2018). Non-compliance may be unintentional or intentional. Marine recreational fisheries regulations vary widely, from permit systems to spatial and temporal closures. Compliance is a critical determinant of regulatory success, though only 11% of surveyed countries reported effective compliance (Potts and others, 2020). Non-compliance is challenging to estimate, as it requires data from within regulatory frameworks, often through covert operations (Ban and others, 2022; Bova and others, 2024). Many jurisdictions have implemented enforcement programs and legal frameworks with punitive measures to address non-compliance (Moutopoulos and others, 2020). Since these approaches have not been universally effective (Bova and others, 2024), there is growing recognition that normative approaches may be more suitable and cost-effective for regulating deliberate non-compliance and improved education to address unintentional non-compliance (Arlinghaus and others, 2010; Arlinghaus and others, 2012; Bova and others, 2017; Mackay and others, 2018).

Normative approaches may prove to be more effective and cost-efficient to regulate all non-compliance compared to punitive measures (Bova and others, 2017; Mackay and others, 2018). While many jurisdictions initiate education and awareness campaigns to improve fisher knowledge and support for fisheries regulations (Lindley and Quinn, 2023), sector-led stewardship initiatives are also becoming more common. Voluntary acceptance of the need and value of managing one's own catch can promote accountability and sustainable recreational fishing through social norms and networks, which significantly influence fisher behaviour (Arlinghaus and others, 2010; Arlinghaus and others, 2012; Cooke and others, 2019). Social dynamics, especially within organized clubs, social media and using ambassadors drive adherence to sustainable practices. Recalibration of social norms through word of mouth and social media networks can be highly effective (Allison and others, 2023), particularly if those that are sharing the message are highly respected among the target audience. When existing social norms are unsustainable or additional information (i.e., scientific evidence) suggests a need for change, localised interventions that leverage normative influence have the potential to incentivise behavioral change and seed new norms (Allison and others, 2023; Bova and others, 2017; Danylchuk and others, 2018; Mackay and others, 2018).

Effective examples include educating fishers on best practices to account for post-release mortality, developed in collaboration with scientists, managers, and angling leaders include programs such as Keep Fish Wet (Danylchuk and others, 2018) or Tuna Champions (Tracey and others, 2023). Others have focused on habitat restoration (e.g. OzFish[43]) and broader sector led contribution to sustainable fisheries (Black, 2023). Once a critical majority has adopted the desired behaviour, social dynamics and pressures (e.g., interpersonal communication, modelling) can trigger widespread shifts, eventually tipping context-specific fisheries towards more sustainable outcomes (Tracey and others, 2023).

[43] OzFish Unlimited | Fish Habitat Restoration Australia

Sustainability pathways

Marine Recreational Fisheries frequently overlap with ecological assets in the marine ecosystem, as fish abundance is closely tied to habitats also affected by aquaculture, commercial fishing, marine parks, port activities, shipping, and offshore energy infrastructure (Laubenstein and others, 2023; Turschwell and others, 2022). As interest grows in the blue ocean economy, with both its potential impacts and benefits for recreational fishing (Stephenson and Hobday, 2024), future marine governance will require integrated planning across multiple sectors, agencies, and jurisdictions (Kidd and others, 2020; Stephenson and Hobday, 2024; Zaucha and Gee, 2019). Moving forward to 2030 and beyond, recognizing diverse stakeholder needs, including those of MRF, is essential for effective MSP, particularly the recreational fishing sector, which offers substantial cultural, social, and economic benefits (Hyder and others, 2020) as well as health, well-being, and food security advantages (Curran and others, 2023). Integrating recreational fishing into MSP frameworks promotes social equity and acknowledges its interconnectedness with tourism and conservation (Noble and others, 2019; Voyer and others, 2017). The process starts by acknowledging that MRF is an important stakeholder with benefits well-beyond just “leisure” and providing MRF interest a seat at the table (Arlinghaus and others, 2019; Grati and others, 2024). Engaging stakeholders through public consultations, advisory committees, and workshops ensures that fishers’ unique perspectives are considered, which will ultimately lead to effective zoning and other regulations that support responsible practices (Bonsu and others, 2024). This collaborative approach fosters sustainability in marine ecosystems and encourages stewardship among recreational fishers (Ehrlich and others, 2023). This should be a priority to implement for successfully achieving more sustainable oceans by 2050 (Kelly and others, 2022). This will require significant change through transformative global governance and political will and understanding of the values of recreational fishing beyond economic return (Arlinghaus and others, 2019; Grati and others, 2024).

As MRFs typically occur alongside commercial fisheries, there is a critical need for robust data on recreational fisheries to support sustainable practices and sector access (Bess and Rallapudi, 2007; MacKenzie and Cox, 2013b; National Academies of Sciences and Medicine, 2021). Unlike commercial fisheries, mandatory reporting for recreational fishing is rare. Most surveys are voluntary and have a vital role in informing fisheries assessments and management (DFO, 2015; Ryan and others, 2016; Ryan and others, 2019; Tracey and others, 2022). Survey sampling methods should be probability-based, designed to minimize uncertainty and biases, making the data suitable for broader inferences (Sparrevohn and Storr-Paulsen, 2012; Vølstad and others, 2011). However, survey errors from declining response rates and lower landline usage pose challenges (Bova and others, 2018; Teixeira and others, 2016). Addressing these challenges and increasing the recreational fisher's self-motivation to provide data is critical to maintaining data quality and reliability (Lewin and others, 2023).

Technological innovations are essential for improving data collection and promoting sustainable fishing practices (Cooke and others, 2021; Lennox and others, 2022). Digital platforms, such as mobile apps, GPS-enabled devices, and social media, allow fishers to

record their activities in near real-time, providing data on fishing effort, catch, species distribution, environmental conditions, and habitat quality (Bradley and others, 2019; Venturelli and others, 2017). These tools support data accuracy, reduce biases (Crandall and others, 2018; Johnston and others, 2021), and facilitate the sharing of information on fishing regulations, conservation initiatives, and responsible fishing practices. Successfully realising the potential of technology platforms to accurately and precisely record and collate recreational catch and effort data by 2030 will be essential to effective stock assessment and appropriately and recognised resource sharing either through direct sector allocations or more dynamic management mechanisms which may be just over the horizon (Venturelli and others, 2017). By 2050, all sources of mortality will need to be identified, and communities and sectors need to understand and accept their impacts and the role they play in maintaining and fostering a vibrant ocean (Bennett and others, 2018; Kelly and others, 2022; Mathevet and others, 2018).

Advanced technologies, such as remote cameras, computer vision, and aerial and underwater drones, further enable in-situ monitoring of fishing activities, species populations, and habitats. These innovations allow for the assessment of fishing pressure and fish behaviour patterns, which can be integrated into existing monitoring programs (Flynn and others, 2018; Hartill and others, 2020; Lennox and others, 2022; Signaroli and others, 2024). Digital reporting methods also necessitate evaluating survey errors to ensure representative and unbiased data collection, as well as addressing non-probability sampling biases (Gundelund and others, 2021).

Novel survey designs and statistical approaches, including probability sampling, are being developed to improve data quality and reduce costs (Ferter and others, 2023; Sande and others, 2022). The integration of these technologies into monitoring programs is supported by appropriate governance frameworks for data collection, storage, and dissemination, fostering responsible fishing and data-driven conservation efforts (Andrachuk and others, 2019; Johnson and others, 2021).

The recreational fishing community is large, harnessing the power of people through an accepted and output focused ‘citizen science’ program should be a priority moving towards 2030 (Gundelund and others, 2020; Kelly and others, 2022; Whyte and others, 2024). A focus should be on how to collect data that is of use and robust to the questions required to successfully manage marine resources (Arlinghaus and others, 2019; MacKenzie and Cox, 2013a). The active involvement of fishers is essential for data collection and monitoring MRF. Effective data collection requires frameworks that support fisher engagement, where individuals share fishing activity data with researchers, who then provide aggregated insights back to the community (Ison and others, 2024). Data collected can be informative and used as the basis or supplement a range of scientific studies (Graba-Landry and others, 2023; Stuart-Smith and others, 2018). Increased engagement between researchers and fishers—spanning levels of ‘inform’, ‘consult’, ‘involve’, ‘collaborate’, and ‘empower’—enhances fisheries management by fostering a cooperative approach between agencies and fishing communities (Johnston and others, 2024; Mason

and others, 2017). This involvement improves stewardship, promotes responsible fishing practices, and supports conservation efforts (Pita and others, 2020; Shephard and others, 2023). Integrating local knowledge with scientific methods offers a more holistic approach to fisheries management, enabling adaptive frameworks that respond effectively to fish population changes and MSP needs (Chollett and others, 2022).

Transdisciplinary governance, where fishers, scientists, and policymakers co-develop solutions, has facilitated practical approaches to fisheries management (Said and others, 2018). Such collaboration also builds community resilience, supporting sustainable fisheries and healthy ecosystems. Recognizing the impact of habitat degradation on fisheries productivity, communities worldwide have initiated habitat restoration projects, including seagrass (Adams and others, 2024; Orth and others, 2020) and oyster reef restoration (Crawford and others, 2020; Gillies and others, 2020). These efforts align with the UN Decade on Ecosystem Restoration (2021–2030), which prioritizes restoring coastal and ocean habitats vital for fisheries and tourism sectors (Waltham and others, 2020; Young and Schwartz, 2019).

Conclusions

Marine recreational fishing is a globally popular activity with significant economic and ecological implications, particularly in coastal ecosystems, and operates within a large fraction of the World's Exclusive Economic Zones. Marine recreational fisheries contribute billions annually, especially in developed countries, supporting local communities through job creation and encouraging marine stewardship. Despite these benefits, MRF are not considered key stakeholders everywhere and the activity also raises own sustainability concerns due to overfishing, catch-and-release mortality, habitat disturbance, pollution, and invasive species introduction as well as conflicts with other fisheries sectors and conservation groups. The rising fishing pressure, fuelled by technological advancements and urbanization, often lacks effective regulation, recreational fishing might pressure stocks already declining from commercial fishing and there is a lack of comprehensive data reporting and regulation, especially in remote areas.

Efforts toward Ecosystem-Based Fisheries Management (EBFM) and MSP aim to balance the needs of recreational and commercial fishing sectors and other interests (e.g., conservation) while promoting sustainable practices. These frameworks emphasize data reliability, transparent catch allocation, and spatial closures and other regulations of fishing, but also equity concerns and concerns about access and infrastructure. In many areas, existing management systems are developed for commercial fisheries, which can lead to marginalizing of recreational fisheries or merely regulating them within commercial fisheries objectives in mind. There is a need for global governance systems that consider objectives and benefits of all sectors involved in fishing, including MRF as an often overlooked or marginalized form of global fisheries (Arlinghaus and others, 2019). However, such management is challenged by data collection gaps, poor capacity, incomplete governance and legislation, inconsistent objectives and regulations, regional differences in culture and governance, and competition over resources between commercial and

recreational sectors, as well as access conflicts involving Indigenous Peoplescommunities.

Integrating information on MRF into stock assessments and management strategies is essential, yet operational objectives, data quality, and performance metrics that go beyond simple management of yield and instead consider full recreational fisheries benefits are lacking. Co-management and adaptive approaches encourage collaboration among stakeholders, fostering conservation and sustainable resource use. Advanced digital tools and community science initiatives can enhance data collection and promote sustainable fishing practices. Additionally, social equity issues, including gender and racial participation barriers, and environmental concerns such as lost gear, present challenges to MRF's social license.

To support sustainable MRF, novel frameworks must address ecological, economic, and social aspects, including improved regulatory compliance, cost recovery models, data integration and mechanisms to promote social development. Effective MSP, combined with fisher engagement in monitoring, can ensure MRF's long-term viability and ecosystem sustainability by aligning management with biological, social, and economic goals, so that MRF can be a flourishing component of a sustainable ocean into the future.

Acknowledgements

RA received support via the German Ministry of Education and Research through the marEEchange project 1LC2326D). Artificial Intelligence has not been used in the writing of this chapter.

References

Adams, D. and others. Range expansion and population shifts of estuarine fishes in a changing subtropical estuary. Marine Ecology Progress Series, vol.728: 221–238, 2024.

Allison, C. and others. Can social media platforms be used to foster improved environmental behaviour in recreational fisheries? Fisheries Research, vol.258: 106544, 2023.

Altieri, A.H. and others. A trophic cascade triggers collapse of a salt-marsh ecosystem with intensive recreational fishing. Ecology, vol.93(6): 1402-1410, 2012.

Andrachuk, M. and others. Smartphone technologies supporting community-based environmental monitoring and implementation: a systematic scoping review. Biological Conservation, vol.237: 430-442, 2019.

Andrews, W.R. and others. A Comparison of Recall Error in Recreational Fisheries Surveys with One- and Two-Month Reference Periods. North American Journal of Fisheries Management, vol.38(6): 1284-1298, 2018.

Arlinghaus, R. Catch uncertainty and recreational fishing attraction: Propositions and future research directions. Fish and Fisheries, vol.25(5): 761-780, 2024.

Arlinghaus, R. and others. A synthesis of a coastal northern pike (Esox lucius) fishery and its social-ecological environment in the southern Baltic Sea: Implications for the management of mixed commercial-recreational fisheries. Fisheries Research, vol.263: 106663, 2023.
Arlinghaus, R. and others. Global Participation in and Public Attitudes Toward Recreational Fishing: International Perspectives and Developments. Reviews in Fisheries Science & Aquaculture, vol.29(1): 58-95, 2021.
Arlinghaus, R. and others. Opinion: Governing the recreational dimension of global fisheries. Proceedings of the National Academy of Sciences, vol.116(12): 5209, 2019.
Arlinghaus, R. and others. Understanding and Managing Freshwater Recreational Fisheries as Complex Adaptive Social-Ecological Systems. Reviews in Fisheries Science & Aquaculture, vol.25(1): 1-41, 2017.
Arlinghaus, R. and others. Recommendations for the future of recreational fisheries to prepare the social-ecological system to cope with change. Fisheries Management and Ecology, vol.23(3-4): 177-186, 2016.
Arlinghaus, R. and others. Explaining participation rates in recreational fishing across industrialised countries. Fisheries Management and Ecology, vol.22(1): 45-55, 2015.
Arlinghaus, R. and others. A Primer on Anti-Angling Philosophy and Its Relevance for Recreational Fisheries in Urbanized Societies. Fisheries, vol.37(4): 153-164, 2012.
Arlinghaus, R. and others. Providing context to the global code of practice for recreational fisheries. Fisheries Management and Ecology, vol.17(2): 146 – 156, 2010.
Arlinghaus, R. and others. Understanding the complexity of catch-and-release in recreational fishing: an integrative synthesis of global knowledge from historical, ethical, social, and biological perspectives. Reviews in Fisheries Science, vol.15(1-2): 75 – 167, 2007.
Audzijonyte, A. and others. High-resolution app data reveal sustained increases in recreational fishing effort in Europe during and after COVID-19 lockdowns. Royal Society Open Science, vol.10(7): 230408, 2023.
Ban, N.C. and others. Decrease in recreational fisher compliance during the COVID-19 pandemic: the case of Rockfish Conservation Areas. ICES Journal of Marine Science, vol.79(8): 2277-2285, 2022.
Barbier, E.B. and others. The value of estuarine and coastal ecosystem services. Ecological Monographs, vol.81(2): 169-193, 2011.
Barnett, A. and others. Sportfisheries, conservation and sustainable livelihoods: a multidisciplinary guide to developing best practice. Fish and Fisheries, vol.17(3): 696-713, 2016.
Battista, W. and others. Behavior Change Interventions to Reduce Illegal Fishing. Frontiers in Marine Science, vol.5, 2018.
Bennett, J.L. and others. Outcomes of a Therapeutic Fly-Fishing Program for Veterans with Combat-Related Disabilities: A Community-Based Rehabilitation Initiative. Community Mental Health Journal, vol.53(7): 756-765, 2017.
Bennett, N.J. and others. Environmental Stewardship: A Conceptual Review and Analytical Framework. Environmental Management, vol.61(4): 597-614, 2018.
Bess, R., and Rallapudi, R. Spatial conflicts in New Zealand fisheries: The rights of fishers and protection of the marine environment. Marine Policy, vol.31(6): 719-729, 2007.

Birdsong, M. and others. Recreational angler satisfaction: What drives it? Fish and Fisheries, vol.22(4): 682-706, 2021.
Biro, P.A., and Post, J.R. Rapid depletion of genotypes with fast growth and bold personality traits from harvested fish populations. Proceedings of the National Academy of Sciences of the United States of America, vol.105(1091-6490 (Electronic)): 2919–2922, 2008.
Black, C. Restoring Australia's vital seagrass meadows through community efforts. Australasian Plant Conservation: Journal of the Australian Network for Plant Conservation, vol.31(4): 10-12, 2023.
Bohaboy, E.C. and others. A simulation framework to assess management trade-offs associated with recreational harvest slots, discard mortality reduction, and bycatch accountability in a multi-sector fishery. Fisheries Research, vol.250: 106268, 2022.
Bonsu, P.O. and others. Co-location of fisheries and offshore wind farms: Current practices and enabling conditions in the North Sea. Marine Policy, vol.159: 105941, 2024.
Bornt, K. and others. Plastic gear loss estimates from a major Australian pot fishery. ICES Journal of Marine Science, vol.80(1): 158-172, 2023.
Bova, C.S. and others. Tools for assessing recreational fisheries compliance—an underappreciated yet essential component of management. Reviews in Fish Biology and Fisheries, 2024.
Bova, C.S. and others. Limitations of the random response technique and a call to implement the ballot box method for estimating recreational angler compliance using surveys. Fisheries Research, vol.208: 34-41, 2018.
Bova, C.S. and others. Assessing a social norms approach for improving recreational fisheries compliance. Fisheries Management and Ecology, vol.24(2): 117-125, 2017.
Bradley, D. and others. Opportunities to improve fisheries management through innovative technology and advanced data systems. Fish and Fisheries, vol.20(3): 564-583, 2019.
Britton, J.R. and others. Global responses to the COVID-19 pandemic by recreational anglers: considerations for developing more resilient and sustainable fisheries. Reviews in Fish Biology and Fisheries, vol.33(4): 1095-1111, 2023.
Bronnmann, J. and others. Willingness to pay for harvest regulations and catch outcomes in recreational fisheries: A stated preference study of German cod anglers. Fisheries Research, vol.259: 106536, 2023.
Brownscombe, J.W. and others. Best practices for catch-and-release recreational fisheries – angling tools and tactics. Fisheries Research, vol.186: 693-705, 2017.
Carruthers, T.R. and others. Evaluating methods for setting catch limits in data-limited fisheries. Fisheries Research, vol.153: 48-68, 2014.
Cevenini, F. and others. Assessing the welfare impacts of changes in recreational fisheries management: A modelling approach for European sea bass. Marine Policy, vol.148: 105408, 2023.
Chollett, I. and others. Toward a better use of fisheries data in spatial planning. Fish and Fisheries, vol.23(5): 1136-1149, 2022.
Cisneros-Montemayor, A.M., and Sumaila, U.R. A global estimate of benefits from ecosystem-based marine recreation: potential impacts and implications for management. Journal of Bioeconomics, vol.12(3): 245-268, 2010.

Coggins Jr, L.G. and others. Effects of cryptic mortality and the hidden costs of using length limits in fishery management. Fish and Fisheries, vol.8(3): 196-210, 2007.
Coleman, F.C. and others. The Impact of United States Recreational Fisheries on Marine Fish Populations. Science, vol.305(5692): 1958-1960, 2004.
Cooke, S.J. and others. Towards vibrant fish populations and sustainable fisheries that benefit all: learning from the last 30 years to inform the next 30 years. Reviews in Fish Biology and Fisheries, vol.33(2): 317-347, 2023.
Cooke, S.J. and others. Technological innovations in the recreational fishing sector: implications for fisheries management and policy. Reviews in Fish Biology and Fisheries, vol.31(2): 253-288, 2021.
Cooke, S.J. and others. Searching for responsible and sustainable recreational fisheries in the Anthropocene. Journal of Fish Biology, vol.94(6): 845-856, 2019.
Cooke, S.J. and others. The nexus of fun and nutrition: Recreational fishing is also about food. Fish and Fisheries, vol.19(2): 201-224, 2018.
Cooke, S.J., and Suski, C.D. Do we need species-specific guidelines for catch-and-release recreational angling to effectively conserve diverse fishery resources? Biodiversity & Conservation, vol.14(5): 1195-1209, 2005.
Cooke, S.J., and Cowx, I.G. The Role of Recreational Fishing in Global Fish Crises. Bioscience, vol.54(9): 857-859, 2004.
Cosby, A.G. and others. Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. Scientific Reports, vol.14(1): 22489, 2024.
Cowx, I. and others. Harmonizing recreational fisheries and conservation objectives for aquatic biodiversity in inland waters. Journal of Fish Biology, vol.76(9): 2194-2215, 2010.
Crandall, C.A. and others. How to Bait the Hook: Identifying What Motivates Anglers to Participate in a Volunteer Angler Data Program. Fisheries, vol.43(11): 517-526, 2018.
Crawford, C. and others. Relationship of biological communities to habitat structure on the largest remnant flat oyster reef (Ostrea angasi) in Australia. Marine and Freshwater Research, vol.71(8): 972-983, 2020.
Curran, K. and others. Humanizing marine spatial planning: A salutogenic approach. Marine Policy, vol.154: 105660, 2023.
Danylchuk, A.J. and others. Keepemwet Fishing—An emerging social brand for disseminating best practices for catch-and-release in recreational fisheries. Fisheries Research, vol.205: 52-56, 2018.
DFO. Evaluation of the Internet Recreational Effort and Catch (iREC) Survey methods. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/059, 2015.
Ding, Q. and others. Dynamic evolution analysis of recreational fisheries development in China. Fisheries Management and Ecology, vol.28(4): 305-316, 2021.
Ehrlich, E. and others. Co-designing management recommendations with stakeholders: A case study about northern pike (Esox lucius) in the southern Baltic Sea. Fisheries Research, vol.263: 106687, 2023.
FAO. Technical Guidelines for Responsible Fisheries: Recreational Fisheries. No. 13. Rome, 2012.
Ferter, K. and others. Integrating complementary survey methods to estimate catches in Norway's complex marine recreational hook-and-line fishery. ICES Journal of Marine Science, vol.80(1): 107-121, 2023.

Ferter, K. and others. Unexpectedly high catch-and-release rates in European marine recreational fisheries: implications for science and management. ICES Journal of Marine Science, vol.70(7): 1319-1329, 2013.
Flink, H. and others. Recreational fisheries selectively capture and harvest large predators. Fish and Fisheries, vol.25(5): 793-805, 2024.
Flynn, D.J.H. and others. Gigapixel big data movies provide cost-effective seascape scale direct measurements of open-access coastal human use such as recreational fisheries. Ecology and Evolution, vol.8(18): 9372-9383, 2018.
Fowler, A.M. and others. Toward sustainable harvest strategies for marine fisheries that include recreational fishing. Fish and Fisheries, vol.24(6): 1003-1019, 2023.
Freire, K.M.F. and others. Estimating Global Catches of Marine Recreational Fisheries. Frontiers in Marine Science, vol.7, 2020.
Freire, K.M.F., and Sumaila, R.U. Economic potential of the Brazilian marine recreational fishery. Boletim Do Instituto De Pesca, vol.45(1): e412, 2019.
Freire, K.M.F. and others. Brazilian recreational fisheries: current status, challenges and future direction. Fisheries Management and Ecology, vol.23(3-4): 276-290, 2016.
Freire, K.M.F. and others. Overview of Inland Recreational Fisheries in Brazil. Fisheries, vol.37(11): 484-494, 2012.
Garibaldi, L. The FAO global capture production database: A six-decade effort to catch the trend. Marine Policy, vol.36(3): 760-768, 2012.
Garner, S.B. and others. Simulating effects of hook-size regulations on recreational harvest efficiency in the northern Gulf of Mexico red snapper fishery. Fisheries Research, vol.228: 105561, 2020.
Gillies, C.L. and others. Conservation status of the Oyster Reef Ecosystem of Southern and Eastern Australia. Global Ecology and Conservation, vol.22: e00988, 2020.
Gómez, S. and others. Cultural heritage and environmental ethical values in governance models: Conflicts between recreational fisheries and other maritime activities in Mediterranean marine protected areas. Marine Policy, vol.129: 104529, 2021.
Graba-Landry, A. and others. Citizen science aids the quantification of the distribution and prediction of present and future temporal variation in habitat suitability at species' range edge. Frontiers of Biogeography, vol.15.1(e58207): 1–22, 2023.
Grati, F. and others. Effective governance of marine recreational fisheries in Europe is needed to maximize the societal benefits of its fisheries. ICES Journal of Marine Science: fsae169, 2024.
Griffiths, S.P., and Fay, G. Integrating recreational fisheries data into stock assessment: implications for model performance and subsequent harvest strategies. Fisheries Management and Ecology, vol.22(3): 197-212, 2015.
Gundelund, C. and others. Evaluation of a citizen science platform for collecting fisheries data from coastal sea trout anglers. Canadian Journal of Fisheries and Aquatic Sciences, vol.78(11): 1576-1585, 2021.
Gundelund, C. and others. Insights into the users of a citizen science platform for collecting recreational fisheries data. Fisheries Research, vol.229, 2020.
Harford, W.J. and others. Multi-Indicator Harvest Strategies for Data-Limited Fisheries: A Practitioner Guide to Learning and Design. Frontiers in Marine Science, vol.8, 2021.

Hartill, B.W. and others. Digital camera monitoring of recreational fishing effort: Applications and challenges. Fish and Fisheries, vol.21(1): 204-215, 2020.
Henry, G.W., and Lyle, J.M. The national recreational and indigenous fishing survey. Canberra, 2003.
Hoyle, S.D. and others. Catch per unit effort modelling for stock assessment: A summary of good practices. Fisheries Research, vol.269: 106860, 2024.
Hyder, K. and others. Marine recreational fisheries — current state and future opportunities. ICES Journal of Marine Science, vol.77(6): 2171-2180, 2020.
Hyder, K. and others. Recreational sea fishing in Europe in a global context—Participation rates, fishing effort, expenditure, and implications for monitoring and assessment. Fish and Fisheries, vol.19(2): 225-243, 2018.
ICES. Workshop on Recreational Fisheries in Stock Assessments (WKRFSA; outputs from 2023 meeting). 2024.
Ihde, T.F. and others. The increasing importance of marine recreational fishing in the US: Challenges for management. Fisheries Research, vol.108(2): 268-276, 2011.
Ison, S. and others. Participatory research in complex marine conservation settings: A review of recent trends and lessons for the future. Ocean & Coastal Management, vol.253: 107053, 2024.
Johnson, N. and others. The Use of Digital Platforms for Community-Based Monitoring. Bioscience, vol.71(5): 452-466, 2021.
Johnston, E.M. and others. Participation in collaborative fisheries research improves the perceptions of recreational anglers towards marine protected areas. Frontiers in Marine Science, vol.11, 2024.
Johnston, F.D. and others. Comparative analyses with conventional surveys reveal the potential for an angler app to contribute to recreational fisheries monitoring. Canadian Journal of Fisheries and Aquatic Sciences, vol.79(1): 31-46, 2021.
Johnston, F.D. and others. Diversity and complexity of angler behaviour drive socially optimal input and output regulations in a bioeconomic recreational-fisheries model. Canadian Journal of Fisheries and Aquatic Sciences, vol.67(9): 1507-1531, 2010.
Johnston, R.J. and others. What Determines Willingness to Pay per Fish? A Meta-Analysis of Recreational Fishing Values. Marine Resource Economics, vol.21(1): 1-32, 2006.
Kadagi, N.I., and Wambiji, N. Recreational and sport fisheries in the EA, SA & IO region. 2021.
Kadagi, N.I. and others. Ocean safaris or food: characterizing competitive interactions between recreational and artisanal billfish fisheries on the coast of Kenya. Ocean & Coastal Management, vol.201: 105432, 2021.
Karachle, P.K. and others. Is shore-based recreational fishing in Greece an unregulated activity that increases catch uncertainty? Regional Studies in Marine Science, vol.36: 101273, 2020.
Kaz, A.L. and others. Early pandemic recreational fishing patterns across the urban-to-rural gradient in the U.S. Fisheries Research, vol.276: 107021, 2024.
Kelly, R. and others. Connecting to the oceans: supporting ocean literacy and public engagement. Reviews in Fish Biology and Fisheries, vol.32(1): 123-143, 2022.

Kidd, S. and others. Marine Spatial Planning and sustainability: Examining the roles of integration - Scale, policies, stakeholders and knowledge. Ocean & Coastal Management, vol.191: 105182, 2020.
Klefoth, T. and others. Toward a mechanistic understanding of vulnerability to hook-and-line fishing: Boldness as the basic target of angling-induced selection. Evolutionary Applications, vol.10(10): 994-1006, 2017.
Kleisner, K.M. and others. Identifying policy approaches to build social–ecological resilience in marine fisheries with differing capacities and contexts. ICES Journal of Marine Science, vol.79(2): 552-572, 2022.
Kleiven, A.R. and others. No fear of bankruptcy: the innate self-subsidizing forces in recreational fishing. ICES Journal of Marine Science, vol.77(6): 2304-2307, 2020.
Kleiven, A.R. and others. Harvest Pressure on Coastal Atlantic Cod (Gadus morhua) from Recreational Fishing Relative to Commercial Fishing Assessed from Tag-Recovery Data. PLoS ONE, vol.11(3): e0149595, 2016.
Kokkalis, A. and others. Good practices for surplus production models. Fisheries Research, vol.275: 107010, 2024.
Laubenstein, T. and others. Threats to Australia's oceans and coasts: A systematic review. Ocean & Coastal Management, vol.231: 106331, 2023.
Lennox, R.J. and others. Digital fisheries data in the Internet age: Emerging tools for research and monitoring using online data in recreational fisheries. Fish and Fisheries, vol.23(4): 926-940, 2022.
Lennox, R.J. and others. What makes fish vulnerable to capture by hooks? A conceptual framework and a review of key determinants. Fish and Fisheries, vol.18(5): 986-1010, 2017.
Lewin, W.-C. and others. Potential biases in angler diary data: The impact of the diarist recruitment process on participation rates, catch, harvest, and effort estimates. Fisheries Research, vol.258: 106551, 2023.
Lewin, W.-C. and others. Potential Environmental Impacts of Recreational Fishing on Marine Fish Stocks and Ecosystems. Reviews in Fisheries Science & Aquaculture, vol.27(3): 287-330, 2019.
Lewin, W.-C. and others. Documented and Potential Biological Impacts of Recreational Fishing: Insights for Management and Conservation. Reviews in Fisheries Science, vol.14(4): 305-367, 2006.
Lindley, J., and Quinn, L. Compliance in recreational fisheries: Case study of two blue swimmer crab fisheries. . PLoS One vol.18: e0279600, 2023.
Lindsay, R.K. and others 2022. Fishing Participation, Motivators and Barriers among UK Anglers with Disabilities: Opportunities and Implications for Green Social Prescribing.
Mackay, M. and others. When push comes to shove in recreational fishing compliance, think ‘nudge’. Marine Policy, vol.95: 256-266, 2018.
MacKenzie, C.J.A., and Cox, S.P. Building legitimacy of the recreational fishing sector in mixed commercial–recreational fisheries. Ocean & Coastal Management, vol.75: 11-19, 2013a.
MacKenzie, C.J.A., and Cox, S.P. Building legitimacy of the recreational fishing sector in mixed commercial-rerecreational fisheries. Ocean & Coastal Management, vol.75: 11 – 19, 2013b.

Mason, J.G. and others. Ocean Research Priorities: Similarities and Differences among Scientists, Policymakers, and Fishermen in the United States. Bioscience, vol.67(5): 418-428, 2017.
Mathevet, R. and others. The concept of stewardship in sustainability science and conservation biology. Biological Conservation, vol.217: 363-370, 2018.
McShane, P. and others. Access and allocation in fisheries: The Australian experience. Marine Policy, vol.132: 104702, 2021.
Moore, A. and others. National Social and Economic Survey of Recreational Fishers 2018-2021. Canberra, Australia, 2023.
Mora, C. and others. Management Effectiveness of the World's Marine Fisheries. PLOS Biology, vol.7(6): e1000131, 2009.
Moutopoulos, D.K. and others. Mapping fisheries hot-spot and high-violated fishing areas in professional and recreational small-scale fisheries. Aquaculture and Fisheries, vol.5(5): 265-272, 2020.
National Academies of Sciences, E., and Medicine 2024. *Assessing Equity in the Distribution of Fisheries Management Benefits: Data and Information Availability.* Washington, DC, The National Academies Press.
National Academies of Sciences, E., and Medicine 2021. *Data and Management Strategies for Recreational Fisheries with Annual Catch Limits.* Washington, DC, The National Academies Press.
Navarro, M. and others. Combining spatial ecology and economics to incorporate recreational fishing into marine spatial planning. ICES Journal of Marine Science, vol.79(1): 147-157, 2022.
NMFS. Fisheries Economics of the United States 2022. 2024.
Noble, M.M. and others. Understanding the spatial diversity of social uses, dynamics, and conflicts in marine spatial planning. Journal of Environmental Management, vol.246: 929-940, 2019.
Nyboer, E.A. and others. Overturning stereotypes: The fuzzy boundary between recreational and subsistence inland fisheries. Fish and Fisheries, vol.23(6): 1282-1298, 2022.
Oinonen, S. and others. International Fisheries Management and Recreational Benefits: The Case of Baltic Salmon. Marine Resource Economics, vol.31(4): 433-451, 2016.
Orth, R.J. and others. Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. Science Advances, vol.6(41): eabc6434, 2020.
Parkkila, K. and others. Methodologies for assessing socio-economic benefits of European inland recreational fisheries. 2010.
Pita, P. and others. The Use of Recreational Fishers' Ecological Knowledge to Assess the Conservation Status of Marine Ecosystems. Frontiers in Marine Science, vol.7, 2020.
Post, J.R. and others. Canada's recreational fisheries: the invisible collapse? Fisheries, vol.27: 6-15, 2002.
Potts, W.M. and others. Understanding the economic activity generated by recreational fishing in South Africa provides insights on the role of recreational fisheries for social development. Fisheries Management and Ecology, vol.29(1): 29-43, 2022.
Potts, W.M. and others. What constitutes effective governance of recreational fisheries?—A global review. Fish and Fisheries, vol.21(1): 91-103, 2020.

Punt, A.E. and others. Essential features of the next-generation integrated fisheries stock assessment package: A perspective. Fisheries Research, vol.229: 105617, 2020.
Ramadhan, A. and others. The human dimension dilemma in marine spatial planning. Marine Policy, vol.146: 105297, 2022.
Rudd, M.B. and others. Catch and Length Models in the Stock Synthesis Framework: Expanded Application to Data-Moderate Stocks. Frontiers in Marine Science, vol.8, 2021.
Ryan, K.L. and others. Recreational fishers' attitudes to fisheries management and compliance. Marine Policy, In Press.
Ryan, K.L. and others. Statewide survey of boat-based recreational fishing in Western Australia 2017/18. . Western Australia, 2019.
Ryan, K.L. and others. Recreational fisheries data requirements for monitoring catch shares. Fisheries Management and Ecology, vol.23(3-4): 218-233, 2016.
Said, A. and others. The Contested Commons: The Failure of EU Fisheries Policy and Governance in the Mediterranean and the Crisis Enveloping the Small-Scale Fisheries of Malta. Frontiers in Marine Science, vol.5, 2018.
Sande, H. and others. Frameless—finding and refining a sampling frame for surveying recreational fisheries: lessons from estimating Swedish harvest of western Baltic cod. ICES Journal of Marine Science, vol.79(4): 1217-1231, 2022.
Sbragaglia, V. and others. Advancing the understanding of spearfisher-fish behavioural interactions and its management implications. Journal of Applied Ecology, vol.61(11): 2594-2604, 2024.
Scheufele, G., and Pascoe, S. Estimation and use of recreational fishing values in management decisions. Ambio, vol.51(5): 1275-1286, 2022.
Shephard, S. and others. Recreational killing of wild animals can foster environmental stewardship. Nature Sustainability, vol.7(8): 956-963, 2024.
Shephard, S. and others. Reviving the unique potential of recreational fishers as environmental stewards of aquatic ecosystems. Fish and Fisheries, vol.24(2): 339-351, 2023.
Signaroli, M. and others. Novel computer vision tools applied to marine recreational fisheries spatial planning. Fisheries Research, vol.271: 106924, 2024.
Solomon, C.T. and others. Frontiers in modelling social–ecological dynamics of recreational fisheries: A review and synthesis. Fish and Fisheries, vol.21(5): 973-991, 2020.
Southwick, R. and others. Estimating marine recreational fishing's economic contributions in New Zealand. Fisheries Research, vol.208: 116-123, 2018.
Sparrevohn, C.R., and Storr-Paulsen, M. Using interview-based recall surveys to estimate cod Gadus morhua and eel Anguilla anguilla harvest in Danish recreational fishing. ICES Journal of Marine Science, vol.69(2): 323-330, 2012.
Stephenson, R.L., and Hobday, A.J. Blueprint for Blue Economy implementation. Marine Policy, vol.163: 106129, 2024.
Stephenson, R.L. and others. Integrating management of marine activities in Australia. Ocean & Coastal Management, vol.234: 106465, 2023.
Strehlow, H.V. and others. Economic impact of resident and nonresident marine anglers to the local economy in Mecklenburg-Western Pomerania, Germany. Fisheries Management and Ecology, vol.n/a(n/a), 2023.

Stuart-Smith, J. and others. Southernmost records of two Seriola species in an Australian ocean-warming hotspot. Marine Biodiversity, vol.48(3): 1579-1582, 2018.
Sutter, D. and others. Recreational fishing selectively captures individuals with the highest fitness potential. Proceedings of the National Academy of Sciences of the United States of America, vol.109(51): 20960-5. , 2012.
Teixeira, D. and others. Investigating bias in recreational fishing surveys: Fishers listed in public telephone directories fish similarly to their unlisted counterparts. Fisheries Research, vol.181: 127-136, 2016.
Tidbury, H.J. and others. Balancing biological and economic goals in commercial and recreational fisheries: systems modelling of sea bass fisheries. ICES Journal of Marine Science, vol.78(5): 1793-1803, 2021.
Tracey, S. and others. The role of the recreational fisher in the stewardship of the Southern Bluefin Tuna fishery: Tuna Champions. Hobart, Tasmania, 2023.
Tracey, S.R., and Stark, K.E. 2022-23 Statewide recreational fishing survey. Hobart, 2024.
Tracey, S.R. and others. Estimating the national fishing mortality of Southern Bluefin Tuna Thunnus maccoyii from Australia's recreational fishing sector. Fisheries Management and Ecology, vol.29(3): 241-253, 2022.
Turschwell, M.P. and others. A review of support tools to assess multi-sector interactions in the emerging offshore Blue Economy. Environmental Science & Policy, vol.133: 203-214, 2022.
van Gemert, R. and others. Data-poor stock assessment of fish stocks co-exploited by commercial and recreational fisheries: Applications to pike Esox lucius in the western Baltic Sea. Fisheries Management and Ecology, vol.29(1): 16-28, 2022.
Venerus, L.A., and Cedrola, P.V. Review of marine recreational fisheries regulations in Argentina. Marine Policy, vol.81: 202-210, 2017.
Venturelli, P.A. and others. Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. Fish and Fisheries, vol.18(3): 578-595, 2017.
Vølstad, J.H. and others. Probability-based surveying using self-sampling to estimate catch and effort in Norway's coastal tourist fishery. ICES Journal of Marine Science, vol.68(8): 1785-1791, 2011.
Voyer, M. and others. Connections or conflict? A social and economic analysis of the interconnections between the professional fishing industry, recreational fishing and marine tourism in coastal communities in NSW, Australia. Marine Policy, vol.76: 114-121, 2017.
Walker, N.D. and others. A spatially explicit individual-based model to support management of commercial and recreational fisheries for European sea bass Dicentrarchus labrax. Ecological Modelling, vol.431: 109179, 2020.
Waltham, N.J. and others. UN Decade on Ecosystem Restoration 2021–2030—What Chance for Success in Restoring Coastal Ecosystems? Frontiers in Marine Science, vol.7, 2020.
Watson, A.R. and others. Source, fate and management of recreational fishing marine debris. Marine Pollution Bulletin, vol.178: 113500, 2022a.
Watson, J.W. and others. Incorporating environmental variability in a spatially-explicit individual-based model of European sea bass☆. Ecological Modelling, vol.466: 109878, 2022b.

Whitehead, J.C. and others. A recreation demand model of the North Carolina for-hire fishery: a comparison of primary and secondary purpose anglers. Applied Economics Letters, vol.20(16): 1481-1484, 2013.
Whyte, D. and others. Planning for citizen participation in the EU mission to restore our ocean and waters by 2030. Maritime studies, vol.23(4): 44, 2024.
Williams, E.H., and Shertzer, K.W. Estimating catch within integrated stock assessments: Distinguishing truth from error in sparse-spike data. Fisheries Research, vol.274: 106994, 2024.
Young, T.P., and Schwartz, M.W. The Decade on Ecosystem Restoration is an impetus to get it right. Conservation Science and Practice, vol.1(12): e145, 2019.
Zaucha, J., and Gee, K. Maritime Spatial Planning: past, present, future, Maritime Spatial Planning. 2019.
Zimmermann, F. and others. Inclusion of recreational fishing in data-limited stocks: a case study on Norway lobster (Nephrops norvegicus) in Norway. Canadian Journal of Fisheries and Aquatic Sciences, vol.79(6): 969-978, 2021.

Section 5A Chapter 3: Energy (introduction)

The ~~section~~chapter includes two subchapters that take an integrated approach to exploration of renewable and non-renewable resources of the World Ocean. The ~~section~~chapter expands on the previous assessment by examining the relevant economic activities, innovative approaches, and social factors at both global and regional scales.

Subchapter on offshore renewable (S5A.C3A), such as wind, wave energy and tidal energy, ~~– offshore renewable energy (ORE),~~ describes potential positive cumulative environmental effects ~~of ORE~~ and highlights that proper handling of these resources can significantly reduce around 10% of the global CO2 emissions. The subchapter underlines that social equity should be prioritised to ensure that the expansion of offshore renewable energy (ORE) does not have a disproportionate impact on already marginalised communities and work to perpetuate existing inequities.

The second subchapter on offshore and deepwater exploration of the non-renewable oil and gas resources (S5A.C3B) starts with description of up-to-date magnitude and scope of these activities followed by deepwater perspectives and projections of hydrocarbon exploration. Further the subchapter deals with potential disasters and impacts from both the hydrocarbon surveying and offshore installations, including longer-term effects. Finally the subchapter provides the social component highlighting that the offshore hydrocarbon industry's operations often intersect with the social and environmental concerns of local communities, leading to conflicts and challenges in securing public acceptance.

~~This section presents a diverse collection of chapters that take an integrated approach to~~ The ~~present section involves a diverse collection of chapters with an integrated approach to exploration and transportation of the non-biological and biological resources of the World Ocean, as well as mitigating the environmental impacts of exploration through established and emerging solutions. mitigation of the impacts of exploration by known and emerging solutions. The section qualitatively extends the previous assessment by detailing economic activities, innovative approaches and social components on global and regional scales. The section expands on the previous assessment by examining the relevant economic activities, innovative approaches, and social factors at both global and regional scales.It starts with description of offshore renewables as wind, wave energy and tidal energy, highlighting that proper handling of these resources can significantly reduce around 10% of the global CO_2 emissions. It is followed by the dDescription of offshore and deepwater exploration of the non-renewable hydrocarbons and mineral resources and, possibilities for disasters and provides magnitude, projections and impacts of these activities impacts to the marine environment from installationson of corresponding infrastructure. Review Chapter on previous offshore renewables, of desalination and salt production, closely linked to previous offshore renewables, describes highlightes potential of these activitiesurther considered are the uses of foraimed on sustainable water management as well as production of critical raw materials from the brine. Further considered are the uses of Use of marine genetic resources, which are UN-defined as "any material of marine plant, animal, microbial or other origin…",. This spans from human health to industrial processes, with a key message of their lack of study and~~

~~exploration in areas beyond national jurisdiction. The review of coastal and ocean tourism highlights vities the dependence and impact of that activity on the health of ocean, natural and cultural resources. The maritime shipping chapter details various impacts from transportation activities and examines sustainability pathways, including decarbonization, ship design, ocean observing and monitoring. The coastal development chapter, using concept of the coastal zone as a concentrated area of global urbanization, describes the status and trends in various seaboard offshore infrastructure andis fit into sustainability pathways, including climate change adaptation and integrated management. The section is concluded by description of geoengineering approaches, comprising carbon dioxide removal, solar radiation modification and structural engineering, stating the need of significant research to use their potential to mitigate climate change.~~

Section 5A
Sub-chapter 3a: Offshore Renewables

Coordinating author: Ewa Spiesz

Co-authors (alphabetic order): Rayenda Brahmana, Ana Brito e Melo, Andrea Copping, Freya Croft, Isa Elegbede, Deborah Greaves, Shenghui Li, Eric Mwangi Njoroge, Henrique Paiva de Paula, Jose Rodrigo Rojas, Rebecca Williams

5A3a.1. Introduction

Key messages:

- Ocean-based or offshore renewable energy (ORE) could deliver around 10% of the global CO_2 emissions reductions required by 2050 to sustain a 1.5-degree pathway and ORE will be a vital tool in meeting the tripling of renewables, as set out at COP28.
- ORE development has a high potential for employment and local economic benefits. Social equity should be prioritised to ensure that the expansion of ORE does not have a disproportionate impact on already marginalised communities and work to perpetuate existing inequities.
- Effective policy strategies like technology push instruments, e.g. R&D grants; market pull instruments e.g. Feed-in Tariffs (FiTs) and Contracts for Difference (CfDs); effective Marine Spatial Planning (MSP are necessary to advance ORE sector and increase roll-out of these technologies.
- Understanding potential cumulative environmental effects of offshore renewables and implementing effective mitigation measures can reduce harm to marine environment and potentially lead toward net positive gain to habitats and ecosystem processes.
- The development of offshore renewables can be part of the solution to limit the climate crisis, while we retain the responsibility and best practices in measuring potential environmental and socio-economic effects by standardised sustainability assessments, mitigate unacceptable changes, and plan to reverse course if we find that irreparable damage is being done.

Developing offshore renewable energy (ORE) globally will be pivotal to the energy transition and to decarbonising the economy [55, 107~~107~~]. Not only can ORE play a role in mitigating global warming and reducing emission through providing a clean and reliable source of energy, but it also provides opportunities for coastal economic revitalisation through enhanced innovation, job creation and providing renewable energy to remote coastal locations, as islands, for a just transition. It offers a clean growth pathway, transitioning the workforce and industrial sectors to meet future needs, while providing a sustainable means of meeting the growing energy demand.

Offshore wind is headed towards large scale production of energy at sea, which will be used to supplant conventional sources on national grids. The more emerging marine energy technologies (wave, tidal currents, ocean thermal energy conversion, salinity gradient energy, and offshore floating solar), can complement offshore wind in large scale electricity production and fill gaps to provide secure, available and equitable energy (in off-grid applications). A key off-grid ORE application is electrifying islands and remote coastal communities, which currently generate electricity mainly from fossil fuels. Offshore renewables can provide stability and resiliency while merging wind, solar and energy storage into sustainable microgrids [76]. Similarly certain marine energy sources can generate power to be used at sea for replacing battery power on ocean observation and navigation platforms, replacing fossil fuels as aquaculture facilities move further offshore, and eventually replace coastal and transoceanic shipping fuels [76]. These emerging ORE solutions can be used to meet the growing need for electricity to power offshore data and computing centres, also needed to support AI.

This chapter provides an overview of ORE technologies, their development status, opportunities and challenges, including environmental and socio-economic considerations, followed by an optimistic vision outlining an ideal pathway to 2050 for ORE development, which emphasises that success will hinge on our ability to address the identified knowledge gaps.

5A3a.2. Offshore renewables technologies - emerging and available on the market

5A3a.2.1. Development status of ORE technologies

This section introduces the different offshore renewable energy (ORE) technologies, including offshore wind, wave energy, tidal energy, offshore floating solar, salinity gradient, ocean thermal energy conversion with a short description of the working principles, resource potential and status. Please note that ORE technologies can also be referred to as marine renewable energy (MRE) technologies (as in WOA II [28]) or ocean energy technologies [16]. According to a report commissioned by the Ocean Panel, ORE could deliver around 10% of the global CO_2 emissions reductions required by 2050 to sustain a 1.5-degree pathway [6464]. The utilization of ORE depends on the efficiency, maturity and cost-effectiveness of the technologies. ORE technologies working principles along with their stages of development are listed in Table 5A.3a.1.

Offshore energy technology	Development status	TRL	Working principle
Offshore wind	Mature and in commercial operation	TRL 9	Wind turbines convert wind energy to kinetic energy via a rotating turbine, and then to electricity directly or via a drivetrain (i.e. the components that transfer the power from the moving blades to the generator) and a generator.

			Gravity base foundations are used for depths up to 10m, monopiles are economic for water depths of 20–40m, and jacket foundations are considered competitive for water depths up to 70m.
Floating offshore wind	Pre-commercial to early commercial phase	TRL 8	For deeper offshore areas, floating turbines are anchored to the seabed via mooring lines and have spar, semi-submersible or tension leg platform designs [70].
Wave energy	Demonstration phase to full-scale prototype phase (depending on technology type)	TRL 6-7	Wave energy converters (WECs) are devices that convert energy from surface waves to electricity. There are three basic WEC types [52] which can be sub-classified into: ● Oscillating water column (OWC) devices which utilize the air pressure difference caused by the wave-induced water surface 'up-down' movement; ● Overtopping devices which collect the water that spills into a device as the waves pass and then passes in through a turbine to generate energy; ● Oscillating bodies which utilize the relative motions between a floating structure and a reference body to drive a generator and produce energy.
Tidal current energy	Demonstration phase with pilot projects in operational environment, first farms under development, up to pre-commercial phase	TRL 7-8	Marine turbines are submerged devices that are used to extract energy from tidal currents. Tidal current turbines operate in seawater but have similarities to wind turbines in that they possess blades, drivetrains and support structures. Marine turbines require far smaller rotor diameters than wind turbines to achieve a similar power output, as seawater is much denser than air. Different configurations and prototypes of tidal turbine designs have been developed and MW-size turbines have been tested at sea [7]. Flow speed is a key factor in assessment of the available energy [74].
Tidal range energy	Mature and in commercial operation	TRL 9	Marine turbines are submerged devices that are used to extract energy from tidal ranges (where turbines form part of the system with a tidal barrage or tidal lagoon).

Offshore floating solar energy	Demonstration phase	TRL 5-6	Solar energy is created by the power from the sun as electromagnetic radiation, or solar irradiance. The intensity of solar irradiance is variable and depends on latitude, season, time of day, weather conditions, solar cycle, etc. In the ocean, solar energy could be extracted using solar panels (photovoltaic (PV) systems) fitted to dedicated floating platforms or to existing offshore structures.
Salinity gradient	demonstration phase	TRL 5-6	Salinity gradient energy, also called the blue energy, can be produced from the salinity difference between seawater and fresh water. This energy is typically generated using either: a) pressure-retarded osmosis (PRO), where salt- and fresh-water are separated by a membrane and mixed via osmosis, with the energy of the physical flow being extracted, b) Reverse Electro Dialysis (RED), where salt ions are transported through membranes to generate a charge [60], c) Ionic Nano Osmotic Diffusion (INOD) technology which is an evolution of RED technology based on nanotechnologies.
Ocean thermal energy conversion (OTEC)	demonstration phase (early demonstration phase for offshore OTEC while onshore the technology is already at TRL 7-8)	TRL 4-7	OTEC uses the thermal gradient between deeper cold seawater and warmer surface water to generate electricity using a heat engine. Areas of largest temperature gradient between deep and surface water (above 20°C, which is the lower threshold for OTEC applications) occur in a belt in the tropics, especially in the western part of the Pacific and Indian Ocean.

Table 5A.3a.1 DEVELOPMENT status of various offshore renewable energy technologies. TRL – Technology Readiness Levels, where TRL1 is an innovative idea and TRL 9 is a solution ready for market.

5A3a.2.2 Opportunities and challenges of respective offshore renewable technologies

Table 5A3a.Suppl.1 shows opportunities and challenges related to the development of ORE. In the first instance, ORE is likely to need price support until supply chain investments are made and industry learning is consolidated (see section 5A3a.3). Governments can play a valuable role in reducing market risks, therefore reducing financing costs and realizing lower fuel bills for consumers [12]. To encourage market readiness, economies can consider appropriate policies, stakeholders, grid connections and financing [93, 25] and there exist some good examples of regulatory frameworks to address these bottlenecks. However, some countries are still at an early planning stage, and so the supply chain and operational readiness to deploy are limited. Developing economies may face additional financing barriers, as well as particular market structures which hinder the penetration of ORE into the energy mix [25, 37]. In all markets the concept of risk sharing, usually between government and private sector is integral to market stimulation as bidding in auctions and tenders requires a project developer to carry a large amount of the financial uncertainty and risk [86] as project approval can be very lengthy.

5A3a.2.3 Prospective development of the technologies including regional potential

Global installed capacity of offshore wind was 75.2 GW in 2023 [14] which represents more than doubling of the installed capacity compared to the time of writing of the previous WOA [28]. IRENA and IEA project that at least 380 GW of offshore wind will be needed by 2030, and over 2000 GW by 2050, to keep the world on track for 1.5 degrees. Around the world in 2023, the industry connected 11 GW of offshore wind to the grid representing a 24% year-on-year increase - the second-best year ever (see Figure 5A.3a.1).

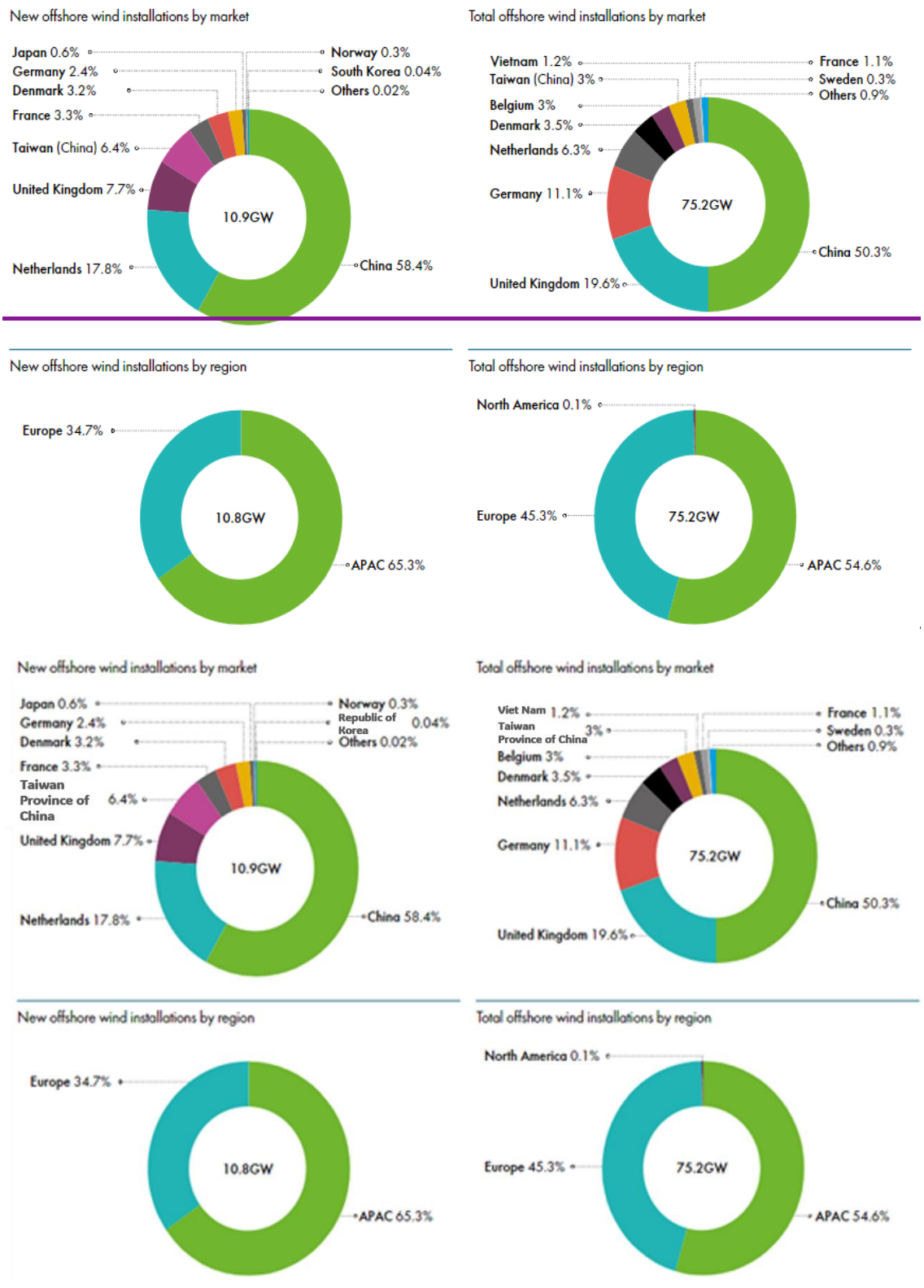


Figure 5A.3a.1 NEW and total offshore wind installations worldwide in 2024 based on GWEC Global Offshore Wind report 2024 [1414].

Membership of the Global Offshore Wind Alliance (GOWA), a diplomatic, multi-stakeholder initiative founded by GWEC, IRENA, and the Government of Denmark has grown to include over 20 governments. These governments have pledged to collaborate towards installing 380 GW of offshore wind by 2030 and 2000 GW by 2050 [1313].

There is still an implementation gap between declared targets and the rate of annual installations. The areas of permitting, finance, supply chain, and grids remain key enablers for growth targets to materialize, and to propel offshore wind power development into a new phase of even faster growth. The World Bank Group found that blended and concessional finance would be important in enabling EMDE's to access financing for offshore wind. A UK report found that, by 2040 the offshore wind workforce needs to grow by 6 times, offshore wind capacity needs to increase by 7 times, and 4 times faster than current capacity and project build out rates if we are to reach 2050 Net Zero goals [65].

The planned uptake of tidal energy in Europe has increased since 2023, with the UK and France contracting 70 MW of tidal stream capacity through the revenue support systems. This is expected to lead to a total of 127 MW over the next 5 years [16].

A total of 13.3 MW of wave energy has been installed in Europe since 2010 of which 1 MW is currently deployed. The other installations have been decommissioned following the completion of testing and demonstration programmes [16]. The rate of deployment of wave energy devices has slowed down recently but is growing again towards pre-covid-19 levels. Beyond Europe, the US and China have stated development targets and public support for offshore renewable energy [16].

5A3a.2.3 Project development including supply chain and grid connection challenges

To unlock the full potential of offshore renewable energy and achieve ambitious targets, a robust supply chain for installation components, installation and maintenance vessels, and the development of harbours for installation purposes is critical. In Europe, US and Asia, several neighbouring countries have set ambitious targets for offshore developments in the coming years (e.g., by 2030), necessitating rapid harbour development and an increase in the qualified workforce. In Oceania, the Australian Government has identified six regions for offshore wind developments to take place, which will also require new or expanded onshore ports and grid infrastructure to support the industry.

The current renewable energy production and decarbonization targets are driving a rapid expansion of offshore renewables worldwide, which will help to mitigate climate change. Many of the ORE components require "critical materials" [8], including cobalt, copper, graphite, iridium, lithium, manganese, nickel, platinum, and selected rare earth elements. Since the sources of these materials are often very localized, ~~they are sensitive to geopolitical dynamics and pose challenges related to economic, political and social impacts. As such~~ their supply involves

structural vulnerability to supply chains disruptions. Various attempts at the diversification of sources of critical materials have been proposed, e.g. Critical Raw Materials Act by the European Commission [12]. Special attention is needed for copper supply, as its demand is rising across multiple sectors, including ORE, other renewable energy technologies, and specific types of car batteries. Looking ahead, copper could become a major bottleneck, not only because of limited geological availability, but due to the rapid acceleration in demand.

Deep-sea mining could become an alternative for a more equitable access to critical materials but comes with a set of potential uncertainties and potential environmental risks, including potential disruptions to ocean carbon sequestration processes, which could amplify climate change [106~~106~~]. A more sustainable and strategic approach is ''urban mining'' – using recycled copper from electronic waste. Urban mines potential is nearly equivalent to land-based reserves. Given that copper is highly recyclable, fostering circular economy strategies is essential.

Another method of critical materials extraction that is currently in advanced stage of research and development is extraction of critical minerals from seawater that contains them at low concentrations. Extraction requires the use of large volumes of seawater - a process being examined in conjunction with emerging ORE technologies like ocean thermal energy conversion (OTEC) [98]. The environmental impact of this new method is to be determined but can likely cause less impact compared to deep-sea mining.

The lack of a stable supply chain of critical materials used for renewable energy devices and long cycles of developing new sources (e.g. exploration and mining infrastructure development) may result in critical materials becoming another bottleneck of ORE large scale rollout. On the positive side, the situation may increase the research and development in circularity of raw materials used in renewables.

Comprehensive project sustainability assessments are vital for fostering resilient ORE investments and ensuring sustainable energy development. This assessment should address the project risks to the sustainability of marine ecosystems. Assessments should consider positive (handprints) and negative impacts (footprints), as well as impacts on ecosystem services, life cycle assessments of components used and other aspects of sustainability [44]. Key risks - technology, deployment, regulatory, financial, and reputational - can be effectively managed to protect the environment. Table 5A3a. Suppl.2 summarizes these risks and their potential impacts.

5A.3a.3. Socio-economic aspects

The increased uptake of ORE is expected to lead to change in some coastal communities, which will bring about social and economic impacts [57]. The socio-economic impacts of global ORE development should be evaluated alongside other offshore energy sectors, like oil and gas, which may have partly comparable impacts [66]. The social impacts of ORE have not been comprehensively considered and there is a need for further research in this space [89]. As outlined in Supplementary Table 5A3a.Suppl 3, in considering socio-economic impacts

clarification is needed relating to the distribution, the geographical and temporal scope, and the nature of the impact [57].

5A.3a.3.1 Social considerations in the continued development of offshore renewables

As outlined in Table 5A3a.4, identifying the social impacts of ORE is complex, however, the need to embed equity in the development of ORE and energy transitions broadly, is the crux of all social considerations. It is imperative that the increased uptake of ORE does not reinforce the status quo and exacerbate wealth inequality and existing inequities. Equity therefore needs to be foregrounded in the processes and outcomes of ORE development, which will subsequently help to advance some sustainability goals [109~~109~~]. Whilst the development of ORE has been linked to advancing the SDGs, the relationship between these is often complex and the development of such infrastructure can both enable and inhibit the advancement of development goals [105~~105~~]. Processes such as planning, procurement and investment, are significant in ensuring the sustainable development of this industry [34].

The social aspect of ORE could involve creating jobs to underrepresented groups including women, ethnic minorities, Indigenous P~~p~~eoples, sexual orientation minorities, persons with reduced mobility and youth. With energy transition underway in many countries, there still seems to be a gap in job creation for underrepresented groups according to International Labor Office (ILO). Furthermore, initiatives such as the 2019 Offshore Wind Sector Deal can play a crucial role in fostering inclusive representation in the offshore renewable energy sector. This UK industry commitment set targets to increase diversity, aiming to raise the representation of women in the offshore wind workforce from 16% in 2018 to at least 33% by 2030, with an ambition to reach 40%.

Beyond voluntary commitments, legal frameworks in several countries also support inclusivity in offshore wind development. In the United States, impact assessments for offshore wind projects under NEPA evaluate the social impacts of Offshore Wind projects. Similarly, Canada's Impact Assessment Act requires assessments of ORE projects to consider gender and other underrepresented groups-based analysis, promoting fair participation in the sector. The UK's Equality Act (2010) provides a legal foundation for advancing diversity and inclusion across industries, reinforcing efforts like the Offshore Wind Sector Deal.

In order to put the rights of Indigenous Peoples into the foreground of energy transitions, including in the development of ORE, and under the United Nations Declaration on the Rights of Indigenous Peoples the principles of free, prior, and informed consent should be upheld [9, 3]. Furthermore, mechanisms should be enabled to support Indigenous Peoples', Traditional ~~owner~~ and Local community Knowledges (ITLK) and Indigenous Peoples' led research and governance and to enhance the importance of Indigenous Peoples' knowledge systems [49] even though

increasing Indigenous Peoples' representation requires simultaneously to recognise the systemic barriers for participation and leadership for Indigenous Peoples [49].

Decisions relating to the use of ocean space should acknowledge the plurality of human relationships to the ocean [21]. Social acceptance can influence the success of the development of ORE projects [89]. Research shows that often there is a disconnect between broad levels of support for the development of offshore renewables, and local resistance in adjacent communities [48]. Place-based understanding and approaches will therefore be essential in the continued development of ORE.

Conflict arising in relation to the use of marine space, including spatial exclusion of fishers can be mitigated by Marine Spatial Planning [53]. Conflict should not be seen as necessarily negative, as it is often through conflict that better social and environmental outcomes can be achieved. However, it is important that appropriate mechanisms for navigating this conflict are developed [75, 103~~103~~, 94].

5A.3a.3.2 Economic Considerations

ORE development, including wind, tidal, wave power, and other technologies, creates demand for a wide range of components and services, leading to new jobs and local economic development. ORE development therefore holds significant potential for job creation, provided training programs expand, and workforce initiatives adapt to evolving demands. The High-Level Panel for a Sustainable Ocean Economy found that offshore wind has a higher capacity for jobs than the fossil fuel industry and in general has a better gender balance [77]. IRENA estimated that a 500MW offshore wind project directly creates 2.1 million person-days of work or about 10,000 person years over its life. Offshore wind presents an opportunity to revitalise coastal towns, cities and communities, where new investments can regenerate areas that have previously faced economic decline.

The projections of potential employment from ORE for certain countries and regions are shown in Table 5A3a.Suppl.4. However, significant challenges remain in ensuring job supply for the growth of the ORE sector. As the sector expands the demand for skilled workers will increase with the ambitious development goals set by multiple nations. Job creation is constrained by the number of large-scale projects, regulatory complexities, technological advancements, and financing and investments, as well as training and skills development. The ORE sector requires a specialised workforce [97, 100], but in many regions, there are not sufficient training programs to meet the sector's needs, leading to skills gaps in areas such as advanced engineering and operational expertise [97, 78]. The high costs of training, alongside rapidly evolving technologies complicate efforts to equip the workforce [100]. Investing in robust training frameworks and

education initiatives is essential to meet the growing employment demands and ensure the long-term sustainability of the sector [23].

5A.3a.3.3 Socio-Economic Impact Assessments

Socio-economic impacts are assessed as part of the Environmental Impact Assessment (EIA) process when developers are applying for a license or consent, with the intention that potential impacts are captured throughout the process, and mitigation and enhancement measures are explored (see guidance from International Association for Impact Assessment). Yet impact assessments may not adequately reflect the risks and opportunities [6] and may not accurately reflect social and cultural values that may not be readily transferable as quantifiable metrics. Qualitative methods, along with quantifiable methods will be needed to accurately measure the full scope of socio-economic impacts [57].

5A.3a.4. Governance of Offshore Renewables

To support the expansion of ORE, strong governance mechanisms and a combination of supportive policies is essential to attract the necessary financial investment, whilst also working towards social and environmental outcomes. Governance is a system of organisation and operation that includes components such as decision-making, compliance and accountability. Supportive policies will enable the technology to reach commercial-scale implementation while ensuring that this expansion aligns with sustainable objectives. It is crucial to foster policies that promote long-term, consistent deployment trajectories, alongside an accelerated cost reduction rate. In this section we explore various effective policy strategies as governance mechanisms that have been encouraging the advance of the sector.

An effective policy for the development of offshore renewable energies is based on both "technology push" and "market pull" instruments. These tools are essential for guiding technology through the various stages of the innovation chain, effectively supporting its development from the conceptual stage to initial adoption and widespread use. Some policy measures are aimed predominantly at advancing technologies in their early stages, while others play a crucial role in later stages, moving toward broad market acceptance.

The International Vision for Ocean Energy, outlined in the roadmap by the International Energy Agency Technology Collaboration Programme on Ocean Energy Systems (IEA-OES), serves as a strong example of how the balance between push and pull policies is critical for advancing ocean energy technologies [15].

"Technology push instruments" are designed to encourage the research and development of new technological ideas and advance them to the stages of demonstration and initial commercialization. Notable examples include tax credits for R&D, grants, prizes, concessional

financing and matched equity funding. This support is critical in the early stages of technology development and implementation, making innovative projects more attractive to private investors. Government funding for R&D is vital for technological innovation in this sector and should include funding for both basic and applied research, as well as support for demonstration projects to prove their feasibility and performance under real sea conditions. It is important that these measures are targeted towards areas identified as priorities to enhance the performance of devices and reduce costs associated with development, implementation, maintenance, and decommissioning. These support mechanisms are particularly suited for promoting international collaborations, a key factor in accelerating cost reduction. Multilateral Development Banks (MDBs), such as the World Bank or the Asian Development Bank, can play a significant role in promoting new technologies because they offer funding and risk mitigation that can attract additional private sector investment, particularly important for large-scale demonstration projects.

A strong illustration of technology push in action is seen in projects funded under the European Commission's Green Deal and Horizon Europe Program. These initiatives include multi-source offshore energy parks [10], tidal array energy parks [90, 11], and wave energy parks supported by the EU Innovation Fund [18, 19]. Furthermore, the EuropeWave program, supported by the Basque Country and Scotland along with the European Commission, represents another example of coordinated efforts to drive innovation in ocean energy technologies.

“Market pull Instruments” are essential for developing a commercial marine energy sector. The two most relevant financial instruments used to encourage the development of marine renewable energies have been Feed-in Tariffs (FiTs) and Contracts for Difference (CfDs) implemented in various countries. FiTs offer long-term contracts to energy producers, guaranteeing them a fixed price for the electricity generated, which helps to mitigate the financial risk associated with the high initial costs of marine renewable energy projects. Similarly, CfDs stabilize revenues for energy producers by ensuring they receive a fixed price for the energy produced, regardless of market fluctuations. An illustrative case is the United Kingdom, where CfDs are the government’s main mechanism for supporting low carbon electricity generation [1]. There have been 6 auctions, or allocation rounds (AR), to date, which have seen a range of different renewable technologies competing against each other for a contract. These have been successfully implemented to boost the offshore wind energy sector and, more recently, the tidal energy sector.

In the US, East Coast offshore wind projects have been experiencing financial stress. Macroeconomic factors, such as rising costs of materials, supply chain disruptions, and increases in cost of capital due to increased interest rates, have combined with regulatory issues to bring about these challenges. Many contracts were agreed prior to the covid pandemic and the war in

Ukraine, and did not feature sufficient indexation linkages. Furthermore, issues such as slow permitting and differing supply chain requirements at state level have increased risk and cost of capital. This experience highlights the need for better financial support mechanisms and risk mitigation strategies, such as indexation of offtake contracts, but also the need for clear governance and regulation, which harmonizes requirements between state and federal regimes, and recognises the importance of efficient permitting procedures.

Another crucial aspect of governance is the setting of clear and ambitious targets, accompanied by a clear and specific plan for the delivery, per year of such targets, for the development of marine renewable energy. These targets demonstrate the government's commitment to renewable energy, encourage investment, and foster technological innovation (see Table 5A3a.Supl.5 for examples in offshore wind from Europe). This is particularly important in the ORE sector, where the long-term financial viability of these projects is critical for investors. Additionally, these goals allow policymakers to align regulations, subsidies, and support mechanisms towards a common objective. Most importantly, targets and associated road maps and plans give confidence to investors and manufacturers to invest in their facilities and projects. Targets act as catalysts for an energy transformation. Here are some global examples: The European Union has set a target of 300 GW of offshore wind capacity by 2050, a significant increase from the approximately 12 GW in recent years. This ambitious goal is part of a broader strategy to achieve carbon neutrality and strengthen the energy independence of the bloc. The Netherlands has set an ambitious target of achieving 3 GW of offshore floating solar capacity by 2030, showcasing its commitment to diversifying and expanding its renewable energy portfolio.

A well-designed regulatory framework is essential for the development of especially the emerging offshore renewables. As this sector progresses globally, concerns about the potential effects of these devices on marine animals, habitats, and the broader environment remain a significant challenge. To address these challenges effectively, a regulatory framework that provides clarity and predictability for developers is needed. Such framework can outline the requirements and procedures necessary for the implementation of projects at sea and ensuring that projects are both feasible and sustainable. To encourage growth in this sector, it is important that regulatory frameworks include effective licensing processes that minimize bureaucratic barriers, thereby speeding up the deployment of new technologies and ensuring that project timelines are manageable, while not compromising on social and environmental standards. Equally important is the need for efficient Environmental Impact Assessments (EIAs). As our understanding of the potential environmental effects of ORE projects grows, EIAs should be streamlined to focus on assessing risks that are significant and warrant careful study. Additionally, the regulatory framework should incorporate mechanisms to retire environmental risks - which means recognizing and managing risks once sufficient data is gathered - enabling the industry to move forward confidently while maintaining high environmental standards. Notably, adaptive

management strategies have been promoted in various countries, allowing adjustments based on real-time environmental monitoring.

Another important aspect of governance is Marine Spatial Planning (MSP), for the strategic allocation of marine spaces, ensuring that offshore renewable energies can coexist with other maritime activities (such as navigation, fishing, and tourism). MSP helps manage the spatial and temporal distribution of human activities in marine environments, optimizing resource use while minimizing conflicts and environmental impacts. An innovative application of MSP is the adoption of multi-use strategies, which involve the co-location of different activities in the same marine area. By gathering data and knowledge for the planning area and engaging with impacted stakeholders, MSP processes can support co-location of different activities in the same area.

As an example, China is now conducting ~~multiple-layer planning for~~three dimensional development of ocean space to encourage more efficient and intensive utilization of marine resources. This approach divides the marine areas into vertical layers (e.g., the surface, water body, seabed and ~~marine airspace~~subsoil), ~~each with distinct resources attributed and development potential~~to determine the right to use the marine area based on actual conditions, as well as co-location of offshore floating solar photovoltaics and aquaculture, offshore wind farms and marine ranching offshore wind farms and tourism. The European Union's Maritime Spatial Planning Directive exemplifies how MSP can be effectively implemented by requiring that EU member states to develop maritime spatial plans that balance economic, social, and environmental objectives including the integration of ORE with other marine uses, supporting the EU's goals for sustainable growth of maritime economies and the responsible use of marine resources. It emphasizes a collaborative approach, involving stakeholders at all levels in the planning process to ensure that the plans reflect a broad range of interests and insights. In this context the "Area Passports" concept in the Netherlands represents an innovative approach to enabling the coexistence of multiple offshore activities, such as energy production, aquaculture, and other uses of the North Sea. The Area Passports help stakeholders understand which activities can be integrated into a particular area, promoting multi-use strategies that optimize the use of marine resources while minimizing conflicts.

5A3a.5. Environmental Impacts

Understanding the risks ORE production can cause to marine animals, habitats, and ecosystem processes requires specificity that links each part of an offshore device or system to species, habitats, or processes. Using a stressor-receptor framework allows the attributes of each stressor

(portion of device or operation that can cause stress, injury, or death) to be linked to the specific receptor (the animals, populations, habitats, oceanographic and ecosystem processes) of concern [61]. The key stressors of concern for offshore renewables are listed in Table 5A3a.7., with the receptors that will potentially be affected by offshore technology. Eight major stressors have been recognized by the marine energy and offshore wind communities [55, 82]:

- Collision risk – Animals colliding with moving turbine blades; underwater for tidal and ocean current turbines, in air for wind turbines
- Underwater noise – Masking natural sounds underwater from marine energy, and referred underwater noise from offshore wind
- Electro-magnetic fields (EMF) – emissions from power export cables and underwater substations
- Changes in habitats – on the seafloor and in the water column
- Changes in oceanographic conditions – due to presence and operation of devices, removing energy from system
- Entanglement – from multiple mooring lines securing systems
- Displacement – presence of many devices affecting animal migration and movements
- Chemical releases – onboard chemicals released into the ocean, for offshore wind, OTEC and salinity gradients.

Levels of confidence for some of the stressor-receptor interactions are still being established, while in some cases (e.g. for the offshore floating solar) are inconclusive and require further research. Further, the general environmental risks and impacts related to deploying infrastructure offshore are like these related to offshore non-renewables as described in sub-chapter 5A3b.

Table 5A3a.7. STRESSORS and Receptors for Offshore Renewables and the Marine Environment, including potential mitigation strategies.

Stressor	Offshore Technology	Receptors	Potential Effects	Mitigation	Citations
Collision Risk	Wave	Seabirds	Considerable underwater structure may provide an enhanced collision or entrapment risk, particularly their moving parts	Generally low risk as seabirds spend limited time underwater as well as depending on the technology employed	[58]
	Tidal, Ocean Current	Marine mammals, fish, sea turtles, diving seabirds	Injury, death	Monitoring for collision, potential for turbine shutdown.	[55]
	OTEC	NA			
	Salinity Gradients	NA			
	Fixed Offshore Wind	Birds and bats (when present)	Injury, death	Monitoring for collision, using radar technology, thermal and optical cameras to detect animal movement potential for turbine shutdown. Early warning systems such as adjusting turbine operation, warning or deterring birds, fewer lights and lower light intensity, vision-based mitigation (e.g.	[81] [43] [79] [83]

				monochromatic painting of a blade to increase visibility).	
	Floating Offshore Wind	Birds and bats (when present)	Injury, death	Monitoring for collision, using radar technology, thermal and optical cameras to detect animal movement potential for turbine shutdown. Early warning systems such as adjusting turbine operation, warning or deterring birds, fewer lights and lower light intensity, monochromatic painting of a blade to increase visibility.	[96~~96~~] [43~~43~~]
	Offshore Floating Solar Photovoltaics	NA			
Underwater Noise	Wave	Marine mammals, some species of fish	Installation noise can cause physical harm, cause animals to leave an area temporarily or permanently. Operational noise can mask critical navigation and communication functions.	Monitor for underwater noise to ensure it does not exceed regulatory or safe levels.	[55]
	Tidal, Ocean Current				
	OTEC				[42]
	Salinity Gradients	NA			

	Fixed Offshore Wind	Marine mammals, some species of fish	Installation noise can cause physical harm and/or cause animals to leave an area temporarily or permanently. Operational noise can mask critical navigation and communication functions.	Scheduling activities to avoid sensitive periods. Installation noise mitigation strategies (e.g. bubble barrier) and using innovative low-noise pile-driving techniques. Establishment of noise-free zones or buffer zones around sensitive species' habitats.	[30] [68] [84] [102~~102~~] [36] [20]
	Floating Offshore Wind				[92]
	Offshore Floating Solar Photovoltaics	NA			
Electrom-magnetic fields (EMF)	Wave	Electro- and magneto-sensitive species: some elasmobranchs (sharks, rays, skates), some	Small amounts of electricity from marine energy EMF signals below levels of harm.	Utilising shielded cables and burying cables to isolate animals from signals.	[55] [26]
	Tidal, Ocean Current				
	OTEC		Offshore floating OTEC cables could emit sufficient EMF to potentially cause harm.		[42]

	Salinity Gradients	bony fish, some crustaceans (crab, lobster, etc.)	NA		
	Fixed Offshore Wind		Offshore wind cables transmit enough power to potentially cause harm.	Bury cables to isolate animals from signals.	[104~~104~~]
	Floating Offshore Wind				[95~~95~~] [62~~62~~]
	Offshore Floating Solar Photovoltaics		Unknown, but likely the same as wind at full scale.		[29]
Habitat Changes	Wave	Anchors, foundations, cables, on the seafloor. Mooring lines and floats/platforms in the water column	Cables often buried, recovery of benthic habitats in weeks to months generally. Loss of soft bottom habitats creates new hard bottom habitats (can be beneficial for some organisms). Pelagic organisms may be attracted to or avoid lines and floats.	Careful siting of farms to avoid rare or fragile habitats.	[55]
	Tidal, Ocean Current				
	OTEC				[42]
	Salinity Gradients	NA	NA		
	Fixed Offshore Wind	Anchors, foundations, cables, on the seafloor. Mooring lines and	Cables often buried, recovery of benthic habitats in weeks to months generally. Loss of soft bottom habitats creates new hard bottom habitats (can be beneficial for some organisms). Pelagic organisms may be attracted to or avoid lines and floats.	Careful siting of farms to avoid rare or fragile habitats	[82]
	Floating Offshore Wind				[92]

	Offshore Floating Solar Photovoltaics	floats/platforms in the water column	Blocking of wind and solar radiation, changes in turbulence and mixing within the water column, and the associated impacts on sediment resuspension near the seabed.		[95]
Oceanographic System Changes	Wave	Energy capture will decrease wave height.	At large scale development, changes in circulation, wave height, sediment transport, possibly water quality and food web changes.	Monitoring and modelling of potential changes	[55]
	Tidal, Ocean Current	Energy capture will alter water movement			
	OTEC	Large volumes of cold deep ocean water pumped to surface for mixing with warm tropical surface water	Return of cold deep ocean water after heat exchange can cause thermal stress and local changes in oceanographic conditions.	Discharge cold ocean water below thermocline at depth to ensure return to appropriate density	[42]
	Salinity Gradients	Osmotic exchange of salt and freshwater from ocean and large rivers	Changes in salinity from brine disposal could alter chemistry for nearshore organisms.		
	Fixed Offshore Wind	Flow around turbines bases will be altered, causing scour.	Changes in sediment transport, possibly water quality and food web changes	Monitoring and modelling of potential changes	

	Floating Offshore Wind	Floating platforms will change surface flow	At large scale development, changes in circulation, wave height, sediment transport, possibly water quality and food web changes		[92]
	Offshore Floating Solar Photovoltaics	Large platforms covering the sea surface, anchored to the seafloor.	At large scale development, changes in circulation, sediment transport, shading, possibly water quality and food web changes.		
Entanglement	Wave	Multiple mooring lines and cables in water column	Large marine animals might become confused, and become trapped by entering into an array of lines and cables.	Only applicable for floating devices. Monitoring for potential risk. Designing turbine & supporting structures to minimise snagging risks and using biodegradable materials.	[55] [30]
	Tidal, Ocean Current				
	OTEC				[42]
	Salinity Gradients	NA			
	Fixed Offshore Wind	NA			
	Floating Offshore Wind	Multiple mooring lines and cables in water column	Large marine animals might become confused and become trapped by entering into array of lines and cables.	Monitoring for potential risk. Designing turbine & supporting structures to	[82] [30]

	Offshore Floating Solar Photovoltaics			minimise snagging risks and using biodegradable materials.	Copping et al. In press [29]
Displacement	Wave Tidal, Ocean Current OTEC	At large scale development the physical presence of many devices in the water may affect animals	Migratory animals may be forced from their routes, resulting in bioenergetic losses, increased predation or competition, potentially affecting population success. Other benthic or pelagic animals may be kept from their essential habitats for feeding, shelter, reproduction.	Sensible site selection to avoid sensitive foraging areas and protected areas (e.g. Natura2000 areas in the EU). Sitting to avoid major migratory routes. Monitoring for potential risk.	[58] [55] [43]
	Salinity Gradients	NA			
	Fixed Offshore Wind Floating Offshore Wind Offshore Floating Solar Photovoltaics	At large scale development, many devices in the water.	Migratory animals may be forced from their routes, resulting in bioenergetic losses, increased predation or competition, potentially affecting population success. Other benthic or pelagic animals may be kept from their essential habitats for feeding, shelter, reproduction.	Sensible site selection to avoid sensitive foraging areas and protected areas (e.g. Natura2000 areas in the EU). Sitting to avoid major migratory routes and installation spacing to allow for animal passage. Monitoring for potential risk.	[43] [102~~102~~] [33] [29]
Chemical Releases	Wave Tidal, Ocean Current	Generally no petroleum products onboard		Managed under hazardous waste and water quality plans in most nations.	

	OTEC	Ammonia or other heat exchange medium could leak into air or ocean, lubricants on board could leak	Spills and hazardous releases may cause injury or death to organisms from bacteria and phytoplankton to whales, altering habitats and ecosystem processes.	Creating realistic exposure scenarios to evaluate potential consequences and advocating for improved regulatory frameworks, such as the Anemoi project.	[45] [54]
	Salinity Gradients	Use of chemicals at plant could leak into coastal waters			
	Fixed Offshore Wind	Lubricants for turbines could leak into ocean			[45] [54]
	Floating Offshore Wind				
	Offshore Floating Solar Photovoltaics	Spills and use of plastics and other materials for operations and maintenance			

1
2

5A3a.6. Impact Mitigation Strategies

There is a growing discussion and deep concern about mitigating the potential negative impact of ORE installations to achieve a biodiversity-compatible energy transition [54, 46, 80, 17]. There has also been growing interest in the potential positive impacts of ORE deployments on marine ecosystems, such as the positive impacts of offshore wind turbines on localized increases in marine biodiversity and small-scale fisheries by limiting industrial-scale fishing activities. Even though uncertainties exist due to insufficient evidence [22], this section discusses the existing mitigation strategies for marine renewable energies through specific risk scales, project time scales and spatial scales.

Understanding the ecosystem effects of ORE is very important for sustainable oceans [32]. However, many knowledge gaps still need to be addressed, especially around cumulative impacts over long distances and long periods while regulations generally focus on one species or habitat at a time [35]. Thus, reconciling renewable energy production with environmental protection and the precautionary ~~principle~~ approach requires a balanced approach that integrates careful planning, robust regulations, and adaptive management. These strategies involve finding compromises and balancing interests among different stakeholders. They can include both spatial and technical solutions, as well as considerations related to the licensing of marine renewable projects and general compensation measures.

Mitigating offshore renewables risk is associated with the stage in the project lifecycle that considers the duration and extent of the pressure exerted by the devices, and the scale of the project (time scale of risk mitigation). It can include actions "before the fact" (e.g. avoiding impact), including design, deployment methods, operational strategies, maintenance methods, and decommissioning actions (Table 5A3a.Suppl.).

The impact mitigation hierarchy provides developers with a logical framework to address the potential negative impacts of development on biodiversity and ecosystem services. It is applicable to projects in any sector, including ORE, and is based on the sequential and iterative application of four actions: avoid, minimise, restore and offset. Several existing mitigation measures can be applied across all the phases of an ORE project. The environmental impact mitigation strategies hierarchy, considering optimal environmental impact minimisation throughout the lifecycle of ORE, is fundamental to best practice environmental management [47]. Multiple decisions in the process of concession, installation and operation of ORE can help avoid environmental impacts through sensible adaptive operations. Adaptive operations include site selection to avoid important seabird feeding areas, construction timing to minimise effects on spawning fish, and routing construction and maintenance vessels to minimise wildlife disturbances. Systematic environmental impact monitoring can provide data necessary to devise and improve such adaptive operation strategies (see section 5A3a.5). A measure that helps reduce environmental impact, focusing on offshore wind farms, is a vision-based mitigation strategy of painting one of the wind turbine blades black or using achromatic patterns on the blades. A study conducted onshore at Smøla in Norway has shown that annual bird fatality could be reduced by 70% compared to turbines without a painted blade [83].

Further solutions along the impact minimisation hierarchy aim at restoring biodiversity. One example is artificial reefs, which are structures designed to mimic the natural characteristics of reefs or other marine habitats [110~~110~~]. They can be strategically placed on the seabed as scour protection of energy infrastructure or in its vicinity to enhance biodiversity and restore food web complexity [85]. The structures serve as substrates for the attachment of various marine species, provide shelter and foraging opportunities for fish, crustaceans, and other aquatic organisms. By fostering the establishment of diverse marine life communities, artificial reefs contribute to offshore ecosystems' overall health and resilience. Finally, impact minimisation measures can include efforts to offset environmental impacts and enhance biodiversity. Ecological compensation may also be 'out-of-kind' and occur in a different location from where the impact happens. An example could be the reoxygenation of seawater using the oxygen byproduct of offshore green hydrogen production, but the technology is yet to be validated in offshore conditions.

All above-mentioned environmental impact minimisation measures can be called nature-inclusive design or biodiversity-positive design. The increasing incorporation of such measures into offshore installations is becoming necessary for the successful application of offshore project developers to build wind and/or multi-source offshore energy parks, as enforced by non-price criteria in offshore wind tenders (for example, in the Netherlands and UK).

To ensure sustainable ORE development, mitigation strategies should be applied at multiple spatial scales, aligned with global, regional, and local governance frameworks. These strategies should integrate ecological and social considerations, particularly net marine gain—the net positive effect on marine biodiversity and ecosystems resulting from development projects.

International policies and frameworks provide a foundation for sustainable offshore energy development. Global instruments, such as the United Nations Convention on the Law of the Sea (UNCLOS), which sets out the legal framework within which all activities within oceans and seas must be carried out, and initiatives like the Sustainable Development Goals (SDGs), that offer high-level guidance on biodiversity protection and climate action.

The transboundary impacts of ORE projects necessitate coordinated regional strategies to mitigate cumulative and shared effects. Regional environmental agreements, such as the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, and cross-border cooperation can ensure that environmental standards are upheld across multiple jurisdictions. Environmental and Social Impact Assessment (ESIA) and Environmental Impact Assessment (EIA) have been used for mitigating local impacts, applying a conservative approach to uncertainty, and managing the cumulative effects of multiple projects in a region to balance renewable generation and environmental protection [47].

At the national and local levels, strategies should be tailored to mitigate the direct impacts of offshore wind projects. These strategies cover local-based innovative and sustainable pathways,

including localised EIAs, Marine Spatial Planning (MSP), and the creation of Marine Protected Areas (MPAs) to strategically manage the location of offshore energy infrastructure, minimising impacts on critical marine habitats and species [71].

5A.3a.7 Pathways to achieving sustainability – a vision for offshore renewable energy in 2030, 2040, 2050.

This section provides a positive vision of future developments in the ORE sector based on predictions rather than evidence therefore the level of confidence for the statements can be considered inconclusive.

By 2030 global and local decision makers understand that a healthy ocean is the basis of the sustainable blue economy and global integrity, and they move beyond business-as-usual approach, targeting simultaneously economic development, ecological sustainability and human well-being. By harnessing the energy from the oceans and winds near the ocean's surface, new potential sustainable energy sources added and new opportunities in the fight against climate change unlocked. Widespread offshore energy development takes place, and tools such as marine spatial planning, adaptive management (or learning by doing), multi-use of offshore space, and application of standardised quantitative blue economy sustainability assessments applied. Efforts to understand interactions of offshore infrastructure with nature, incorporating nature-inclusive design of offshore installations and adaptive operations to ensure no harm, have resulted in emerging trends of environmentally friendly installations to provide net marine biodiversity gain. These actions have enabled sustainable growth of ORE focused on avoiding and minimising environmental impacts on the oceans.

By 2040, robust and sustainable business models and financing structures are developed that support economically sustainable commercial arrays of multiple types of offshore energy production, including not only offshore wind but also wave and tidal, OTEC, salinity gradients, floating solar, and other emerging technologies. Design of global technology facilitation mechanisms enables knowledge sharing and access to science, technology, and innovation in ORE technologies, to help close the equity gap in access, enabling the roll-out of the economically and environmentally sustainable technologies in the developing countries.

By 2040 comprehensive quantitative socio-environmental impact assessment tools are widely applied by decision-makers. This results in fair assessments of local and global, adverse and beneficial, impacts of offshore energy on the oceans, as well as solutions that ensure energy justice and equity. The tools are accessible, enabling development of a sustainable blue economy on all continents, while preserving the health of the ocean. New offshore installations worldwide focus on nature preservation and nature-inclusive design to protect and restore ocean biodiversity.

The ORE sector, as a part of a sustainable blue economy in 2050, encompasses multiple sectors and cross-sectoral activities related to the ocean in a sustainable manner, including environmental sustainability, economic growth, social inclusion and equity. Increasing

coordination and cooperation among different marine sectors maximises the sustainable use of the oceans. Further promotion of ORE technologies in developing countries including concessional and preferential terms, mutual understanding and fair equity sharing, results in a large-scale roll-out of sustainable offshore technologies all around the world.

The surface of the oceans occupied by offshore renewable energy increases 10-fold in 2050 as compared to the time of writing, while yield increases 40-fold by moving further away from shore due to technology advancements. Offshore space combines multiple sources of ORE (offshore wind and offshore floating solar or wave energy) and/or aquaculture, hydrogen production, or critical mineral recovery, for best use of ocean space. Nature-inclusive and environmentally friendly designs helped avoid and minimise environmental impacts, and increased biodiversity, mitigating climate change and the biodiversity crisis.

Most governments adopt renewable energy goals including the offshore renewable energy and the rapid scale-up of ocean energy technologies beyond offshore bottom-fixed wind, including offshore floating wind, wave, tidal, offshore floating solar and OTEC (as well as combinations of these), resulting in 4 terawatts of ocean energy installed worldwide by 2050, limiting global warming to 1.5°C.

5A.3a.8 – Offshore Renewables – summary

Understanding risks related to ORE development can lead to designs, deployment methods, operational modes, maintenance tasks, and decommissioning pathways that will minimize disturbances and harm to marine animals, habitats, and ecosystem processes. Similarly, effective mitigation measures can be designed to minimize these risks. With the application of nature-based designs and operational modes, sustainable offshore renewable energy development can support climate change mitigation as well as supporting biodiversity protection and improvements.

The increased uptake of offshore renewable energy is expected to lead to change in coastal communities. Social equity should be prioritised when considering the socio-economic impacts. The rights of Indigenous Peoples and communities needs to be foregrounded in the planned and continued development of ORE. ORE development has a high potential for employment and local economic benefits, but investment in training, education and capacity building is essential to overcome potential challenges. Assessing the impacts on coastal communities will require further research and will need to include both qualitative and quantitative analyses.

Knowledge gaps to be filled to enable the ORE vision outlined in section 5A.3a.7:

- Research and innovation are needed in new and emerging technologies including hybrid solutions, grid integration, cost reduction, derisking, circular economy for ORE components, and a whole system approach.

- Lack of access especially for some (developing) countries to accurate data or methodologies on resource characterization, technology assessment, environmental risks, application of nature-based social and economic assessments, lifecycle assessments, and financial direction, sea-bed conditions data and living marine resources and potential environmental risks.

- Lack of access to knowledge and best practices for developing and implementing marine governance in many nations.

- Lack of qualified personnel in key government departments and agencies to deal with certain aspects of the project development lifecycle, such as permitting.

- Lack of financing possibilities for ORE technologies in Least Developed Countries and limited financing possibilities in some of the Emerging Market and Developing Economies resulting in a lack of incentives and/or slow uptake of these technologies by 2030. In the view of SDG 17.6 - Knowledge sharing and cooperation for access to science, technology and innovation, there exists a possibility to close the gap in access to ORE technologies through design of global technology facilitation mechanisms.

- Limited promotion of the development, transfer, dissemination and diffusion of ORE technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed (SGD 17.7).

- Need for open data and information access that follows FAIR and FARR principles, so that all decision-makers, developers have access to the same high-quality information. Currently large amounts of environmental data are held as proprietary information when they could be open and readily available.

Supplementary materials

Offshore energy technology	Opportunities	Challenges
All ORE technologies	ORE could deliver around 10% of the global CO_2 emissions reductions required by 2050 to sustain a 1.5-degree pathway and ORE will be a vital tool in meeting the tripling of renewables, as set out at COP28.	Relatively high levelized cost of energy (LCoE), initial capital outlay, credit accessibility and insurance, inadequate support mechanisms and power pricing schemes [100]. Port and harbours require investment to facilitate growth.

	Harnessing the power of the oceans enhances energy independence and security for coastal communities. ORE causes less noise disturbance than onshore solutions, and is located close to demand centres, as almost three-quarters of the world's population live within 50km of the coast.	Lack of a stable supply chain of critical materials used for renewable energy devices and long cycles of developing new sources. Extreme weather events, availability of suitable points of interconnection, lack of servicing and maintenance capabilities, experience in cable installations [60]. Ocean-use conflict, insufficient marine spatial planning, public awareness, social acceptance, and reliable metocean data [30, 41, 93]. Discussions arise from differing viewpoints on the impact of these technologies on marine ecosystems and the visual effects on coastal landscapes.
Fixed Offshore Wind	High-capacity factors offshore and generally very large project size (GW scale). Proven technology with significant cost reduction achieved in mature markets. Generating economic growth by initiating green jobs which can be sustained over the 25-year lifetime of a project. The supply chain stimulates the economy of coastal communities, incl. new opportunities for local development, investments, knowledge transfer and capacity	Limited to shallow water depths. Port and harbours require investment to facilitate growth. Decommissioning and recycling of materials.

	building [41, 2](see also section 5A3a.3).	
Floating offshore wind	Higher capacity factor compared to fixed-bottom wind and other renewables. 80% of global potential in deeper water [69, 24]. The environmental impacts of floating offshore wind are lower than fixed-bottom offshore wind, particularly during installation, decommissioning, and operation. According to IUCN, floating wind requires less seabed disturbance, generates less underwater noise. Floating wind may result in lesser conflicts with ocean users due to its farshore location. Continuous data collection and assessment are needed to further support these statements [72, 24]. The technology is delivering power to grids, with multiple floating wind farms already in service (in Scotland, Portugal and China). The USA and other countries have conducted auctions specifically for floating offshore wind energy. The Bureau of Ocean Energy Management (BOEM) held notably an offshore wind lease sale in the Pacific region, focusing on areas off the coast of California.	Need for enabling regulatory frameworks for floating offshore wind development. Innovation in foundations, moorings and grid infrastructure ongoing, with several component concepts being explored (no convergence achieved yet) [24]. Investment needed to achieve greater project scales. Technological consolidation required for increased standardization and certification and to facilitate stable growth [72, 24]. While progress is evident, further cost reductions and scaling up are still needed to achieve full commercial maturity.

Wave energy	Immense potential and promise, predictability [27]. The theoretical potential annual global wave energy production is estimated to be 29,500TWh [5151] [27]. Global cumulative installed wave energy potential is 23.3MW (51% in Europe) [1616].	Technology not matured in the case of grid integration, mass production, and commercialization [50, 27]. High costs of installation and ongoing maintenance. Impact on marine life not fully understood [50].
Tidal current energy	The estimated global tidal energy available for extraction per year ranges between 150 and 800TWh, with theoretical potential estimates up to 1200TWh [5]. The global cumulative installed tidal current energy potential (i.e. the total capacity of all tidal current devices that have been installed, even if some of them have now been removed, operating at their maximum in ideal conditions) is 36.3MW (nearly 77% are in Europe) [16]. Significant growth in recent years [67]. Highly predictable resource. Advancements in technology, improving efficiency and cost-effectiveness. Growing evidence on low environmental impact [67].	High initial costs and infrastructure requirements. Concentration of resource in specific regions, limiting widespread implementation [59, 87, 91]. Continuing permitting challenges due to uncertainty of effects
Tidal range energy	Highly predictable resource. Established technology.	High-cost infrastructure. Significant impact on marine ecosystems.

Offshore floating solar energy	Significant resource potential. The sector has been rapidly developing over the past five years in Europe (the Netherlands, Belgium and France), as well as in Singapore and China where two pilot deployments have shown survivability through major storms. Multi-source offshore energy parks or co-use of offshore space by combination ORE technologies like offshore wind with offshore floating solar or wave energy, has been promising a diversification in (and complementarity of) electricity sources, to help overcome the inherent intermittence of (offshore) renewables.	In seas with relatively high waves, survivability can be an issue due to the large forces exerted by waves, meaning higher strength floating platforms are needed [111~~111~~]. Survivability and maintenance can be an issue in offshore locations due to wave action and distance to shore although automated maintenance is under development.
Salinity gradient energy	SGE is highly available and predictable; plants can be located either at naturally occurring gradient sites such as where rivers flow into the sea, or alongside other infrastructure such as desalination plants [40]. Blue energy can be produced without any operational CO_2 emissions. Environmental impact can be minimized, as neither water nor salt is consumed in the process, and the installations can be located underground or in low buildings. No significant noise pollution [73]. The worldwide theoretical potential for salinity gradient power has been estimated at 1,650 TWh/year [99].	Technological challenges to upscale include quality of the membranes; bio-fouling; development of the membrane modules; pre-treatment of water; production of durable and affordable membranes at scale. Operation and maintenance costs are high.
Ocean thermal	Continuously available and offers a significant resource potential, and a	Low energy conversion efficiency [38]

energy conversion (OTEC)	very high capacity to produce energy [88], [63]. Can be utilized for baseload power generation, refrigeration, seawater desalination and deep-water aquaculture, greatly improving economic benefits.	Need to improve thermal efficiency using solar energy or industrial heat. High project capital costs exacerbated by relatively low power outputs [4, 88].

Supplement Table 5A3a.Supl1. OPPORTUNITIES and challenges related to various offshore renewable energy technologies.

Risk Dimension	Definition	Cause of Risk	Mitigation	Environmental Impact	References
Technology Risk	Risk of failure or underperformance of ORE technologies.	Equipment manufacturers, technology developers, and research institutions.	Insurance, proven technology, and comprehensive technology evaluations	Hazardous material spills Lower energy production	[56, 112~~112~~, 108~~108~~]
Deployment/survival	Risk of challenges in installing and maintaining ORE infrastructure.	Contractors, environmental conditions	Project risk assessments, experienced contractors, and regular maintenance.	Disrupt marine habitats and biodiversity Debris that harms marine life Injured contractors	[39]

Regulatory	Risk from changes in laws or regulations affecting ORE projects.	legislators, regulatory agencies, and changes in government policy.	Engage with policymakers, monitor regulations, and ensure compliance.	Increased environmental degradation due to non-compliance Disruption to biodiversity due to delayed project	[56, 112~~112~~]
Financial	Risk arising from scarcity of capital or insufficient income-generating streams.	Traditional financial institutions, investors, and market behaviour	diverse funding sources (e.g., crowdfunding or P2P lending), strong investor relations	Compromise environmental protections during construction and operation.	[56, 101, 112~~112~~]
Reputational	Risk of damage to a company's image due to environmental or operational issues.	Media, environmental organizations, and public perception.	Transparent communication, public engagement, and strong ESG practices.	Decreased support for renewable energy initiatives. Heightened scrutiny impedes project development.	[112~~112~~]

Table 5A3a.Suppl.2 RISKS related to offshore renewable installations deployment.

Socio-economic impact criteria	Examples

Distribution of Impacts Understanding the ways in which the harms and benefits are distributed. Are specific groups more marginalized than others? Do specific groups benefit more than others? Are there issues of equity or environmental justice?	The development of large-scale ORE infrastructure may impact already marginalised communities, both positively and negatively [3434]. Often the most marginalised may be the ones who are most negatively impacted in the development of ORE. Mechanisms may be used to ensure that there is an appropriate distribution of the harms and benefits, such as through community benefit schemes, compensation for loss of livelihood, provisions to support women and minority-owned businesses in the supply chain [3434]. Ensuring equitable distribution of impacts begins in the energy planning process, including in siting, and involves early, frequent and appropriate community engagement. Equitable processes include appropriate engagement and decision making, such as giving communities a voice in decision making processes. It works best when appropriate mechanisms for transparency and accountability are included.
Spatial Scale of Impacts How to define who the 'community' is by which to measure impacts?	There are many components that comprise ORE infrastructure and this spatial scope is important as the social impacts may be broad in geographical scope when the whole supply chain is considered. Furthermore, there is no clear delineation of what constitutes a community in relation to offshore infrastructure as there would be on land. The infrastructure is offshore, but the people but the people who are impacted live onshore and potentially comprise a range of different groups, based in different locations who are impacted in different ways.
Temporal Scope Over what period to consider the impacts?	There are several phases in the lifecycle of ORE infrastructure, with different activities taking place in each one. These will generate different impacts, and there may also be impacts associated with the transition between phases. Understanding the cumulative impacts of ORE developments on coastal communities is therefore significant. Research suggests there is a need for more long-term longitudinal studies on the socio-economic impacts of ORE [3131].

Nature of the Impact	The nature of the impact can be tangible, intangible, direct or in-direct. Impacts can also be negative (such as loss of income, or damage to visual amenity), or can be positive (such as a reduction in air pollution leading to increased health outcomes, or an equitable community benefits scheme). Specific sectors, or groups of people may be more impacted that others. Existing ocean users such as fishers are a good example of this. In terms of fisheries, there are the social impacts due to the displacement of fishing activities to enable offshore renewable energy developments. The displacement of fishing activities can lead to further impacts and displacements within the community which are likely to be different from place to place differ regionally. These impacts are not only felt in economic terms but in social terms through loss of tradition and social fabric.

Table 5A3a.Suppl.3. COMPLEXITIES of identifying socio-economic impacts of offshore renewables infrastructure development.

No	Region/Country	Timeframe	Capacity	Employment Impact
1	UK	2030	50 GW	100,000 jobs
2	US	2030	30 GW	15,000 to 58,000 jobs
3	EU	2030	70 GW	77,000 jobs
4	China	2025	140 GW	Not available
5	Japan	2030	10 GW	35,000 jobs
6	Republic of Korea	2030	14 GW	770,000 jobs

Table 5A3a.Suppl.4. PROJECTIONS for job creation potential in ORE sector [14]. Level of confidence established but incomplete.

Year	*2027*	*2030*	*2035*	*2040*	*2045*	*2050*
European Union		111				317

UK	50*				
Netherlands	22.2		50		70
Germany	30	40		>70	
Denmark	12.9				
Belgium	5.7		8		
France		18			45
Poland	10.9**				
Norway			30		
Ireland	7		20		37
Spain	3				
Portugal	2				
Greece	2				

Table 5A3a.Supl.5. OFFSHORE wind targets in GW set by European countries [14~~14~~], * Including 5 GW floating wind, ** in operation or under development.

Table 5A3a.Suppl.6 ENVIRONMENTAL impact mitigation strategies hierarchy throughout ORE lifecycle.

Mitigation Hierarchy	Project Phases	Key Points and Approaches
Avoid	Design & Planning Phase	Careful siting to avoid ecologically sensitive areas; marine spatial planning
	Operational Strategies	Adaptive operations (e.g. turning installations off during species migration to enable safe passage)
	Deployment Methods	Incorporating spatially explicit biodiversity data for considering potential cumulative impacts on biodiversity; Designing devices that minimise disruption to natural water flow; employing advanced technologies and minimising physical footprint; Construction timing to minimise impact;

Minimise		Construction vessels routing to minimise disturbances
Restore	Operational Strategies	Implementing real-time monitoring systems and adaptive management; Maintenance vessels routing to minimise disturbances; Adaptive operations coupled with systematic environmental monitoring; Vision-based impact minimisation (e.g. painting installations in monochromatic patters to improve their visibility)
	Maintenance Methods	Restoration of habitats post-construction, adding nature-inclusive design (or biodiversity-positive) elements e.g. structures with positive artificial reef effect designed to mimic natural characteristics of marine habitats
Offset	Operation and Decommissioning Actions	Sustainable transition to artificial reefs or industry tourism destinations; Seawater reoxygenation; Ecological compensation (also out-of-kind)

References

[1] https://www.cfdallocationround.uk/about.

[2] Oersted report. advantages of offshore wind. Technical report.

[3] United nations declaration on the rights of indigenous peoples - resolution, 2007. Adopted by the General Assembly, A/RES/61/295, 2.

[4] Ocean thermal energy conversion. technology brief. Technical report, International Renewable Energy Agency, 2014.

[5] Innovation outlook: Ocean energy technologies. Technical report, International Renewable Energy Agency (IRENA), 2020.

[6] Scotland's marine assessment https://marine.gov.scot/sma/, 2020.

[7] Tidal current energy developments. highlights. Technical report, Ocean Energy Systems, 2021.

[8] Geopolitics of the energy transition: Critical materials, 2023.

[9] *Development Co-operation Report 2024: Tackling Poverty and Inequalities through the Green Transition*. OECD, July 2024.

[10] Eu-scores: European scalable offshore renewable energy sources project https://euscores.eu/, 2024.

[11] Euro-tides project https://www.euro-tides.eu/, 2024.

[12] European commission critical raw materials act, 2024.

[13] Global offshore wind alliance (gowa) https://www.irena.org/energy-transition/partnerships/gowa, 2024.

[14] Global wind report 2024. Technical report, Global Wind Energy Council, 2024.

[15] The international vision for ocean energy, 2024.

[16] Ocean energy stats & trends 2023. Technical report, Ocean Energy Europe, 2024.

[17] Oceans and the law of the sea: oceans and the law of the sea. resolution 79/144 adopted by the general assemblyon 12 december 2024. Technical report, United Nations, 2024.

[18] Saoirse wave energy project https://saoirsewaveenergy-prd-web-01-01.azurewebsites.net/info, 2024.

[19] Seaworthy project https://floatingpowerplant.com/commercial-demonstrator-project/, 2024.

[20] Aguilar N. Canadas A. Engel M. Frantzis A. Hatch L. Hoyt E. Kaschner K. LaBrecque E. Martin V. Agardy, T. and G. Notarbartolo di Sciara. A global scientific workshop on spatio-temporal management of noise. Technical report, In Report of the Scientific Workshop (Vol. 51). Puerto Calero, Lanzarote: Leviathan Sciences, 2007.

[21] Edward H. Allison, John Kurien, Yoshitaka Ota, Dedi S. Adhuri, J. Maarten Bavinck, AndrÃ©s Cisneros-Montemayor, Michael Fabinyi, Svein Jentoft, Sallie Lau, Tabitha Grace Mallory, Ayodeji Olukoju, Ingrid van Putten, Natasha Stacey, Michelle Voyer, and Nireka Weeratunge. *The*

Human Relationship with Our Ocean Planet, pages 393–443. Springer International Publishing, 2023.

[22] Mathias H. Andersson and Marcus C. Ã–hman. Fish and sessile assemblages associated with wind-turbine constructions in the baltic sea. *Marine and Freshwater Research*, 61(6):642, 2010.

[23] B.K. Arbic, E. Mahu, and et al. Ocean decade vision 2030 white papers challenge 9: Skills, knowledge, technology, and participatory decision making for all., 2024.

[24] 34.BVG Associates. Guide to a floating offshore wind farm, 2023.

[25] RS Aswani, Shambhu Sajith, and Mohammad Younus Bhat. Is geopolitics a threat for offshore wind energy? a case of indian ocean region. *Environmental Science and Pollution Research*, 28(25):32683–32694, February 2021.

[26] Ertugrul Ayyildiz and Melike Erdogan. A comprehensive approach to evaluate risk mitigation strategies in offshore wind farms using spherical fuzzy decision making analysis. *Ocean Engineering*, 311:118881, 2024.

[27] Arnob Barua and Md Salauddin Rasel. Advances and challenges in ocean wave energy harvesting. *Sustainable Energy Technologies and Assessments*, 61:103599, January 2024.

[28] Maria Bebianno, Hilconida Calumpong, Sanae Chiba, Karen Evans, Carlos Garcia-Soto, Osman Kamara, Enrique Marschoff, Essam Mohammed, Henn Ojaveer, Chul Park, Ylenia Randrianarisoa, R. Ruwa, JÃ¶rn Schmidt, Alan Simcock, Anastasia Strati, Joshua Tuhumwire, Ca Vu, Juying Wang, and Tymon Zielinski. *World Ocean Assessment II, Chapter 8a, Coastal communities and maritime industries*. 04 2021.

[29] Steven Benjamins, Benjamin Williamson, Suzannah-Lynn Billing, Zhiming Yuan, Maurizio Collu, Clive Fox, Laura Hobbs, Elizabeth Masden, Elizabeth Cottier, and Ben Wilson. Potential environmental impacts of floating solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 199:114463, 05 2024.

[30] L. Bennun, J. van Bochove, C. Ng, C. Fletcher, D. Wilson, N. Phair, and G. Carbone. *Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers*. IUCN, International Union for Conservation of Nature, February 2021.

[31] Samantha Bingaman, Jeremy Firestone, and David Bidwell. Winds of change: examining attitude shifts regarding an offshore wind project. *Journal of Environmental Policy & Planning*, 25(1):55–73, June 2022.

[32] EU Marine Board. European offshore renewable energy: towards a sustainable future. future science brief. Technical report, 2023.

[33] Paul A.J. Bonar, Ian G. Bryden, and Alistair G.L. Borthwick. Social and ecological impacts of marine energy development. *Renewable and Sustainable Energy Reviews*, 47:486–495, 2015.

[34] Sam Bourg-Meyer, Vero / Schacht. Offshore wind and equity: State of the states report. Technical report, Clean Energy States Alliance, 2022.

[35] Suzanne J. Boyes and Michael Elliott. Marine legislation. the ultimate horrendogram: International law, european directives & national implementation. *Marine Pollution Bulletin*, 86(1â€“2):39–47, September 2014.

[36] MJ Brandt, AC Dragon, A Diederichs, MA Bellmann, V Wahl, W Piper, J Nabe-Nielsen, and G Nehls. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in germany. *Marine Ecology Progress Series*, 596:213–232, May 2018.

[37] D. Cevasco, S. Koukoura, and A.J. Kolios. Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications. *Renewable and Sustainable Energy Reviews*, 136:110414, February 2021.

[38] Wei Chen and Erguang Huo. Opportunities and challenges of ocean thermal energy conversion technology. *Frontiers in Energy Research*, 11, May 2023.

[39] Jui-Sheng Chou, Pin-Chao Liao, and Chung-Da Yeh. Risk analysis and management of construction and operations in offshore wind power project. *Sustainability*, 13(13):7473, July 2021.

[40] Micale G. Cipollina, A. *Sustainable Energy from Salinity Gradients*. Elsevier, 2016.

[41] Allianz Commercial. A turning point for offshore wind. global opportunities and risk trends. opportunities and risks in offshore wind. Technical report, Allianz Report, 2023.

[42] H. Copping, A.; Farr. Feasibility, environmental effects, and social acceptance of ocean thermal energy conversion. Technical report, Report by Pacific Northwest National Laboratory (PNNL). Report for US Department of Energy (DOE)., 2023.

[43] Donald A. Croll, Aspen A. Ellis, Josh Adams, Aonghais S.C.P. Cook, Stefan Garthe, Morgan Wing Goodale, C. Scott Hall, Elliott Hazen, Bradford S. Keitt, Emma C. Kelsey, Jeffery B. Leirness, Don E. Lyons, Matthew W. McKown, Astrid Potiek, Kate R. Searle, Floor H. Soudijn, R. Cotton Rockwood, Bernie R. Tershy, Martin Tinker, Eric A. VanderWerf, Kathryn A. Williams, Lindsay Young, and Kelly Zilliacus. Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds. *Biological Conservation*, 276:109795, December 2022.

[44] Laura Vittoria De Luca Pena, Jo Dewulf, Jan Staes, Ine Moulaert, Sara Vandamme, Johanna J. Heymans, and Sue Ellen Taelman. Assessing the sustainability of blue economy

activities using an ecosystem and life cycle-based approach: Possibilities, challenges and implications for an informed policy making. *Ocean & Coastal Management*, 257:107360, 2024.

[45] Bavo De Witte. Towards minimal chemical pollution and greater sustainability of offshore wind energy production, 2023.

[46] Steven Degraer, Jennifer Dannheim, Andrew B. Gill, Han Lindeboom, and Dan Wilhelmsson. Preface: the winmon.be 2013 conference: steps towards an efficient and effective offshore wind farm environmental impact assessment. *Hydrobiologia*, 756(1):1–2, May 2015.

[47] the Environment Department of Climate Change, Energy and Canberra Water. Guidance-key environmental factors for offshore windfarm environmental impact assessment under the environment protection and biodiversity conservation act 1999, 2023.

[48] Patrick Devine-Wright and Yuko Howes. Disruption to place attachment and the protection of restorative environments: A wind energy case study. *Journal of Environmental Psychology*, 30(3):271–280, September 2010.

[49] Andreanne Doyon, Jonathan Boron, and Stephen Williams. Unsettling transitions: Representing indigenous peoples and knowledge in transitions research. *Energy Research & Social Science*, 81:102255, November 2021.

[50] Earth.org. The pros and cons of wave energy https://earth.org/the-pros-and-cons-of-wave-energy/, 2023.

[51] Ocean Energy Europe. Wave energy https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/, 2024.

[52] AntÃ³nio F. de O. FalcÃ£o. Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3):899–918, April 2010.

[53] Executive Agency for Small, Medium sized Enterprises, European MSP Platform, S.Pro., University of Liverpool., Thetis., and ECORYS. *Addressing conflicting spatial demands in MSP: considerations for MSP plannersâ€¯: final technical study.* Publications Office, 2019.

[54] Menchaca I. Seeger I. Nurmi M. McDonald H. Garmendia J.M. Pouso S. Borja Ã. Galparsoro, I. Mapping potential environmental impacts of offshore renewable energy. etc/ icm report 2/2022: European topic centre on inland, coastal and marine waters. Technical report, 2022.

[55] Copping A. E. Hemery L. G. Freeman M. C. editors. Garavelli, L. Oes-environmental 2024 state of the science report: Environmental effects of marine renewable energy development around the world. report for ocean energy systems (oes). Technical report, 2024.

[56] Nadine Gatzert and Thomas Kosub. Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks. *Renewable and Sustainable Energy Reviews*, 60:982–998, 2016.

[57] John Glasson, Bridget Durning, Tokunbo Olorundami, and Kellie Welch. Guidance on assessing the socio-economic impacts of offshore wind farms (owfs). 2020.

[58] Deborah Greaves, Daniel Conley, Davide Magagna, Eduardo Aires, JosÃ© Chambel LeitÃ£o, Matthew Witt, Clare B. Embling, Brendan J. Godley, Anthony W.J. Bicknell, Jean-Baptiste Saulnier, Teresa Simas, Anne Marie Oâ€™Hagan, John Oâ€™Callaghan, Brian Holmes, Jan Sundberg, Yago Torre-Enciso, and Dorleta Marina. Environmental impact assessment: Gathering experiences from wave energy test centres in europe. *International Journal of Marine Energy*, 14:68–79, June 2016.

[59] Green.org. Advantages and disadvantages of wave and tidal energy., 2024.

[60] Xiong-Wei Han, Wei-Bin Zhang, Xue-Jing Ma, Xia Zhou, Qiang Zhang, Xu Bao, Yao-Wen Guo, Lun Zhang, and Jianping Long. Reviewâ€"technologies and materials for water salinity gradient energy harvesting. *Journal of The Electrochemical Society*, 168(9):090505, September 2021.

[61] Daniel J. Hasselman, Lenaig G. Hemery, Andrea E. Copping, Elizabeth A. Fulton, Jennifer Fox, Andrew B. Gill, and Brian Polagye. â€˜scaling upâ€™ our understanding of environmental effects of marine renewable energy development from single devices to large-scale commercial arrays. *Science of The Total Environment*, 904:166801, December 2023.

[62] Annemiek Hermans, Hendrik V. Winter, Andrew B. Gill, and Albertinka J. Murk. Do electromagnetic fields from subsea power cables effect benthic elasmobranch behaviour? a risk-based approach for the dutch continental shelf. *Environmental Pollution*, 346:123570, April 2024.

[63] Jorge Herrera, Santiago Sierra, and Asier Ibeas. Ocean thermal energy conversion and other uses of deep sea water: A review. *Journal of Marine Science and Engineering*, 9(4):356, March 2021.

[64] Northrop E. et al. Hoegh-Guldberg, O. The ocean as a solution to climate change: Updated opportunities for action. Technical report, Commissioned by High Level Panel for Sustainable Ocean Economy, 2023.

[65] Supergen ORE Hub. Ore outlook 2040uk offshore renewable energy in 2040:building a sustainable and competitive ore sector on a pathway to net zero by 2050, 2024.

[66] United Nations Environment Program Finance Initative. Harmful marine extractives: Understanding the risks & impacts of financing non-renewable extractive industries. offshore oil and gas., 2022.

[67] Groove Insights. Wave and tidal energy market: Challenges, opportunities, and growth drivers and major market players forecasted for period from 2023 - 2030., 2023.

[68] Anastasia Ioannou, Andrew Angus, and Feargal Brennan. Informing parametric risk control policies for operational uncertainties of offshore wind energy assets. *Ocean Engineering*, 177:1–11, 2019.

[69] IRENA. Floating offshore wind outlook. Technical report, International Renewable Energy Agency, 2024.

[70] Zhiyu Jiang. Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews*, 139:110576, April 2021.

[71] Niall O'Dea Julio Cordano. Informal summary report of the 2024 ocean and climate change dialogue on the topic "technology needs for the ocean, including climate action and finance links"2024. Technical report, UNFCCC, 2024.

[72] Michael Kausche, Frank Adam, Frank Dahlhaus, and Jochen GroÃŸmann. Floating offshore wind - economic and ecological challenges of a tlp solution. *Renewable Energy*, 126:270–280, 2018.

[73] Frank Kempener, Ruud; Neumann. Ocean energy technology. salinity gradient energy technology brief. Technical report, International Renewable Energy Agency (IRENA), 2014.

[74] Vikas Khare, Cheshta Khare, Savita Nema, and Prashant Baredar. *Prefeasibility Assessment of a Tidal Energy System*, pages 115–188. Elsevier, 2019.

[75] Maaike Knol-Kauffman, KÃ¥re Nolde Nielsen, Gunnar Sander, and Peter Arbo. Sustainability conflicts in the blue economy: planning for offshore aquaculture and offshore wind energy development in norway. *Maritime Studies*, 22(4), October 2023.

[76] Al LiVecchi, Andrea Copping, Scott Jenne, Alicia Gorton, Robert Preus, Gary Gill, Robi Robichaud, Rebecca Green, Simon Geerlofs, Simon Gore, David Hume, William McShane, Carrie Schmaus, and Heather Spence. *Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Various Maritime*. April 2019.

[77] Jane Lubchenco and eds. Peter M. Haugan. *The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy*. Springer International Publishing, 2023.

[78] MarÃ-a LÃ³pez-Morado, LucÃ-a Santiago CaamaÅ„o, and Vicente DÃ-az CasÃ¡s. Bridging the skills gap of workers in the offshore renewable energies industry by creating a set of guidelines to promote innovative training. In *2024 IEEE Global Engineering Education Conference (EDUCON)*, pages 1–7. IEEE, May 2024.

[79] Jens LÃ¼deke. Offshore wind energy: Good practice in impact assessment, mitigation and compensation. *Journal of Environmental Assessment Policy and Management*, 19(01):1750005, March 2017.

[80] Thilo Marauhn, Ayse-Martina Boehringer, and Magdalena Jas-Nowopolska. Mitigating negative impacts of marine renewable energy on biodiversity: The role of international environmental law. *Prawo Morskie*, (No XLII):47–75, 2022.

[81] Graham R. Martin and Alex N. Banks. Marine birds: Vision-based wind turbine collision mitigation. *Global Ecology and Conservation*, 42:e02386, April 2023.

[82] Sara M. Maxwell, Francine Kershaw, Cameron C. Locke, Melinda G. Conners, Cyndi Dawson, Sandy Aylesworth, Rebecca Loomis, and Andrew F. Johnson. Potential impacts of floating wind turbine technology for marine species and habitats. *Journal of Environmental Management*, 307:114577, April 2022.

[83] Roel May, Torgeir Nygard, Ulla Falkdalen, Jens Astrom, Oyvind Hamre, and Bard G. Stokke. Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, 10(16):8927–8935, July 2020.

[84] Goodluck Msigwa, Joshua O. Ighalo, and Pow-Seng Yap. Considerations on environmental, economic, and energy impacts of wind energy generation: Projections towards sustainability initiatives. *Science of The Total Environment*, 849:157755, November 2022.

[85] Janne Nauta, Marjolijn J. A. Christianen, Ralph J. M. Temmink, Gregory S. Fivash, Beatriz Marinâ€Diaz, ValÃ©rie C. Reijers, Karin Didderen, Emma Penning, Annieke C. W. Borst, Jannes H. T. Heusinkveld, Maarten Zwarts, Peter M. J. M. Cruijsen, Nadia Hijner, Wouter Lengkeek, Leon P. M. Lamers, Tjisse van der Heide, Tjeerd J. Bouma, Daphne van der Wal, Han Olff, and Laura L. Govers. Biodegradable artificial reefs enhance food web complexity and biodiversity in an intertidal softâ€sediment ecosystem. *Journal of Applied Ecology*, 60(3):541–552, January 2023.

[86] D. Niezrecki. Why us offshore wind power is struggling the good the bad and the opportunity. the conversation, May 2024.

[87] Tim ODoherty, Daphne M. ODoherty, and Allan Masonâ€Jones. Tidal energy technology, March 2018.

[88] OES. White paper on ocean thermal energy conversion (otec). Technical report, IEA Technology Programme for Ocean Energy Systems (OES), 2021.

[89] European Court of Auditors. *Offshore renewable energy in the EU: ambitious plans for growth but sustainability remains a challenge. Special report 22, 2023.* Publications Office, 2023.

[90] Offshore-energy.biz. Nova innovation secures â,¬20m from eu for 4mw tidal energy project, 2024.

[91] Joe Onoufriou, Debbie J.F. Russell, Dave Thompson, Simon E. Moss, and Gordon D. Hastie. Quantifying the effects of tidal turbine array operations on the distribution of marine mammals: Implications for collision risk. *Renewable Energy*, 180:157–165, December 2021.

[92] Fatemeh Rezaei, Pasquale Contestabile, Diego Vicinanza, and Arianna Azzellino. Towards understanding environmental and cumulative impacts of floating wind farms: Lessons learned from the fixed-bottom offshore wind farms. *Ocean & Coastal Management*, 243:106772, September 2023.

[93] Shambhu Sajith, R S Aswani, Mohammad Younus Bhatt, and Anil Kumar. Challenges and opportunities for offshore wind energy from global to indian context: directing future research. *International Journal of Energy Sector Management*, July 2024.

[94] Fred Saunders, Ralph Tafon, Maaike Knol-Kauffman, and Samiya Ahmed Selim. Introductory commentary: Marine conflicts and pathways to sustainability in an era of blue growth and climate change. *Maritime Studies*, 23(1), January 2024.

[95] Heye S. Troost T. Schneider, L. Impact of offshore floating solar on the marine environment. Deltares review 11208338-000-zks-0008, Deltares, 2023.

[96] Stephanie R. Schneider, Sharon H. Kramer, Sophie B. Bernstein, Scott B. Terrill, David G. Ainley, and Shari Matzner. Autonomous thermal tracking reveals spatiotemporal patterns of seabird activity relevant to interactions with floating offshore wind facilities. *Frontiers in Marine Science*, 11, April 2024.

[97] Perra V. M. Tsafonias G. Boile M. & Lago L. F. Sdoukopoulos, E. *Boosting offshore renewable energy in Europe: Skills shortages and gaps in education and training.*, pages 559–566. 2019.

[98] Basel Abu Sharkh, Ahmad A. Al-Amoudi, Mohammed Farooque, Christopher M. Fellows, Seungwon Ihm, Sangho Lee, Sheng Li, and Nikolay Voutchkov. Seawater desalination concentrateâ€"a new frontier for sustainable mining of valuable minerals. *npj Clean Water*, 5(1), March 2022.

[99] Øystein S. Skråmestø, Stein Erik Skilhagen, and Werner Kofod Nielsen. Power production based on osmotic pressure. 2009.

[100] Jeremy Stefek, Chloe Constant, Caitlyn Clark, Heidi Tinnesand, Corrie Christol, and Ruth Baranowski. *U.S. Offshore Wind Workforce Assessment*. October 2022.

[101] Bjarne Steffen. Estimating the cost of capital for renewable energy projects. *Energy Economics*, 88:104783, May 2020.

[102] Uwe Stoeber and Frank Thomsen. How could operational underwater sound from future offshore wind turbines impact marine life? *The Journal of the Acoustical Society of America*, 149(3):1791–1795, March 2021.

[103] Ralph Tafon, Bruce Glavovic, Fred Saunders, and Michael Gilek. Oceans of conflict: Pathways to an ocean sustainability pact. *Planning Practice & Research*, 37(2):213–230, May 2021.

[104] Bastien Taormina, Juan Bald, Andrew Want, Gerard Thouzeau, Morgane Lejart, Nicolas Desroy, and Antoine Carlier. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, 96:380–391, November 2018.

[105] Jing Tian, Sam Anthony Culley, Holger Robert Maier, and Aaron Carlo Zecchin. Is renewable energy sustainable? potential relationships between renewable energy production and the sustainable development goals. *npj Climate Action*, 3(1), May 2024.

[106] Norman Toro, Pedro Robles, and Ricardo I. Jeldres. Seabed mineral resources, an alternative for the future of renewable energy: A critical review. *Ore Geology Reviews*, 126:103699, 2020.

[107] Secretariat UNFCCC. Nationally determined contributions under the paris agreement. synthesis report by the secretariat. Technical report, UN Climate Change Conference - Baku, November 2024.

[108] Maria M. Vanegas-Cantarero, Shona Pennock, Tianna Bloise Thomaz, Henry Jeffrey, and Matthew J. Dickson. Beyond lcoe: A multi-criteria evaluation framework for offshore renewable energy projects. *Renewable and Sustainable Energy Reviews*, 161:112307, 2022.

[109] Paola Villavicencio Calzadilla and Romain Mauger. The uns new sustainable development agenda and renewable energy the challenge to reach sdg7 while achieving energy justice. *Journal of Energy & Natural Resources Law*, 36(2):233–254, October 2017.

[110] Baptiste Vivier, Jean-Claude Dauvin, Maxime Navon, Anne-Marie Rusig, Isabelle Mussio, Francis Orvain, Mohamed Boutouil, and Pascal Claquin. Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. *Global Ecology and Conservation*, 27:e01538, 2021.

[111] Thi Thu Em Vo, Hyeyoung Ko, Junho Huh, and Namje Park. Overview of possibilities of solar floating photovoltaic systems in the offshore industry. *Energies*, 14(21):6988, October 2021.

[112] Shan Zhou and Pu Yang. Risk management in distributed wind energy implementing analytic hierarchy process. *Renewable Energy*, 150:616–623, 2020.

Section 5A
SubChapter 3B : Non-renewable Energies – Offshore Hydrocarbons

1. Keynotes

- Offshore oil and gas production accounts for nearly one-third of global output, with deepwater and ultra-deepwater reserves driving recent exploration growth in regions such as the North and South Atlantic, West Africa, and Southeast Asia.
- Oil spills cause prolonged ecological disruption, with hydrocarbons persisting in food webs and affecting health, reproduction, and population dynamics for a long time.
- Despite the growth in the volume of the world's oil production, there is a downward trend in the number of oil spill incidents and in the amount of oil released to the ocean due to improved regulation and technology.
- Technological advances in oil and gas are cutting costs, risks, and emissions, but new remote-operation challenges and climate goals demand deeper efficiency and reduced demand.
- Offshore hydrocarbon development provides infrastructure growth, job creation, and increased government revenues, yet its benefits are often unevenly distributed, leading to social tensions with local communities.

- ~~Magnitude and scope of the offshore Oil and gas industry~~
- ~~Deepwater perspectives and projections~~
- ~~Offshore installation disasters and their impacts, including longer-term effects.~~
- ~~Impacts to the marine environment from acute or chronic discharges of offshore oil and gas exploration~~
- ~~CONFLICTS AND PUBLIC ACCEPTANCE IN THE OFFSHORE HYDROCARBON~~

2. Introduction

In the last 20 years, offshore has been responsible for 30% of world oil production. 43% of this offshore production is concentrated in 5 nations: in a confortable first place with 13% of the global total is Saudi Arabia, and then Brazil, Mexico, Norway and United States, and although the exploration and development activity coincides with these geographic focus, there are important developments underway in shallow water and deep water exploration projects (Fig. 1)

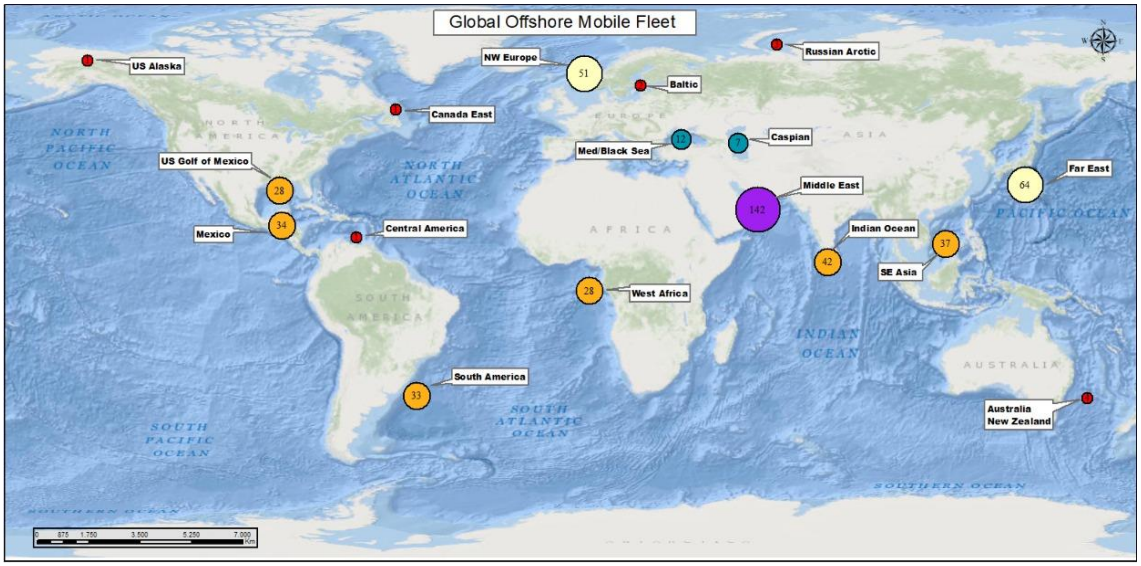


Fig. 1: Global offshore Mobile fleet (G. Olmedo, Rigzone.com)

Asia and offshore hydrocarbon activity have prospered nonpareil: In the Far East, Malaysia and Indonesia are at the forefront of deepwater developments and offshore shelf expansión, more to the South east region big China Deep wáter developments and ultradeep from Viet Nam and Brunei Darussalam, in the South China Sea. And in the South Pakistan offshore deepwater´s and offshore shelf exploration and shallow water long data productive fields in India. Angola, Nigeria, Ghana, and Mozambique have emerged as key players in the African offshore sector. The west africa deep water exploration prospects and results has captured the attention of the operators in a global context.

In the caribean region Guyana's discoveries offshore oil and natural gas resources are currently located within the Guyana-Suriname Basin of the Atlantic Ocean , and is game changer to Guyana that has become key contributor to global crude oil after Brazil .

In the South Atlantic, although hydrocarbon volumes are not as significant as in the Caribbean, there is active exploration in both shallow and deep waters. Mainland Argentina and Uruguay are pursuing exploratory drilling in the Argentina Norte and Punta del Este basins, while the Falkland Islands (Malvinas)[44], have seen intensive exploration in the North Falkland Basin.

~~in the South Atlantic without such exuberant hydrocarbon volumes but with intensive exploration of shallow waters and projects in deep waters, Mainland Argentina and Uruguay, and the Falkland Islands (Malvinas)* in the disputed EEZ.~~

~~* 'A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).'~~

Offshore exploration and production activities

[44] A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).

The deeper the water, the higher the extraction costs but with the high-resolution geophysical exploration technology, many major new deposits have been discovered around 10 times larger than newly discovered onshore fields, which makes deepwater and ultra-deepwater production an attractive prospect despite the higher costs. (Fig. 2)
The deepwater and ultra-deepwater sectors are thus becoming ever more important: oil and gas extraction at water depths greater than 400 metres is currently limited in scale, amounting to just 7 per cent of global production.

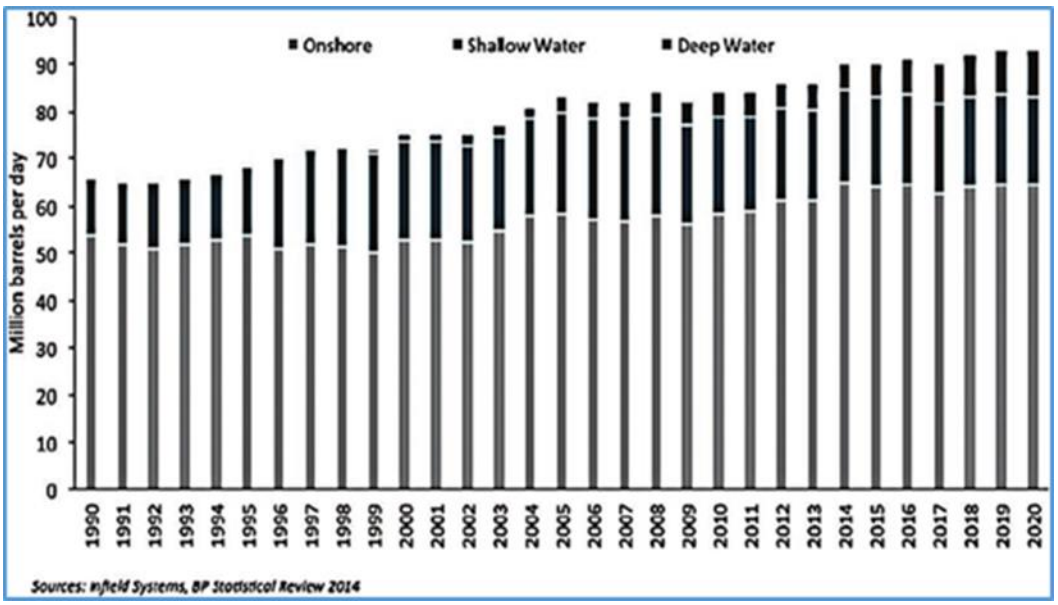


Fig. 2: Offshore water depths vs cost of offshore water drilling (Infield Systems, BP statistical Review)

The largest mobile offshore drilling units region remains the Middle East, with just over 29% of the global fleet (shallow water jackups). The second- and third-largest regions are still the Far East, with approximately 13% of the fleet, and Northwest Europe, which has just over 10% of the fleet. South America region has become largest to an increase in Brazil and Guyana. Northwest Europe continued to be the leading region for semisubmersibles, with almost 40% of the global fleet. The Far East and South America round out the top three regions for semisubmersibles. Key statistics from the 2023 census include the positive developments for global mobile offshore drilling units with a 79% equipment occupancy rate.

Production

The year 2024 marks the 77th anniversary of the first commercial offshore oil well drilled by a "mobile" rig out-of-sight of land. Since then, operators have moved progressively further and deeper in search of exploration and production opportunities, aided and accompanied by rapid technological advances.

Offshore oil and gas production are explored in many parts of the world, with the top producing areas being the Middle East, the North Sea, Brazil, the Gulf of Mexico, Africa in the Gulf of Guinea and the Caspian Sea. In addition to resource development, some elements of the supply chain that used to be exclusively onshore – notably liquefaction of methane and storage and re-gasification of liquefied natural gas (LNG) – are now increasingly taking place on specially designed offshore vessels.

Offshore has also been a focus of exploration activity. The largest recent oil and gas finds have all been in deepwater (defined in IEA analysis as water depth greater than 400 m): deepwater finds on average have accounted for about 50% of the discovered conventional oil and gas volumes for the past ten years. Some of these have been oil, notably the prolific "pre-salt"3 finds in Brazil, but more than half of all the new hydrocarbon resources discovered over the last decade have been gas, such as the Zohr and Leviathan fields in the Mediterranean, the Rovuma basin finds off Mozambique and Tanzania, and recent discoveries off Mauritania, Senegal and Côte d'Ivoire (in 2021 and 2024).

In recent years, under the influence of low oil prices and the global "COVID-19" pandemic, offshore oil production has grown slowly. However, due to the rapid decline of onshore oil and gas recoverable reserves, offshore oil's proportion of world oil production increased instead.

In 2022, global crude oil production increased by a record 5.4% rate, much above its 2021 growth (+1.6%) and its 2010-2019 average (+1.3%/year), in a context of global economic growth and progressive OPEC+ crude oil production adjustment (+0.4 mb/d each month until phasing out the 5.8 mb/d production adjustment).

Analysis of perspectives and projections

Global deepwater oil resources are mainly concentrated in the middle and south sections of the Atlantic Ocean. Deepwater gas resources are relatively widely spread and mainly distributed in the northern part of Atlantic Ocean deepwater basins, the deepwater basins of East Africa, the deepwater basins of the Neo-Tethys region ~~(Fig. 3)~~ and the deepwater basins around the Arctic Pole.

There will be six domains for future oil-gas exploration of global deepwater basins which are characterized by "two old and four new" domains; specifically, "two old" domains referring to the Atlantic offshore deepwater basins and offshore deepwater basins of the Neo-Tethys structural domain ~~(Fig. 4)~~, where the exploration degree is relatively high, and the potential is still great. While the "four new" domains stand for pre-salt and ultra deepwater basin formations, offshore deepwater basins surrounding the North Pole area and West Pacific

offshore deepwater basins and the new fields will be the main fields of deepwater oil and gas exploration in the future.

Pressures and Impacts

3.1. Environmental Impacts

Offshore oil and gas exploration can cause significant environmental impacts, both acute (from spills, and blowouts) but also from transport (pipeline breakage or ship accidents) and chronic (long-term, often from routine discharges). Natural seepage can also be substantial in some areas contributing to increased background levels.

Key impacts include:

I. Oil Spills and Hydrocarbon Release

- **Acute Impacts:** Large oil spills result in immediate harm to marine life, coating animals and plants, impairing their ability to breathe, move, and feed (e.g. Beyer et al., 2016).
- **Chronic Impacts:** Continuous release of smaller amounts of hydrocarbons and chemicals can lead to bioaccumulation, disrupting the food chain and impacting species over time.

II. Chemical Discharges (Drilling Muds and Cuttings)

- **Acute Impacts:** Drilling muds, often laden with toxic chemicals, can smother benthic (seafloor) organisms and contaminate the surrounding water, harming fish, corals, and other marine life.
- **Chronic Impacts:** Persistent exposure to low levels of toxic chemicals, such as heavy metals in drilling fluids, can lead to reproductive and growth issues in marine species.

III. Noise Pollution

Seismic Surveys

- **Acute Impacts:** Loud blasts from seismic surveys can cause physical harm to marine mammals, especially those reliant on echolocation (e.g., whales, dolphins), leading to temporary or permanent hearing loss.
- **Chronic Impacts:** Continuous noise pollution disrupts communication, migration, and mating behaviors in various marine species, potentially reducing population levels over time.

IV .Platform installation and decommissioning

- Offshore O&G (Oil and Gas) platforms generate noise during their continuous operation along years of active exploitation of each oil field. An assessment of operation noise of six floating platforms off the coast of Australia has shown that median radiated levels do not depend on platform size or operation mode, and are on the order of 181 dB re 1muPa in the band 20 – 2500 Hz (Erbe et al., 2013).

V. Produced Water Discharge

- **Acute Impacts:** Produced water contains oil, heavy metals, and naturally occurring radioactive materials (NORM), which can be toxic if released in large quantities, especially in shallow waters.
- **Chronic Impacts:** Constant release of produced water contaminates the marine environment, leading to chronic exposure for marine species and resulting in developmental, reproductive, and genetic harm (OSPAR, 2021).

VI. Habitat Alteration and Physical Disturbance

- **Acute Impacts:** Activities like seabed drilling and pipeline installation disrupt habitats, displacing or killing benthic organisms, and damaging coral reefs and seagrass beds.
- **Chronic Impacts:** Ongoing physical disturbance from infrastructure maintenance, anchor placement, and drilling activities can gradually degrade fragile marine ecosystems, leading to loss of biodiversity.

VII. Air Pollution and Atmospheric Deposition

- **Chronic Impacts:** Flaring and other emissions release pollutants (e.g., sulfur oxides, nitrogen oxides, greenhouse gases) that can be deposited into the ocean, leading to acidification and eutrophication, which harm marine life and coral reefs.

Overall, both acute and chronic discharges from offshore oil and gas exploration create lasting and cumulative effects on the marine environment, impacting biodiversity, food webs, and the health of coastal and oceanic ecosystems.

3.2. Seismic Surveys

Seismic exploration is a technique based on the analysis of the reflection of acoustic waves on bottom layers of different density for estimating layer thickness, geo-technical properties and eventually for detecting large oil/gas reservoirs.

Seismic signals can be heard thousands of kilometers away from the area being surveyed. Moreover, the emitted power is concentrated in the frequency band shared with a broad range of cetaceans, among which most of baleen whales (mysticetes), that furrows the ocean in long migration paths. Thus seismic survey signals heavily interfere with their orientation, communication and feeding habits (Fig. 3).

Overall, marine species impacts depend on the extent of water sound propagation, noise frequency, noise duration and distribution over the habitat, species sensitivity, and spectral hearing. Zooplankton species, mostly copepods exhibit decreased abundance and significant mortality under air gun signal (McCauley et al., 2017). In the case of fish and cephalopods, behavioral responses have been observed up to 5 km away from the seismic survey, expressed as changes in depth distribution, schooling behavior, and startle responses to high-level sounds. Fishers experience these impacts as reduced catch rates (40%–80%) and decreased abundance, in the vicinity of seismic surveys. Seismic surveys may also affect marine fish eggs and larvae, imposing decreased egg viability, increased embryonic mortality, or decreased larval growth. Prolonged stress and displacement from habitats are seen in seals, sea lions, and walrus populations. As the noise footprint of seismic surveys is relatively large in deep waters, marine mammals, mostly cetaceans are highly affected (Kavanagh et al., 2019). Impacts include stress increase, behavioral changes, hearing loss, and even death by drowning or strandings.

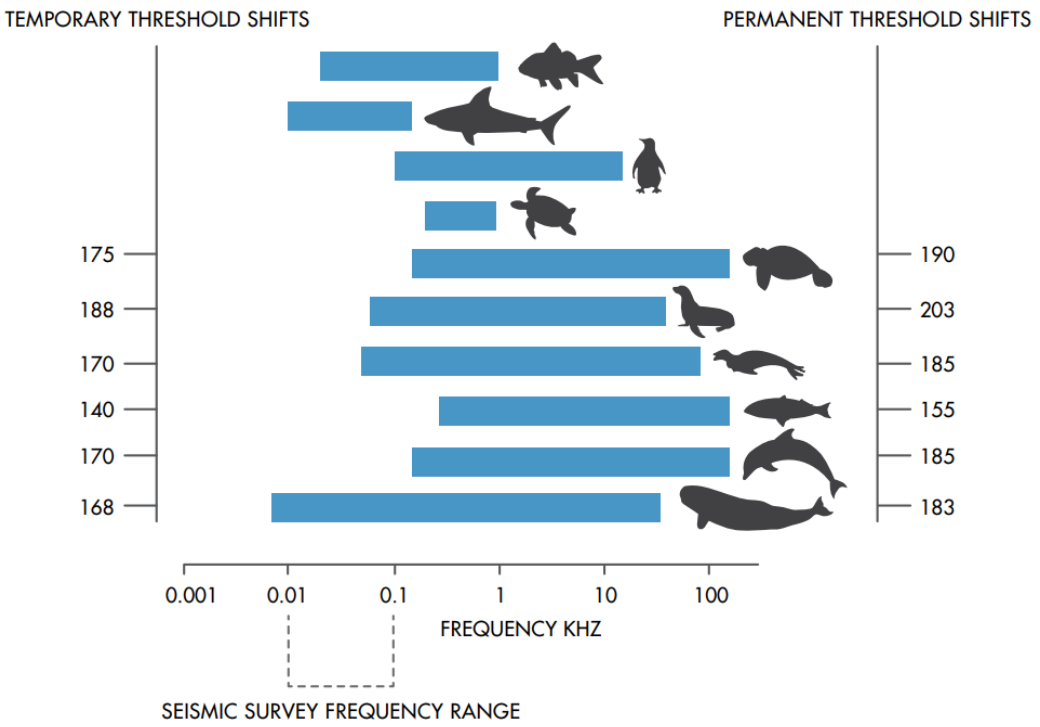


Figure ~~43~~: Temporary and permanent impacts of seismic surveys on marine fauna (after Pourdon, 2018).

As a result of the documented impacts of seismic surveys on marine fauna, several countries have taken steps to minimize these impacts. The UK introduced the first regulations formulated by the Joint Nature Conservation Committee (JNCC). Regulations introduced mitigation methods, like the use of the lowest practicable volume throughout the survey, the reduction of high-frequency output, the delineation of exclusion zones, the adoption of "soft-start" principles in sound emission, the visual and passive acoustic monitoring of marine mammals during the survey ~~.~~

3.3 *Impacts of offshore installation disasters*

Oil spills occur frequently in the marine environment, sometimes with devastating socio-environmental consequences. Marine oil spills are the result of shipping-related accidents or accidents in offshore fixed installations. Spills from fixed infrastructure can involve "live" crude oil, presenting distinct challenges in terms of environmental impact and response strategies. The 1979 Ixtoc I and the 2010 Deepwater Horizon (DWH) oil well blowouts in the Gulf of Mexico were two of the largest spills of oil in the history of marine oil drilling operations having released 3.5 and 4.9 million barrels of oil respectively before being finally contained.

The DWH spill was unique in that it was the first ever significant deepwater-well blowout with live oil (i.e., a mixture of dissolved natural gas and oil) (Passow & Overton 2021). Leaking at a depth of 1500 m bsl, the DWH well blowout brought forward the realisation that remote and largely unknown deep-sea ecosystems are susceptible to the impacts of offshore drilling accidents. Damage to offshore infrastructure (platforms, pipelines) that result to accidental oil leaks may also be caused by extreme weather events, mudslides and seafloor erosion

In 2004, hurricane Ivan caused a massive mudslide on the Gulf of Mexico seafloor that sank an entire drilling platform. The site had been leaking an average of 9-108 barrels of oil per day for 15 years until an underwater containment system was installed in 2019 (Mason, Taylor & MacDonald 2019). In the wake of Hurricane Ida in 2021, one of the largest reported spills (off Port Fourchon, Louisiana) was attributed to oil leaking from decommissioned pipelines that were left on the seafloor (Arslan et al. 2023). In all cases, assessing the environmental damage and the recovery of ecosystems after the spill has been problematic due to lack of baseline (pre-spill) data and/or delays in deploying scientific surveys (or lack thereof). DWH is the best studied oil spill ever due to extensive research efforts established during the spill including the 10-year program Gulf of Mexico Research Initiative (GoMRI). GoMRI terminated active research in June 2020 having produced an unprecedented understanding of the impact of the DWH oil spill on the environment and public health in the Gulf of Mexico.

Recent breakthroughs in drilling technology are propelling the growth of deepwater and ultra-deepwater exploration and production that currently dominate the offshore drilling market. Technological advancements in subsea robotics, real-time monitoring and sensors, and the use of blowout preventers have increased operational safety however the risks associated with deepwater drilling cannot be eliminated. As of 2023, the oil and gas reserves discovered in deep and ultra-deep waters account for 62% of the total offshore oil and gas reserves (Wen et al. 2023). These are mainly located in deepwater basins of the Atlantic (Gulf of Mexico, Brazil, west Africa, Norway), the East African continental margin, the West Pacific Ocean (South China Sea and southeast Asia), the northwest shelf of Australia, the Eastern Mediterranean Sea and the Arctic (Barents Sea). The current world record water depth for an oil and gas well is held by the Ondjaba 1 well offshore Angola, reaching 3628 m in 2021 (Enverus, 2024). The deepwater and ultra-deepwater drilling market is expected to grow significantly in the coming years due to the increasing global demand for oil and natural gas. It follows that the risk of an oil spill in deep waters akin to DWH in the future is also increasing.

3.4 Persistence of hydrocarbons in the marine environment

The severity of the impact of an oil spill depends on a variety of factors, including the physicochemical properties of the oil itself and quantity spilled, external conditions, such

as the prevailing climatic and sea conditions, as well as the types of habitats it affects. Oil spill residues persist for decades in certain low-energy, and often, hypoxic environments, such as coastal mangrove forests, salt marshes and deep-sea sediments. Partially weathered oil and high molecular weight polycyclic aromatic hydrocarbons (PAHs) from the 1979 Ixtoc I oil spill are still present in mangrove forests and sediments underlying >500 m of water in the southern Gulf of Mexico (GoM), 40 years after the incident (Radovic et al. 2020, Lincoln et al. 2020). Similarly, recalcitrant oil residues from the 2010 DWH spill were still detected 8 years later in deep (Diercks et al. 2021) and coastal marsh sediments of the northern GoM (Turner et al. 2019). In the Arctic, where oil degradation is limited by low temperatures and the short duration of Arctic summers, residual oil is still present in beach sediments 40 years after an experimental oil spill (Schreiber et al. 2023). To compare, in the warm and aerated sandy beaches of the GoM stranded DWH oil was degraded within a year (Huettel et al. 2018). These environments (coastal wetlands, deep benthic) can be considered as chronic “reservoirs” of oil residues and a continued source of toxicants to living organisms for decades (Murawski et al. 2023, Turner et al. 2019). This may result from the resuspension of contaminated sediments by physical processes (e.g. bottom currents, storms), burrowing behaviour of certain taxa or feeding on benthic infauna. In contrast, weathering processes (photooxidation, spreading, dispersion, dissolution, evaporation, biodegradation) acting on oil in open waters lead to the removal of hydrocarbons from the water column within a relatively short period of time – a few weeks after the spill ended in the case of DWH (Liu et al. 2016, Ward et al. 2018). The role of biodegradation is elevated in deep waters as it is the only pathway to remove oil from these environments (Scoma et al. 2017). Microbial hydrocarbon oxidation data under high hydrostatic pressure conditions are lacking owing to methodological challenges and the difficulty to obtain samples (Marietou 2018; Nguyen 2018; Antoniou et al. 2022). These are urgently needed to improve understanding of the interplay between temperature and hydrostatic pressure on biodegradation considering the rapid expansion of oil and gas drilling into deeper waters (Kostka et al. 2020).

Early developmental stages of fish have been shown to be particularly vulnerable to crude oil exposure and several studies have demonstrated that such exposure is toxic to the developmental heart producing cardiotoxicity and edema in fish embryos .

Exposure to oil and concentrations as low as 0.1 ug total polyaromatic hydrocarbon (TPAH)/l have been shown to give developmental toxicity in haddock (*Melanogrammus aeglefinus*) (Sørhus et al., 2023).

Also, effects on juvenile haddock I sdemonstrated after exposure to different PAH types extracted from produced water and crude oil (dominated by 3-ring PAHs). With regard to

the most sensitive biomarker, DNA adducts detected by ^{32}P postlabelling tissue, it was not possible to distinguish between the DNA adducts from the different sources (Meier et al., 2020).

3.5 Impact of Oil Spills

All biological systems, including those in environments where oil *per se* is not retained for a long time, show prolonged impacts due to cascading effects that impact functional connections within and between communities (Halanych et al. 2021). For example, DWH-derived toxicants (polycyclic aromatic hydrocarbons; PAHs), were present in eggs of mesopelagic fish at levels above those known to cause sub-lethal effects 6 years after the spill (Romero et al. 2018) as a result of food web incorporation and maternal transfer. Prolonged exposure to PAHs has been associated with negative health effects (decreased body condition and energy reserves, susceptibility to diseases) that may have serious consequences for long-term population viability (Snyder et al. 2019). DWH-affected fish species, such as tilefish, groupers and red snapper, showed elevated PAH concentrations in their tissues, external skin lesions and other morphological and histopathological symptoms consistent with continued chronic exposures (Pulster et al. 2020, Snyder 2019). Chronic spill effects from lingering oil in sea otters and harlequin ducks persisted for at least two decades after the Exxon Valdez oil spill in Alaska and had a larger influence on population dynamics over the long term than acute effects of the spill (Esler et al. 2018). Upper trophic levels exhibit considerable delayed impacts and slower rates of recovery due to smaller population sizes, longer generation times and bioaccumulation of toxicants in their tissues. Killer whale pods that were affected by the Exxon Valdez spill have not yet recovered but more likely due to demographic factors rather than long-term toxicity effects (Esler et al. 2018). Another characteristic example is the population of bottlenose dolphins living within the DWH oil spill footprint. This population experienced high mortality rates and impaired reproduction rates in surviving individuals from 2011 onwards (Kellar et al. 2017, Murawski et al. 2021). In contrast, lower trophic levels, such as zooplankton, show increased resilience because of shorter generation times and high fecundity that allow faster adaptation to altered environmental conditions (Halanych et al. 2021, Patterson et al. 2023). Deep sea and mesopelagic environments show less resilience than shallow; this is because deep-sea organisms generally exhibit a slower pace of life than their shallower-water counterparts owing to the generally low temperatures and low energy supply in the deep benthic and pelagic realms (Cordes et al. 2016). Extensive and persistent declines in abundance of both meso- and bathypelagic fishes and macrocrustaceans appear to be ongoing in GoM a decade after DWH (Sutton et al. 2022).

3.6 Disruption of ecosystems

The petroleum hydrocarbons oil spill disaster has major impacts on the marine environment and ecosystem, mostly affecting fisheries, wildlife, and coastal and marine habitats (Sayed et al., 2021). The ecological impacts appear directly related to the dynamics of the spill, including oil characteristics, spill volume, release rate, trajectories, and response action (Baron et al., 2020). Impacts also depend on the vulnerability of affected ecosystems and individual species, i.e., impacting species' natural mortality and affecting their predators (Zhang et al., 2019). Ambient temperature affects oil viscosity which controls oil spreading and degradation rates, while incident solar radiation affects phototoxicity of organisms. The environmental impacts are directly related to oil persistence, since it may remain in the water column for as long as half a year, but is usually diluted and sedimented to background levels much more rapidly than this (Teal and Howarth, 1984). The physical characteristics of oil and its toxic chemical constituents can cause major effects on marine life, affecting critical processes, like feeding, breathing, and thermoregulation, eventually leading to physical suffocation. Chemical components absorbed into organs, tissues, and cells may result in chemical toxicity. Acute toxic effects from oil ingestion, inhalation, smothering, drowning, and hypothermia affect the mortality of marine vertebrates and invertebrates, mammals, and seabirds (Peterson et al., 2003). However, even marine organisms far away from the spillage may also be affected, directly by exposure to oil, or indirectly through the trophic web, e.g., exposure to their prey (Olsen et al., 2019). In the pelagic ecosystem, planktonic copepods exposed to oil may experience immediate death, acute toxicity, decreased feeding, delayed egg production, sluggish hatching rates, decreased swimming speeds, and reproductive abnormalities. However, as plankton is plentiful and naturally experiences extremely high mortality rates, plankton deaths occurring after a spill rarely have long-term effects (ITOPF, 2023). Heavier oils and worn residues may affect the benthic ecosystem. Although it doesn't always result in death, it can have short-term consequences like narcosis and tissue tainting.

Studies have shown that although individual marine organisms can suffer significant harm, due to coating and oil ingestion, populations tend to be more resilient (Murawski et al., 2023). Ecosystems may recover two to ten years after the incident, even facing significant disturbances and mortality.

3.7 Impact on reproduction and development

Adult fish typically have greater resistance to oil effects than eggs and larvae, which may be more vulnerable (Singh, et al., 2020). Fish sense unfavorable water conditions and actively swim away, declining fish stocks in offshore and coastal waters after oil spills. In shallow or confined waters, very high, localized concentrations of dispersed oil may cause mass

mortalities. Adult fish exposed to high oil concentrations experienced acute cardiotoxicity, heart failure, decreased swimming speeds, and breathing rate reduction.

3.8 Sub-lethal effects

Numerous investigations have demonstrated the sub-lethal effects of polycyclic aromatic hydrocarbons (PAHs) on fish, including decreased rates of growth and feeding, genetic damage, mortality of fish eggs and larvae, increased susceptibility to starvation, and incapacity to flee from predators (Langangen et al., 2017). Sub-lethal effects of oil exposure can affect marine organisms, including marine mammals, leading to enhanced or suppressed cell proliferation, decreased phagocytosis, and induced cell apoptosis, eventually resulting in disease, decreased resilience, community structure changes, mortality, and ultimately population declines (Lee et al., 2018). After the DWH, demersal fish species presented pathological changes in the skin and suffered from increased incidences of bacterial infections, i.e., skin lesions (Murawski et al. 2014). Additionally, body weights, germinal epithelium thickness, oocyte diameters, and gonadal somatic indices of killifish at the oil-impacted sites were lower than those from non-impacted sites (Carr et al. 2018).

3.9 Impacts to fishing

Fisheries and mariculture resources could suffer significantly from oil spills (Andrews et al., 2021). Physical contamination can impede access to fishing sites or foul gear, which affects stocks and business operations. The loss in fishery production resulting from direct mortality, habitat loss, or access restriction due to harvesting bans and closures, typically impacts commercial fisheries and aquaculture enterprises. A decrease in market demand due to concerns about contaminated products also results in losses To speed up the compensation process, all fishery damage must be recorded and, if feasible, backed up by proof. This frequently calls for exacting scientific sampling and analysis. Accurate estimates of spill-related damages require comparing post-spill recovery against pre-spill fishing (ITOPF, 2023). However, it is frequently challenging to distinguish between the consequences of an oil spill and other elements like industrial pollution and overfishing (ITOPF, 2023).

Although the financial impact is typically less severe, oil spills can pose a serious threat to other marine-based industries such as port operations, sea-based transportation, and industries that depend on saltwater for regular operations, like power plants and desalination facilities (Chang et al., 2014; ITOPF, 2023). Both the aftermath of an oil spill and the subsequent clean-up efforts can cause disruptions to other forms of coastal industry, including shipyards, ports, and harbors (ITOPF, 2023). In addition, reduced disposable

income or market demand may result in pure economic losses for the larger economy (Taleghani and Tyagi, 2017).

3.10 Oil spill from tanker incidents

The term “oil spill” refers to the pollution type caused by the unintentional release of liquid petroleum hydrocarbons into the maritime environment. Numerous factors, like the oil spills released from floating oil rigs or platforms, due to human error, fatigue loading or explosions; damages in underwater oil pipelines; ship collisions, bunkering, groundings, and hull failures. According to ITOPF (2023), over the last fifty years, large spills were primarily caused by groundings (32%), and allisions/collisions (30%) (Figure 1). Despite the growth in the volume of the world's oil trade (ITOPF, 2023), there is a downward trend in the number of oil spill incidents and the amount of oil released from tankers, worldwide (Chen et al., 2019).

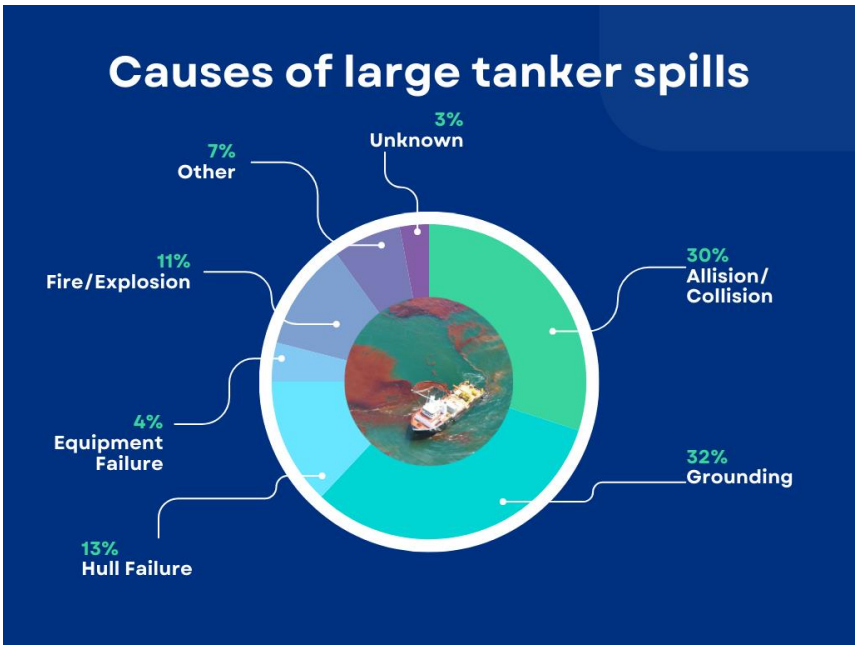


Figure ~~5~~4: Causes of large tanker spills (>700 tonnes) in 1970–2022.

In any case, the human factor accounts for at least 80% of tanker accidents, worldwide (Wan and Chen, 2018), related to overwork, insufficient experience in specific operations, inadequate communication, or outdated navigational charts.

A database maintained by ITOPF including tank vessels (combined carriers, FPSOS and barges) shows that over the past 50 years the frequency of oil spill larger than 7 tonnes has demonstrated a marked downward trend (Figure 1). The average number of spills per year was approximately 79 in the 1970s and has decreased by over 90 % to 6.3 in the 2010s and remains at the same level for the last decade: this trend has continued together with an increasing trend in oil trading over the period (FIG. ~~6)~~5)

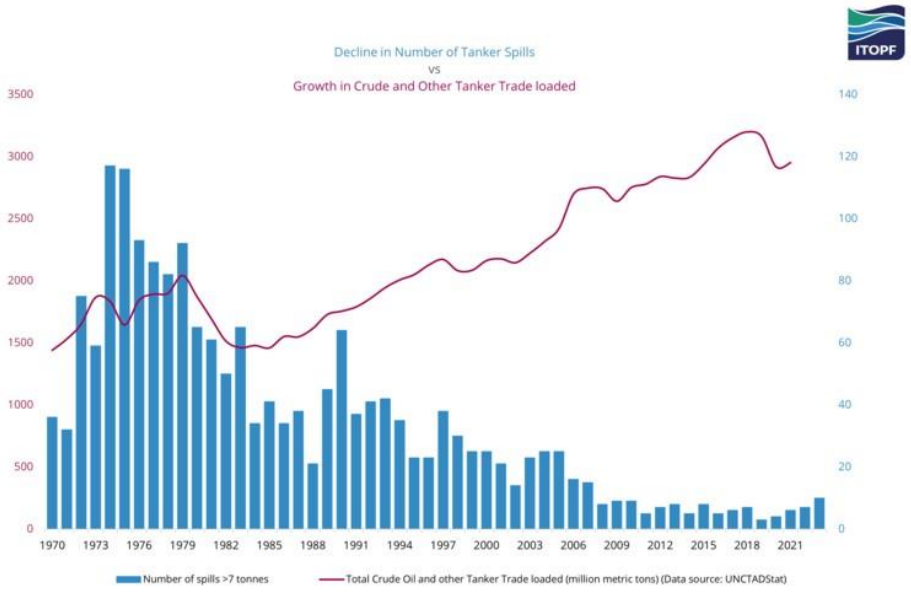


Fig. ~~65~~: Number of >700 ~~tonnes~~ tonnestanker spills vs vs growth in crude and other tanker trade loaded, 1970-2023.Figure taken from https://www.itopf.org/knowledge-resources/data-statistics/statistics/.

4. Socio-economic considerations

The offshore hydrocarbon industry's operations often intersect with the social and environmental concerns of local communities, leading to conflicts and challenges in securing public acceptance (Sovacool, 2022).

These conflicts can arise from a range of factors, including the perceived inequitable distribution of economic benefits, environmental degradation, and the disruption of traditional livelihoods. One of the primary sources of conflict is the uneven distribution of the economic gains from offshore hydrocarbon activities. While these operations can bring employment opportunities and revenue to the region, the local communities may feel that they are not receiving a fair share of the benefits (Sovacool, 2022).
This can lead to resentment and a sense of marginalization, fueling social unrest and resistance to the industry's presence.

These environmental concerns often clash with the industry's pursuit of economic growth, leading to protests, legal challenges, and a general lack of public trust. In response to these challenges, the offshore industry has sought to improve its social and environmental performance through various strategies, such as community engagement programs, environmental impact assessments, and corporate social responsibility initiatives.

However, the success of these efforts has been mixed, and a more comprehensive and collaborative approach is often required to address the underlying social and environmental issues. Fostering public acceptance of offshore hydrocarbon activities requires a delicate

balance between economic development, environmental protection, and social equity. By prioritizing inclusive and sustainable practices, the industry can work to build trust with local communities and mitigate the potential for conflicts (Sovacool, 2022).

4.2 Communities reliant on hydrocarbon activities: Economic Dependence, Infrastructure Development, Social Impact, Environmental Concerns

A review of literature by Andrews et al. (2021) showed varied economic outcomes with regard to communities' reliance on the offshore hydrocarbon industry. Oil discovery usually initially shows optimistic hopes for economic development and improved livelihoods (Andrews et al (2021), Stergiou (2022),). Generally, there is an increase in public expenditure, which can improve social welfare benefits and results in infrastructure development, including improved car, bus, and plane access to coastal towns or cities, as well as increased maritime infrastructure and traffic. This further results in greater mass tourism due to access to what can sometimes be previously remote areas (Andrews et al (2021),; Stergiou (2022),). It can also result in job creation, both directly on oil rigs and within surrounding industries, as well as the creation of a cycle of spending which may boost local industries and economies. Oil discoveries also provide governments with the opportunity to impose and reap benefits from additional taxes, e.g. corporate income tax, which can be equitably distributed (Stergiou (2022),). Some studies have found that a key factor in determining whether local communities will economically benefit from the hydrocarbon industry is if government policies mandate the use of local goods and services by the industry. These policy actions have seen improvements in oil sector economies in Angola, Ghana, Nigeria, Norway and Venezuela (Andrews et al (2021),). However, offshore hydrocarbon development can result in a "double deprivation" for coastal communities, as they may be excluded both from utilising the ocean as a resource to sustain their livelihoods and from employment by the offshore hydrocarbon industry Andrews et al (2021,). Where the offshore hydrocarbon industry is predominantly operated by foreign companies, evidence shows that impacts for local communities are less likely. In Ghana, for example, there is little employment opportunities for local people because the industry benefits are offshore and capital and technology intensive (Andrews et al (2021),).

The offshore hydrocarbon industry can have significant negative impacts on small-scale fishers. Hydrocarbon Infrastructure, pipelines, and exclusion zones created around rigs impact the areas that are accessible for fishers from local communities (Andrews et al (2021), p 6; Bennett et al (2021), p 3). Oil development has resulted in a lack of access to fishing areas that have historically been used, loss in fishing time,

destruction of fishing gear and spatial displacement of small-scale fishers and Indigenous Peoples (Andrews et al (2021), p 6; Bennett et al (2021), p. 2 and 5). Evidence from global studies also indicates that hydrocarbon pollutants in the marine environment leads to a reduction in fish populations (Ite et al (2024), p 6). Studies have shown dissatisfaction among fishers in Peru, Ghana, and UK coastal communities (Andrews et al (2021), p 6). Protests and conflicts between small-scale fisher communities and the oil industry have been recorded in various countries globally, such as the Gulf of Mexico, Peru, and Argentina (Andrews et al (2021), p 6; Morea (2023).

Some offshore hydrocarbon projects require shore-based processing facilities to be built, and these have impacts on coastal communities that should also be considered. These construction sites provide jobs in local areas. However, because their pay rates are higher than local jobs, this can result in a loss of workers from essential, but low-paid local jobs. An increased number of workers from outside the area with higher pay can cause increases in the value of property, land, and everyday commodities, negatively impacting existing local economies (UNEPFI (2022), pp. 29 – 32). In addition to environmental challenges, these large-scale developments may inhibit access to coastal areas, limit established economic activities such as fishing and tourism, and block access to sites of cultural significance and recreational areas (UNEPFI (2022), pp. 29 – 32; Bennett et al (2021), p 4).

The cultural identities, value systems, and traditions of rural communities may also be undermined by oil development. For example, in the Niger Delta a cultural new year's tradition where women ceremonial bathe in coastal streams has been phased out because of oil spill contamination (Ite et al (2024), p 10). There has been substantial research on environmental injustices caused by the oil industry, which has provided evidence of long-term health-related issues. Oil rigs and pipelines may release toxins for years after the operations have concluded (Bennett et al (2021), p. 3).

The initial hope for economic progress that oil discovery brings often goes unrealised, particularly for communities that are situated adjacent to the resource. In the substantial literature reviews conducted by Andrews et al (2021, p. 7) and Bennett et al (2021, p 3) it was reported that oil cities or countries often failed to improve, and sometimes worsened, the lives and economic realities of their populations.

4.3 PIRACY:

Piracy has emerged as a significant threat to the offshore oil and gas industry, posing risks to the safety and security of personnel, as well as the operational and financial stability of the companies involved.

The remote and often poorly secured nature of offshore facilities makes them vulnerable targets for criminal activities, with the Gulf of Guinea region being a global hotspot for such incidents.

The presence of offshore hydrocarbon activities can contribute to the marginalization of coastal communities, leading to resentment and a sense of disenfranchisement, which can fuel the rise of piracy and other criminal activities.

In response to this challenge, the United Nations and various regional organizations have implemented a range of strategies to combat piracy in the offshore domain (United Nations, 2022). These include enhanced maritime security measures, improved surveillance and intelligence-sharing, and collaborative efforts with local law enforcement agencies.

The social aspects of offshore hydrocarbon activity, particularly in relation to piracy, require a nuanced understanding of the complex interplay between economic, political, and cultural factors.

5. Sector-relevant governance

The great advances in the oil and gas industry refer to the use of technology to reduce risks, costs and impacts. Automation and remote operations allow the reduction of personnel on board and consequently of support cost, such as transportation, lodging and meals (IOGP, 2018) and of GHG emissions. There has been a rise of remote technologies, such as uncrewed surface vessels, drones, robotics, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).

While removing personnel from platforms and vessels may reduce risk of personnel accidents and injuries, it prevents the observation of the physical operations with physical models, sight, vibrations, smell, and sounds, increasing the reliance on information systems and clues from the digital environment (ESREL, 2023).

Remote operation may vary from full operation of the site to remote control, engineering, maintenance and/or monitoring. Implementing remote functions creates additional risks including cyber security risks, ability to enforce control of work policies, to define division of functions and responsibilities between remote and local operations and to assure the reliability of remote communications. Along with traditional risk analysis, these new risks shall be considered when design the operating philosophy (IOGP, 2023).

Another huge challenge imposed to oil and gas exploration and production is to reduce GHG operations emissions to achieve the world's climate goals. According to the International Energy Agency, in 2022, oil and gas consumption responded for around half of total energy-related CO2 emissions, equivalent to over 18 Gt CO2 (IEA, 2024).

Production, transport and processing correspond to just under 15% of total energy-related GHG emissions. To reduce scope 1 and 2 emissions, O&G (Oil and Gas) industry must eliminate all non-emergency flaring, adopt energy-efficient solutions, electrify upstream facilities with low-emissions electricity, equip oil and gas processes with carbon capture utilisation and storage (CCUS), and most important, reduce methane emissions (IEA, 2024; WEF, 2023).

Global Methane Pledge counted 158 participants who have agreed to voluntarily reduce methane emission by 30% below 2020 levels (GMP, 2024). If there is financial resources and gas market available, methane abatement technologies may be implemented without added costs when considering the value of recovered gas (WEF, 2023). Another voluntary initiative, the Zero Routine Flaring by 2030 was endorsed by 36 countries and 58 oil and gas companies. (ZRF, 2024)

In the Net Zero Emissions by 2050 Scenario, global average emissions intensity of oil and gas production falls by more than 50% between 2022 and 2030, to a number close to the emissions intensity of the best operators today. But operational efficiency and new technologies are not enough, in the NZE Scenario, oil and gas demand decline by more than 5% each year on average to 2050 (IEA, 2024).

According to the World Economic Forum, in five key areas readiness scale – technology, infrastructure, demand, policy and capital – the oil and gas is the readiest industry for energy transition. Technology readiness levels (TRLs) is classified as Stage 4, out of 5, depending mostly on a combination of Technologies (WEF, 2023).

6. Sustainability Pathways

Mitigation measures and environmental standards are in place in many regions to reduce the impacts of offshore hydrocarbon activities.

The information was discussed with OECD and are waiting for the incorporation in the chapter.

7. References

1- International energy agency – Oil MArket report -14 march 2024

2- Sovacool, B.K. (2022) 'Conflicts over offshore hydrocarbon activities: A global review of community resistance and social acceptance', Energy Research & Social Science, 83, p. 102351. doi: 10.1016/j.erss.2021.102351.
3- United Nations. (2022) United Nations Editorial Reference Guide. New York, NY: United Nations.
4- Global Methane Pladge (GMP) (2024). About the Global Methane Pledge. Available at: https://www.globalmethanepledge.org/. Accessed 17 aug 2024.
5- ESREL 2023 - Proceedings of the 33rd European Safety and Reliability Conference: The Future of Safety in the Reconnected World, 3 – 7 September 2023, University of Southampton, United Kingdom. 2023, 2288-2295. 10.3850/978-981-18-8071-1_P271-cd. Accessed 17 aug 2024.
6- IEA (International Energy Agency) (2024). The Oil and Gas Industry in Net Zero Transitions. Revised version, December 2023 and February 2024. Available at https://www.iea.org/reports/the-oil-and-gas-industry-in-net-zero-transitions. Accessed 17 aug 2024. Accessed 17 aug 2024.
7- IOGP (International Oil Association of Oil and Gas Producers) (2018). Selection of system and security architectures for remote control, engineering, maintenance, and monitoring. Report 627. Available at https://www.iogp.org/bookstore/product/iogp-report-627-selection-of-system-and-security-architectures-for-remote-control-engineering-maintenance-and-monitoring/. Accessed 17 aug 2024.
8- WEF (World Economic Forum) (2023). The Oil and Gas Industry in Net Zero Transitions World Energy Outlook Special Report https://www.weforum.org/publications/net-zero-industry-tracker-2023/. Accessed 17 aug 2024.
9- ZRF (Zero Routine Flaring by 2030 Initiative) (2024). Endorser. Available at ZRF Initiative Endorsers (worldbank.org). Accessed 17 aug 2024.
10- Sandra Kloff & Clive Wicks: Gestion environnementale de l'exploitation de petrole offshore et du transport maritime
11- Hamid N. AlSadi & al. : Introduction the the Seismic Exploration, First Edition, 2020
12- Hydrophones, fundamental features, design considerations, and various structures: A review - ScienceDirect
13- Decommissioning of offshore oil and gas platforms: A systematic literature review of factors involved in the process - ScienceDirect
14- The US Energy Information Administration
15- 2002 World Petroleum Congress , Brazil
16- Andrews, N., Bennett, N.J., Le Billon, P., Green, S.J., Cisneros-Montemayor, A.M., Amongin, S., Gray, N.J., Sumaila, U.R., 2021. Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. Energy Research & Social Science, 75, 102009, https://doi.org/10.1016/j.erss.2021.102009.

17- Baron, M.G., 2011. Ecological Impacts of the Deepwater Horizon Oil Spill: Implications for Immunotoxicity. Toxicologic Pathology, 40, 2, https://doi.org/10.1177/0192623311428474
18- Baron, M.G., Vivian, D.N., Heintz, R.A., Hyuk Yim, U., 2020. Long-Term Ecological Impacts from Oil Spills: Comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. Environmental Science and Technology 54, 6456-6467.
19- Carr, D.L., Smith, E.E., Thiyagarajah, A., Cromie, M., Crumly, C., Davis, A., Dong, M.J., Garcia, C., Heintzman, L., Hopper, T., Kouth, K., Morris, K., Ruehlen, A., Snodgrass, P., Vaughn, K., Carr, J.A., 2018. Assessment of gonadal and thyroid histology in Gulf killifish (Fundulus grandis) from Barataria Bay Louisiana one year after the Deepwater Horizon oil spill. Ecotoxicology and Environmental Safety, 154, 245–254. https://doi.org/10.1016/j.ecoenv.2018.01.013.
20- Chen, J., Zhang, W., Wan, Z., Li, S., Huang, T., Fei, Y., 2019. Oil spills from global tankers: Status review and future governance. Journal of cleaner production, 227, 20-32. https://doi.org/10.1016/j.jclepro.2019.04.020
21- Carroll, A.G., Przeslawski, R., Duncan, A., Gunning, M., Bruce, B., 2017. A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. Marine Pollution Bulletin, 114 (1), 9-24, https://doi.org/10.1016/j.marpolbul.2016.11.038.
22- Kavanagh, A.S., Nykänen, M., Hunt, W. et al., 2019. Seismic surveys reduce cetacean sightings across a large marine ecosystem. *Sci Rep* **9**, 19164, https://doi.org/10.1038/s41598-019-55500-4.
23- McCauley, R., Day, R., Swadling, K. et al., 2017. Widely used marine seismic survey air gun operations negatively impact zooplankton. *Nat Ecol Evol* **1**, 0195 (2017). https://doi.org/10.1038/s41559-017-0195.
24- Aniefiok E. Ite, Idaresit A. Ite, Eventus D. Edem, Joseph E. Okon, 'Nigeria's Oil and Gas Exploration and Production: Socioeconomic Implications, Environmental Impacts, and Mitigation Strategies,' Socio Economy and Policy Studies 4(2) (2024) 100-114.
25- Juan Pablo Morea, 'The economic, social and environmental impacts of offshore oil exploration in Argentina: A critical appraisal,' The Extractive Industries and Society 15 (2023) 101295, https://doi.org/10.1016/j.exis.2023.101295
26- Nathan Andrews, Nathan J. Bennett, Philippe Le Billon, Stephanie J. Green, Andres M. Cisneros-Montemayor, Sandra Amongin, Noella J. Gray g, U. Rashid Sumaila, 'Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance,' Energry Research and Social Sciences 75 (2021) 102009, https://doi.org/10.1016/j.erss.2021.102009
27- Nathan James Bennett, Jessica Blythe, Carole Sandrine White, Cecilia Campero, 'Blue growth and blue justice: Ten risks and solutions for the ocean economy,' Marine Policy 125 (2021) 104387 https://doi.org/10.1016/j.marpol.2020.104387
28- Andreas Stergiou, 'Socioeconomic and environmental impact of exploitation of hydrocarbons in maritime areas: The case of Greece,' Resour Environ Econ, 2022, 4(1): 333-342. https://doi.org/10.25082/REE.2022.01.006

29- United Nations Environment Programme Finance Initiative (Geneva, 2022) Harmful Marine Extractives: Understanding the risks & impacts of financing non-renewable extractive industries. Available at: https://www.unepfi.org/wordpress/wp-content/uploads/2022/05/Harmful-Marine-Extractives-Deep-Sea-Mining.pdf
30- Beyer J, Trannum HC, Bakke T, Hodson PV, Collier TK. 2016. Environmental effects of the Deepwater Horizon oil spill: A review. Marine Pollution Bulletin 110; 28-51. http://dx.doi.org/10.1016/j.marpolbul.2016.06.027
31- Meier S, Karlsen Ø, Le Goff J, Sørensen L, Sørhus E, Pampanin DM, Donald CE, Fjelldal PG, Dunaevskaya E, Romano M, Caliani I, Casini S, Bogevik AS, Olsvik PA, Myers M, Grøsvik BE. 2020. DNA damage and health effects in juvenile haddock (Melanogrammus aeglefinus) exposed to PAHs associated with oil-polluted sediment or produced water. PLoS ONE 15(10): e0240307. https://doi.org/10.1371/journal.pone.0240307
32- OSPAR Commission 2021. Report on impacts of discharges of oil and produced water on the marine environment. Publication number: 804/2021. Pp 49.
33- Sørhus E, Sørensen L, Grøsvik BE, Le Goff J, Incardona JP, Linbo TL, Baldwin DH, Karlsen Ø, Nordtug T, Hansen BH, Thorsen A, Donald CE, van der Meeren T, Robson W, Rowland SJ, Rasinger JD, Vikebø FB, Meier S. 2023. Crude oil exposure of early life stages of Atlantic haddock suggests threshold levels for developmental toxicity as low as 0.1 µg total polyaromatic hydrocarbon (TPAH)/L. Marine Pollution Bulletin 190, 114843. https://doi.org/10.1016/j.marpolbul.2023.114843
34- Antoniou E, Fragkou E, Charalampous G, Marinakis D, Kalogerakis N, Gontikaki E. 2022. Emulating Deep-Sea Bioremediation: Oil Plume Degradation by Undisturbed Deep-Sea Microbial Communities Using a High-Pressure Sampling and Experimentation System. Energies 15, 4525.
35- Arslan N, Majidi Nezhad M, Heydari A, Astiaso Garcia D, Sylaios, GA. 2023. Principal Component Analysis Methodology of Oil Spill Detection and Monitoring Using Satellite Remote Sensing Sensors. Remote Sens. 15, 1460.
36- Cordes EE, Jones DOB, Schlacher TA, Amon DJ, Bernardino AF, Brooke S, Carney R, DeLeo DM, Dunlop KM, Escobar-Briones EG, Gates AR, Génio L, Gobin J, Henry L-A, Herrera S, Hoyt S, Joye M, Kark S, Mestre NC, Metaxas A, Pfeifer S, Sink K, Sweetman AK and Witte U. 2016. Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. Front. Environ. Sci. 4:58
37- Enverus 2024. https://www.enverus.com/blog/offshore-drilling-keeps-getting-deeper/#:~:text=The%20current%20record%20is%20held,reaching%203%2C628m%20in%202021.
38- Esler D, Ballachey BE, Matkin C, Cushing D, Kaler R, Bodkin J, Monson D, Esslinger G, Kloecker K. 2018. Timelines and mechanisms of wildlife population recovery following the Exxon Valdez oil spill, Deep Sea Res. Part II: Topical Studies in Oceanography 147, 36-42.

39- Diercks AR, Romero IC, Larson RA, Schwing P, Harris A, Bosman S, Chanton JP and Brooks G. 2021. Resuspension, Redistribution, and Deposition of Oil-Residues to Offshore Depocenters After the Deepwater Horizon Oil Spill. Front. Mar. Sci. 8:630183.
40- Halanych KM, Ainsworth CH, Cordes EE, Dodge RE, Huettel M, Mendelssohn IA, Murawski SA, Paris-Limouzy CB, Schwing PT, Shaw RF, Sutton T. 2021. Effects of petroleum by-products and dispersants on ecosystems. Oceanography 34(1): 153-163.
41- Huettel M, Overholt WA, Kostka JE, Hagan C, Kaba J, Wells WB, Dudley S. 2018. Degradation of Deepwater Horizon oil buried in a Florida beach influenced by tidal pumping. Mar. Poll. Bull. 126: 488-500.
42- Kellar NM, Speakman TR , Smith CR , Lane SM , Balmer BC, Trego ML, Catelani KN, Robbins MN , Allen CD , Wells RS , Zolman ES , Rowles TK , Schwacke LH. 2017 Low reproductive success rates of common bottlenose dolphins Tursiops truncatus in the northern Gulf of Mexico following the Deepwater Horizon disaster (2010–2015). Endangered Species Res. 33: 143–158.
43- Kostka JE, Joye SB, Overholt W, Bubenheim P, Hackbusch S, Larter SR, Liese A, Lincoln SA, Marietou A, Móller R, Noirungsee N, Oldenburg TBP, Radović JR, Viamonte J. 2020. Biodegradation of Petroleum Hydrocarbons in the Deep Sea. In: S. A. Murawski et al. (eds.), *Deep Oil Spills*, Springer Nature Switzerland AG.
44- Lincoln SA, Radović JR, Gracia A, Jaggi A, Oldenburg TBP, Larter SR, Freeman KH. 2019. Molecular Legacy of the 1979 Ixtoc 1 Oil Spill in Deep-Sea Sediments of the Southern Gulf of Mexico. In: Murawski, S., *et al.* Deep Oil Spills. Springer, Cham. https://doi.org/10.1007/978-3-030-11605-7_19
45- Liu Z, Liu J, Gardner WS, Shank GC, Ostrom NE. 2016. The impact of Deepwater Horizon oil spill on petroleum hydrocarbons in surface waters of the northern Gulf of Mexico. Deep Sea Res. II: Topical Studies in Oceanography 129: 292-300,
46- Marietou A, Chastain R, Beulig F, Scoma A, Hazen TC and Bartlett DH. 2018. The Effect of Hydrostatic Pressure on Enrichments of Hydrocarbon Degrading Microbes From the Gulf of Mexico Following the Deepwater Horizon Oil Spill. Front. Microbiol. 9:808.
47- Mason AL, Taylor JC, and MacDonald IR (eds.). 2019. An Integrated Assessment of Oil and Gas Release into the Marine Environment at the Former Taylor Energy MC20 Site. NOAA National Ocean Service, National Centers for Coastal Ocean Science. NOAA Technical Memorandum 260. Silver Spring, MD. 147 pp. doi: 10.25923/kykm-sn39
48- Murawski SA, Grosell M, Smith C, Sutton T, Halanych KM, Shaw RF, Wilson CA. 2021. Impacts of petroleum, petroleum components, and dispersants on organisms and populations. Oceanography 34(1): 136-151.
49- Murawski SA, Schwing PT, Patterson WF III, Sutton TT, Montagna PA, Milligan RJ, Joye SB, Thomas L, Kilborn JP, Paris CB, Faillettaz R, Portnoy DS and Gilbert S. 2023.

Vulnerability and resilience of living marine resources to the Deepwater Horizon oil spill: an overview. Front. Mar. Sci. 10:1202250.

50- Nguyen UT, Lincoln SA, Valladares JuaÂrez AG, Schedler M, Macalady JL, MuÈller R, et al.. 2018. The influence of pressure on crude oil biodegradation in shallow and deep Gulf of Mexico sediments. PLoS ONE 13(7): e0199784.

51- Passow U & Overton EB. 2021. The complexity of oil spills: the fate of the Deepwater Horizon oil. Annu. Rev.Mar. Sci. 2021. 13:109–36.

52- Patterson WF III, Robinson KL, Barnett BK, Campbell MD, Chagaris DC, Chanton JP, Daly KL, Hanisko DS, Hernandez FJ Jr, Murawski SA, Pollack AG, Portnoy DS and Pulster EL. 2023. Evidence of populationlevel impacts and resiliency for Gulf of Mexico shelf taxa following the Deepwater Horizon oil spill. Front. Mar. Sci. 10:1198163.

53- Pulster EL, Gracia A, Armenteros M, Carr BE, Mrowicki J, Murawski SA. 2020. Chronic PAH exposures and associated declines in fish health indices observed for ten grouper species in the Gulf of Mexico. Sci. Total Environ. 703,135551.

54- Radović, J.R., Romero, I.C., Oldenburg, T.B.P., Larter, S.R., Tunnell, J.W. (2020). 40 Years of Weathering of Coastal Oil Residues in the Southern Gulf of Mexico. In: Murawski, S., *et al*. Deep Oil Spills. Springer, Cham. https://doi.org/10.1007/978-3-030-11605-7_20

55- Romero IC, Sutton TT, Carr B, Quintana-Rizzo E, Ross SW, Hollander DJ, Torres JJ. 2018. Decadal assessment of polycyclic aromatic hydrocarbons in mesopelagic fishes from the Gulf of Mexico reveals exposure to oil-derived sources. Environ. Sci. Technol. 52: 10985-10996.

56- Schreiber L, Hunnie B, Altshuler I, Góngora E, Ellis M, Maynard C, Tremblay J, Wasserscheid J, Fortin N, Lee K, Stern G, Greer CW. 2023. Long-term biodegradation of crude oil in high-arctic backshore sediments: The Baffin Island Oil Spill (BIOS) after nearly four decades. Environ. Res. 233: 116421.

57- Scoma A, Yakimov MM, Daffonchio D, Boon N. 2017. Self-healing capacity of deep-sea ecosystems affected by petroleum hydrocarbons. EMBO rep 18: 868 – 872.

58- Snyder SM, Pulster EL, Murawski SA. 2019. Associations Between Chronic Exposure to Polycyclic Aromatic Hydrocarbons and Health Indices in Gulf of Mexico Tilefish (*Lopholatilus chamaeleonticeps*) Post *Deepwater Horizon*. Environ. Toxicol. Chem.38(12): 2659-2671.

59- Sutton TT, Milligan RJ, Daly K, Boswell KM, Cook AB, Cornic M, Frank T, Frasier K, Hahn D, Hernandez F, Hildebrand J, Hu C, Johnston MW, Joye SB, Judkins H, Moore JA, Murawski SA, Pruzinsky NM, Quinlan JA, Remsen A, Robinson KL, Romero IC, Rooker JR, Vecchione M and Wells RJD. 2022. The Open-Ocean Gulf of Mexico After Deepwater Horizon: Synthesis of a Decade of Research. Front. Mar. Sci. 9:753391.

60- Turner RE, Rabalais NN, Overton EB, Meyer BM, McClenachan G, Swenson EM, Besonen M, Parsons ML, Zingre J. 2019. Oiling of the continental shelf and coastal

marshes over eight years after the 2010 Deepwater Horizon oil spill, Environ. Poll. 252: 1367-1376.

61- Ward CP, Sharpless CM, Valentine DL, French-McCay DP, Aeppli C et al. 2018. Partial photochemical oxidation was a dominant fate of *Deepwater Horizon* surface oil. *Environ. Sci. Technol.* 52:1797–805

62- Wen Z, Wang J, Wang Z, He Z, Song C, Liu X, Zhang N, Ji T. 2023. Analysis of the world deepwater oil and gas exploration situation. Petrol. Explor. Develop. 50(5): 1060–1076.

Section 5A
Chapter 4: Tourism

Contributors: Peter Schuhmann (coordinating author), Eliza Northrop, Sergio Alvarez, Alan Fyall, Antonia Correia, Adriana Ressurreição

4.1 Key points

- Coastal and ocean tourism can support all pillars of sustainable development~~Coastal and ocean tourism has the potential to contribute to all sustainable development pillars~~
- Coastal and ocean tourism relies heavily on ocean and marine ecosystem health while also contributing to various negative impacts on natural and cultural resources ~~Coastal and ocean tourism is critically dependent on the health of ocean and marine ecosystems and is the source of numerous detrimental impacts on natural and cultural resources~~
- Sustainable tourism remains difficult to achieve due to data gaps concerning the hidden costs of tourism and the value of natural and cultural capital ~~Sustainable tourism remains largely elusive due to information gaps related to the hidden costs of tourism and the benefits of natural and cultural capital~~
- Visitor arrivals create opportunities for data collection, dissemination of information regarding sustainability, and harnessing tourists' willingness to contribute to sustainable outcomes
- Transitioning the tourism sector toward a more sustainable paradigm will require significant political will and leadership to shift away from the prioritization of low cost, mass tourism and towards the adoption of a more holistic view of tourism success that promotes reinvestment into the local community, culture and environment

4.2 Introduction

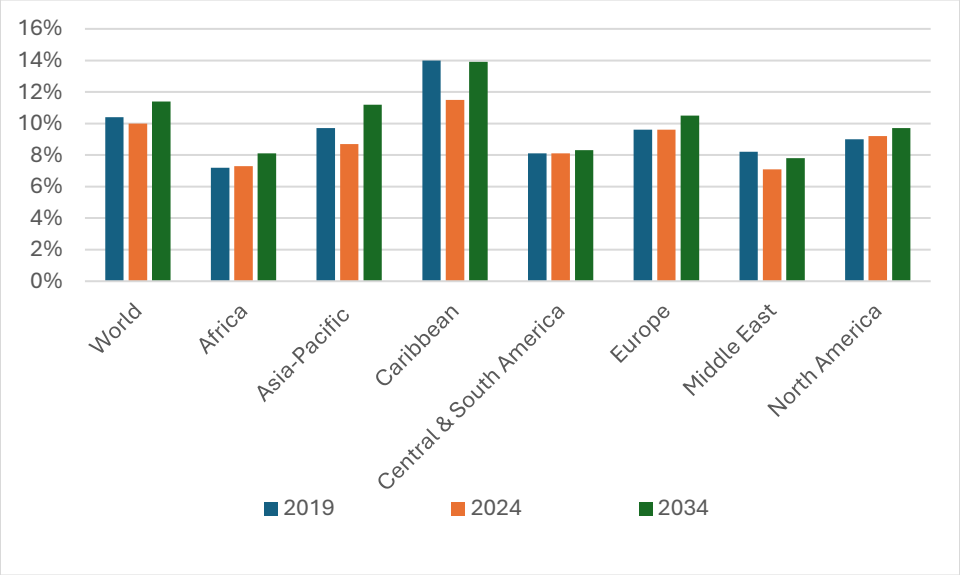
The purpose of this chapter is to provide an overview of the scope and extent of coastal and ocean tourism, highlight pressures and impacts from tourism on ecosystems and human wellbeing, and provide alternative pathways for improved governance and more sustainable outcomes. Travel and tourism comprise one of the largest economic sectors in the world. Despite severe impacts on the sector from the COVID-19 pandemic [S5b.C7] from 2020-2022, travel and tourism contributed $10.15 trillion to global GDP (9.2%) and accounted for approximately 330 million jobs, or 10% of the global workforce, in 2023. Supported by strong tourism demand across regions, the global economic contribution of travel and tourism is estimated to reach an all-time high of $11.1 trillion (10% of global GDP) supporting 348 million jobs in 2024 (WTTC, 2024). Looking forward, the travel and tourism sector is expected to grow faster than other sectors of the global economy, contributing $16 trillion to global GDP (11.4%) and accounting for 450 million jobs (12.2% of the global workforce) by 2034.

As made clear in prior Assessments, identifying the contribution of coastal and ocean tourism to the overall size of global tourism is challenging. Recent estimates by Northrop et al. (2022) suggest that coastal and ocean tourism comprises at least 50 percent of all tourism spending, thereby accounting for more than US$5.5 trillion or 5 percent of global GDP and employing roughly 174 million people. Importantly, coastal and ocean tourism is growing at a faster rate than international tourism as a whole

and is expected to surpass offshore oil and gas as the largest sector of the ocean economy by 2030 (OECD, 2016). In small island, archipelagic and coastal States, coastal tourism is often the predominant form of tourism, having a more pronounced impact on economic activity (Pratt, 2015; Mcelroy, 2003).

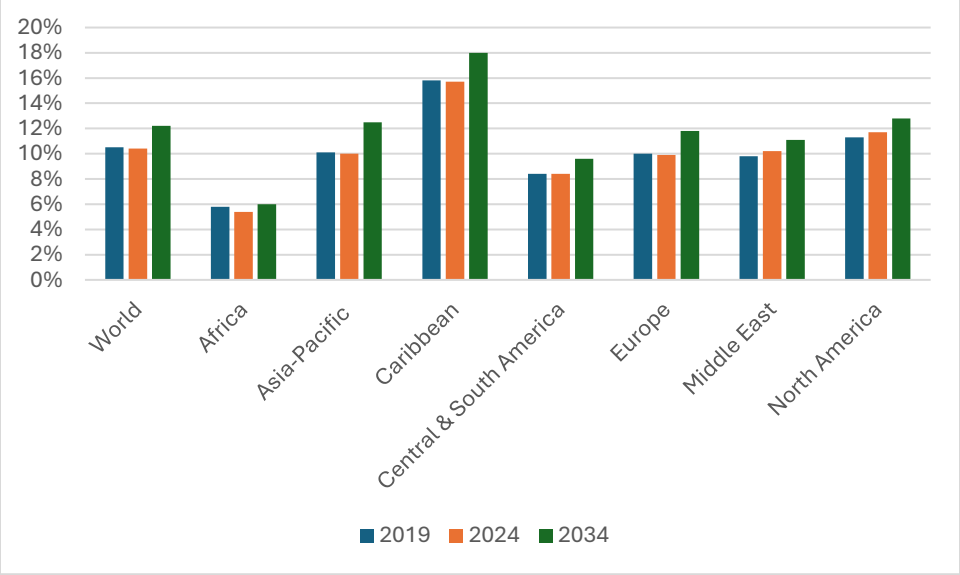
As shown in Figures 1 and 2, the Caribbean remains the most tourism dependent region in the world. In 2019, tourism accounted for approximately 14% of the region's GDP, 16% of employment and more than 20% of export earnings (WTTC, 2024). Tourism's share of employment in the Caribbean is forecast to increase over the next decade to 18%, supporting nearly 1 in 5 jobs in the region. The Asia-Pacific region is also heavily dependent on tourism, accounting for 11.2% of GDP and 12.5% of employment by 2024.

Figure 1: Travel and Tourism's total contribution to GDP 2019, 2024, 2034



Source: World Travel and Tourism Council Factsheets https://researchhub.wttc.org/

Figure 2: Travel and Tourism's total share of jobs 2019, 2024, 2034



Source: World Travel and Tourism Council Factsheets https://researchhub.wttc.org/

By 2034, WTTC forecasts that the travel and tourism sector is expected to grow by 3.7% per year, outpacing the expected 2.4% annual growth in the broader global economy, and contributing $16 trillion (11.4%) to global GDP, 101 million new jobs and employment for 449 million, roughly 12.2% of the global workforce. Between 2024 and 2034, the Asia-Pacific region is expected to experience the fastest growth in travel and tourism (6.1%), with China projected to surpass the United States with the largest absolute contribution of tourism to GDP (WTTC, 2024). Significant gains are also expected in India and Saudi Arabia.

Given its cross-cutting nature, importance to economic activity and human wellbeing, and critical dependence on environmental and cultural assets, tourism is uniquely positioned to contribute to all sustainable development pillars. However, when not properly managed, tourism can damage and degrade natural systems, deplete local resources and dilute culture, potentially diminishing destination appeal and offsetting economic gains from visitor spending. Strains on natural and cultural capital imposed by tourism can exacerbate vulnerability to climate change and economic shocks, leaving coastal communities increasingly at risk.

To balance the often-competing needs of economic, environmental and community health and wellbeing [S5B.C3], it is necessary to not only make investments targeting market-based economic returns from tourism, but to also invest in the protection of ecosystem health and function, preservation of cultural amenities and heritage, and equitable outcomes for local people. Contrary to the current trend towards mass tourism, evidence suggests that marine ecotourists spend more time and money at destinations than traditional tourists (Ressurreição et al., 2022; Topelko and Dearden, 2005).

Justifying public investment in natural and cultural capital is inherently challenging. While the economic value of tourism is relatively easy for policymakers to observe and appreciate in terms of arrivals and employment, the value to tourism of healthy coastal and marine environments and culture, and the economic costs that tourism creates remain largely hidden and underappreciated due to their indirect, non-market nature. The future sustainability of coastal and marine tourism will depend on closing the science-policy gap through targeted use of data and analytics to understand the links between tourism, the environment and human wellbeing and communicating those connections to decision makers, investors, travelers and coastal communities. Below we outline links between tourism, coastal and ocean resources and socioeconomic outcomes and provide alternative avenues for targeted investments to promote a more sustainable tourism sector.

4.3 Pressures and impacts

Coastal and ocean tourism is highly dependent on the health of natural resources, including beaches [S4.C5a], reefs [S4.C5d], mangroves [S4.C5h], marshes [S4.C5i], seagrasses [S4.C5g], seawater, and numerous forms of wildlife, including birds [S4.C4g], fish [S4.C4d], sea turtles, pinnipeds and cetaceans. The health of these assets and their ability to attract visitors and contribute to economic activity and human wellbeing [S5B.C3] are under threat from an array of local and global pressures and impacts (Mafruhah et al., 2020; Mehvar et al., 2018; Mejjad et al., 2022).

Coastal tourism infrastructure, shoreline maintenance and protection: As pointed out in the first two World Ocean Assessments, increasing use of the coastal zone for leisure has transformed many of the world's coastlines [S5A.C9], making them more accessible for tourism and recreation, but also reducing their aesthetic appeal and the quantity and quality of ecosystem services that are vital to economic value and human wellbeing [S5B.C3]. Compounded by sea level rise [S4.C3], many coastlines are receding [S4.C6.sub2; S5B.C4] due to the loss of natural protection afforded by these ecosystems (de Schipper et al., 2021). To counter the loss of beaches and protect coastal real estate, many destinations have engaged in active shoreline maintenance and protection, including beach nourishment through sand replacement or the installation of shoreline armoring structures [S4.C6.sub3] such as jetties, seawalls, and groynes (Griggs, 2024; Hill, 2015; de Schipper et al., 2021). These changes can impact water flow, diminish water quality, and create loss of valuable ecosystem services (Cooper et al., 2020; Henderson et al., 2020; Liu et al., 2023). Coastal tourism development can also create issues of environmental justice when privatization of coastal lands, crowding and physical impediments imposed by built structures inhibit residents' access to and enjoyment of the coastline.

Solid waste: Tourism can generate large volumes of solid waste from lodging and leisure activities (Yusoff et al., 2022). Coastal tourism is the main source of plastic litter [S4.C6.sub5] on beaches (Garcés-Ordóñez et al., 2020; Khadanga et al., 2022), the most common being food packages from beachgoers (Lamb et al., 2018). Solid waste management poses a challenge to small island destinations with tourism-based economies with poorly developed waste infrastructure, limited land area and geographical isolation (Almroth and Kershaw, 2024). Islands are heavily dependent on imported goods but have little control over imported waste byproducts, and many must accept solid waste from cruise ships. This can lead to waste production exceeding management capacity, leaving few options other than landfills and incineration (Wang et al., 2021). Poor solid waste management can have a negative effect on destination image and tourists' choices (Chaudhry and Sachdeva, 2021; Koliotasi et al., 2023).

Sewage and water pollution: Urbanization caused by tourism leads to water pollution [S4C6.sub5] through sewage or septic effluent and nonpoint source pollution from rain, stormwater or snowmelt runoff. Polluted water that enters the ocean adds nutrients and induces excessive plant and algae growth, which can lead to hypoxia or "dead zones" in the water. Some algae are known to produce harmful toxins which can create negative impacts on tourism visitation in coastal destinations (Berdalet et al., 2022; Yan et al., 2022; Nilsson and Gossling, 2012). In the US state of Florida, for example, a bloom of the dinoflagellate *Karenia brevis* in 2018 caused $2.7 billion in economic losses to tourism-related businesses (Alvarez et al., 2024). Discharge of sewage and runoff also reduces seawater quality leaving local and visitor populations vulnerable to illness (Rangel-Buitrago et al., 2024).

Greenhouse gas emissions: Energy production to meet the demands of coastal and ocean tourism generated an estimated 1.57 billion tonnes of CO2e emissions in 2023, 3% of global GHG emissions. Roughly 50% stems from supply chain sources (referred to as Scope 3 emissions), 25% from direct emissions from sources owned or controlled by an organization, such as domestic transport (referred to as Scope 1 emissions), 7% from indirect emissions from purchased energy (Scope 2 emissions) and 19% from international transport (WTTC, 2024b). In many industrialized nations, the climate impact from long-distance travel (one-way trips exceeding 100 km) is greater than that from short-distance travel.

Aviation is the major emitter in this segment, generating 2.4% of global anthropogenic CO_2 emissions in 2017 (Åkerman et al., 2021). Cruises are a particularly carbon-intense type of travel. While two of the major cruise liners report 2% annual improvements in carbon intensity in recent years and aim to continue this going forward (Royal Caribbean Group, 2021; Carnival Corporation & PLC, 2022), these figures refer to scope 1 and 2 emissions only, and a 2% reduction in carbon intensity is likely to be cancelled out by the expected 6–7% passenger growth (Hoegh-Guldberg et al, 2022).

Interactions with wildlife: Opportunities for wildlife-based recreation can yield significant benefits to tourists and local communities. For example, ecotourism based on marine megafauna is one of the fastest growing sectors of ecotourism (Guidino et al., 2020). In Semporna, Malaysia, shark-diving tourism provided more than $9.8 million in direct expenditures per year (Vianna et al., 2018). Shark and ray tourism in Indonesia produces an estimated $22 million USD in direct expenditures annually, or at least 7% of the $1 billion USD in revenue from marine tourism in the country (Mustika et al., 2020). Recent evidence suggests that the popularity of shark diving could double in the next 20 years (Cisneros-Montemayor et al., 2020). However, interactions between tourists and wildlife, including noise and physical disturbance caused by human visitors, can impact the behavior and fitness of animals through changes in foraging, migration and aggregation patterns, and displacement from preferred habitat, negatively affecting wildlife populations (Niella et al., 2023; Cattano et al., 2021; Shamir et al., 2019; Pavez et al., 2015). Populations that are spatially constrained, closed to immigration and emigration, or food limited are most sensitive to tourism pressures and impacts (New et al., 2020). Beyond recreation, tourism can be an important driver of food systems and can lead to an increased demand for seafood [S5A.C1e, S5A.C1f], which has been associated with increases in fishing effort and unsustainable harvest practices (Miller, 2022). Touristic vessels are also a known pathway for the introduction of non-native species [S4.C6.sub1] into marine environments and may have a disproportionate effect on the risk of introduction to marine protected areas (Parretti et al., 2020; Slišković et al., 2021). As highlighted in WOA II, Antarctic and Arctic tourism have been growing rapidly in recent years. Coupled with heightened pressures on native biodiversity caused by the increasing pace of environmental change in polar regions, the seasonal timing of human presence in these regions increases the chances of direct human-wildlife conflicts, adverse impacts on endemic fauna and flora and the establishment of non-native species [S4.C6.sub1] (Tejedo et al., 2022).

Mass tourism: The arrival of large amounts of visitors, although a means of economic activity and diversification, can negatively reshape local economies by increasing the cost of property and overall cost of living (Garza and Ovalle, 2019) potentially leading to crowding out of locals and depopulation of original residents (Zanini, 2017). Such trends can also hasten change in the skill requirements necessary to prosper to the detriment of the resident workforce and may impact equitable access to essential services (Albalate and Bel, 2010; Milano et al., 2019). Tourism's rapid recovery from the pandemic [S5B.C7] exacerbated problems associated with tourist volume and overtourism. Following the COVID-19 pandemic there was a marked increase in tensions between tourism and residents and heightened attention to pushback by locals due to impacts from overtourism on housing prices and availability, public services, and degradation of natural areas and cultural sites (Amrhein and Langer, 2025; Milano et al., 2024; Stojcic et al., 2024; Gonzalez-Reverte and Soliguer Guix, 2024). Calls for limits on tourism

included protests in popular coastal destinations in Greece, Italy and Spain and several locations in the US, including New York City, San Francisco, Los Angeles and Oahu. Several coastal destinations in Europe and Asia have imposed bans or restrictions on short-term rental platforms to mitigate tourism impacts on housing prices and availability (Wessel et al., 2024). Destinations in France, USA, Spain, China, and Italy have implemented economic incentive policies such as tourist fees to quell crowds (e.g., Choi et al., 2024). More radical proposals include complete or partial bans on cruise ships in port destinations like Venice, Amsterdam, Barcelona, Santorini, Mykonos and Dubrovnik to offset the negative impacts of tourist crowding (Nepal and Kumar Nepal, 2021).

As the top destination for coastal and ocean tourism for millions of tourists, islands are particularly vulnerable to the impacts of mass tourism while also dependent on visitor spending (Lagarias et al., 2023; Butler and Dodds, 2022). However, the cost of managing tourism frequently outpaces the revenue generated and retained. Small islands often accumulate public debt as tourist arrivals rise (Peterson, 2023; Peterson and DiPietro, 2021). In the Maldives, for example, tourism grew to represent 80 percent of the economy, while public account balances fell, leaving the nation in debt. Such 'operational externalities' generated by costs on public infrastructure can leave nations with insufficient financing to manage tourism impacts (Epler Wood et al., 2019). An example of the scale of tourism that many SIDS face is the Caribbean island of Aruba, which has a population of 105,000 and land area around 178 square kilometers yet hosted over a million tourists in 2017 (Hampton and Jeyacheya, 2020).

Cruise tourism: Despite comprising less than 3% of all travel, the cruise industry is one of the fastest-growing sectors of tourism, with approximately 40 million passengers expected by 2027, supported by a fleet of over 330 cruise ships (CLIA, 2024). It is one of the most common forms of mass tourism and is the dominant form of tourism in many coastal and ocean destinations (Bresson and Logossah, 2011; Domènech et al., 2020). North America and Europe remain the largest source markets for cruises, accounting for 57% and 26% of passenger volume, with the Caribbean and Mediterranean the most popular cruise destinations, receiving roughly 44% and 19% of travelers. For some island destinations in the Caribbean, the annual number of cruise passengers far exceeds the local population (World Tourism Organization, 2023). Although the impacts of cruise passenger spending are the subject of debate due to short length of stay, limited spatial movement of passengers on shore (Spalding et al., 2023), and availability of onboard services and amenities (Gouveia and Eusébio, 2019), cruise ship arrivals can generate positive economic impacts for coastal communities (Chen et al., 2019; Artal-Tur et al., 2021). Large volumes of temporary visitors also create pressures on local water, food and waste disposal resources and produce large volumes of emissions, solid waste, sewage, greywater, and oily bilge water (Lloret et al., 2021). The cruise industry releases 300,000 gallons of sewage, 8 tons of solid waste, 25,000 gallons of bilge water and other by-products weekly to destinations and national waters, causing a multitude of stress on marine ecosystems (Epler Wood, 2017; Kotrikla et al., 2021; Lloret et al., 2021). Despite comprising less than one percent of the merchant fleet (CLIA, 2024) cruise ships release up to 25% of all fleet waste (Butt, 2007). Other impacts from cruise tourism include modification of nearshore ecosystems to accommodate cruise ships (Lester et al., 2016), damage from anchoring (Forrester et al., 2015; Rogers and Garrison, 2001; Small and Oxenford, 2022) and breakdown of the socio-cultural makeup of destinations (Hoarau-Heemstra et al., 2023).

Recent estimates of carbon intensity based on annual reports from the three largest cruise lines (Carnival, Royal Caribbean, and Norwegian) (Hoegh-Guldberg et al., 2022) suggest that the global cruise sector emitted approximately 60 Mt CO2e in 2018; comparable to the annual emissions of many countries. With expected growth of 6 percent per year, emissions of 40 Mt CO2e (scope 1 and 2 emissions) or 80 Mt CO2e (scope 1, 2 and 3 emissions) are expected by 2030, trends that stand in stark contrast to global ambitions to halve emissions by 2030 (Hoegh-Guldberg et al., 2022).

4.4 Social Components

The social and cultural sustainability of coastal and ocean tourism is also of considerable importance (Leposa, 2020). Opportunities for recreation and access to blue spaces motivate travel to coastal and ocean locations and contribute to visitors' mental health, physical activity, enhanced psychological connection to the natural world [S5B.C2] and pro-environmental behaviors (Gascon et al., 2017; White et al., 2020). Evidence suggests that sustainable tourism initiatives can also generate significant social capital for coastal populations through economic diversification, cultural heritage preservation, and educational infrastructure development (Papageorgiou, 2016; Bennett et al., 2017). Tourism revenues can be harnessed as a means of boosting employment and addressing core issues in poverty (Zhang et al., 2023). Marine ecotourism can also empower community members to serve as environmental stewards, finance and expand marine protected areas and promote ocean literacy and citizen science (Bushell and Bricker, 2017; Cusak et al., 2019; Morse et al., 2024; Miers et al., 2017; Ressurreição et al., 2013). It can also facilitate the transmission of traditional ecological knowledge and reinforcing place-based cultural identities (Pomeroy et al., 2017).

However, there are socio-cultural challenges associated with ocean tourism development, particularly regarding power asymmetries between external stakeholders and local populations, and adverse effects on residents' wellbeing from the above noted pressures and impacts. The phenomenon of cultural commodification presents a documented concern, wherein culturally significant marine practices undergo transformation into commercialized experiences for tourist consumption (Mostafanezhad and Norum, 2019). Other adverse socioeconomic impacts from tourism such as congestion, higher prices, seasonal unemployment, economic leakage, distributional inequality, and dilution of culture can induce negative host attitudes toward tourism and restrain sustainable development of the sector (Canavan, 2016; Fan et al., 2019; Frent, 2016). Dissimilarities between the social and cultural norms of visitors and host communities can also create tensions, resentment, irritation and conflict (Lehto et al., 2020). This will be evidenced in the coming years with the entry into coastal tourism development of countries like Saudi Arabia. Returns from their recent, and significant, tourism investments may hinge on accommodating visitors in a culturally sensitive manner and blending tourism development with the socio-cultural norms that befit the religious home of Islam (Ghaderi et al., 2024; Zamani-Farahani and and Henderson, 2010).

4.5 Sector-relevant governance

The tourism industry is highly fragmented, comprising a variety of product and service markets including transportation, accommodation, attractions, nightlife, recreation and food and

beverage, and is intrinsically connected to other economic sectors and the broader macroeconomy. Coastal and ocean tourism involves public and private goods, asymmetric power across stakeholder groups, and a coupling of dependence and impact between the economy and the natural environment.

Owing to these challenges and complexities in governance, progress toward sustainable coastal and ocean tourism requires policy coherence across numerous private and civil society stakeholders operating at local, national, regional and international levels, and clear and accurate understanding of the magnitude and direction of change (Leotaud et al., 2024; Dwyer, 2003). Increased interest in new forms of governance for sustainable tourism has been driven in recent years by heightened sustainability awareness, smarter tourism development and management for both tourists and residents, a rising call for social inclusion, new technologies, a growing need for resilience and increasing governmental interest in destination governance and stewardship (Imbsen et al., 2021; Reinhold et al., 2023). Prerequisites include a unified vision and organization at destination, national and regional levels, effective use of data and information, clear communication and cooperation across a range of stakeholder groups (Scott, 2013).

Current research advocates for governance frameworks characterized by collaborative decision-making mechanisms that allocate substantive authority to local actors regarding marine tourism development trajectories (Milne & Ateljevic, 2022). Such community-forward frameworks necessarily encompass equitable labor standards, support for local enterprise development, and protocols for cultural exchange predicated on community-determined parameters (Su et al., 2020). There is also an imperative to integrate Indigenous Peoples' knowledge systems as foundational elements within sustainable tourism paradigms rather than as peripheral considerations (Nursey-Bray and Rist, 2009). Engaging local communities in the visioning, planning and co-management of sustainable tourism initiatives can generate and renew knowledge, awareness and pride in local ecosystems, history and traditions, foster local ownership, stimulate interest and investment in preservation and ensure that tourism practices align with ecological and cultural values (Bichler, 2021; Kuba et al., 2024; UNESCO, 2021).

The integration of environmental, social and governance (ESG) principles into tourism business models has increased in recent years in response to consumer and investor pressure for responsible practices and to build organizational resilience against environmental and social risks in an increasingly volatile global context (Gössling et al. 2020). ESG practices can improve operational efficiency related to environmental impacts associated with food, water and waste management systems, while enhancing community engagement and advancing the fair treatment of employees (Back, 2024). While research into the impact of corporate ESG strategies on financial returns is limited, preliminary evidence suggests that engaging in CSR activities can yield positive returns to tourism and hospitality firms in terms of performance and market value and that factors related to governance and stakeholder engagement are critical components of success (Ionescu et al., 2019; Legendre et al., 2024).

At the destination level, the creation of a central tourism management organization involving private and public sector tourism interests and community leaders can be effective in coordinating goals across the complex and multi-stakeholder nature of the sector and ensuring open and inclusive participation (Bichler

et al., 2019; Waligo et al., 2013). To assist destinations in advancing inclusive destination governance, the WTTC has a Destination Stewardship Governance Diagnostic Framework that provides alternative destination stewardship scenarios, and a diagnostic tool to identify triggers and barriers to effective destination stewardship, assess different aspects of destination governance and identify priority areas for improvement (WTTC, 2021).

Modes of regional governance can provide many benefits to coastal and ocean tourism destinations, including opportunities for capacity building, improved access to data and resources, risk-sharing and efficiency gains from economies of scale (Tausch, 2016). Establishing regional coordination through governance mechanisms can also help minimize price competition between locations which can induce a 'race to the bottom' in terms of sustainability (Dwyer, 2003; Grydehøj, 2017). International cooperation and collaboration can be enhanced through the formation of regional clubs designed to promote shared values and understanding across diverse tourism actors and unite economic and social interests. Coordination of environmental policies between countries (e.g., standards for cruise ships, tourist fees earmarked for conservation, environmental tax rates) can address the concerns of domestic industries that may be vulnerable to international competition (Coste et al., 2018).

4.6 Sustainable Pathways

The future of coastal and ocean tourism will be shaped by global economic conditions such as the availability of disposable income and leisure time, the costs of energy and travel, information technology and demographics, and global environmental change. Ocean acidification and rising sea temperatures [S4.C3] are expected to have continued detrimental impacts on nearshore ecosystems (School et al., 2024; von Schuckmann et al., 2024), impacting destination appeal and leaving coastal destinations increasingly vulnerable to changing climate (Hoegh-Guldberg et al., 2007; Ward et al., 2016). Despite commitments by member states at COP 28 and noticeable progress since the Paris Agreement, a large climate action gap remains and appears unlikely to close soon (World Economic Forum, 2024), suggesting that coastal and ocean destinations should anticipate continued impacts from changes in temperature and rainfall, warmer seas, rising sea levels (Cazenave and Mitchum, 2024) and hazardous weather events (Catalano et al., 2020).

Younger, wealthier travelers, a larger middle class, low transportation costs and increasing demand for experiential travel suggest that tourism volume and "overtourism" will continue, bringing continued pressures and tensions between visitors and local populations. As with all economic sectors, the tourism sector will be characterized by increasing access to richer and more comprehensive data, indicators, and processing power, including machine learning and AI tools, providing unprecedented opportunities for visitor engagement and improved understanding of tourist preferences, behaviors and impacts (Spalding et al., 2023).

Transitioning toward a more sustainable future will involve investments to mitigate dependence on tourism and build resilience to the above noted pressures and impacts, while safeguarding the economic viability of the sector by restoring and regenerating the natural and cultural capital that attracts visitors and supports local communities (Gounder and Cox, 2022; Northrop et al., 2022; Richardson and Witkowski, 2010). Given the diverse array of coastal and ocean destinations across the globe, and the complex and

highly contextual relationships between tourism and economic, environmental, social and cultural outcomes, there is not a one-size-fits-all prescription for the future of the sector (Brida et al., 2020; Nunkoo et al., 2020).

Below we present four complementary pathways for reorienting coastal and ocean tourism toward more sustainable outcomes. These pathways assume that other ocean sectors (e.g., capture fisheries [S5A.C1a, S5A.C1b], shipping [S5A.C6], extraction of energy resources [S5A.C3b]) will continue and that unfettered market forces will not provide efficient investment in protection and regeneration of ecosystems and cultural resources (Schuhmann, 2020).

Each of these pathways addresses the array of environmental and social impacts created by tourism highlighted above and relies on purposeful planning and investment. A key challenge in achieving investments in environmental and social capital is that the associated returns are often not observable in terms of traditional economic indicators and may only be apparent over a time frame that is longer than election cycles. Most nations have limited fiscal space for long-term investments with unclear returns. Key elements of sustainable pathways across destinations therefore include improving access to financial resources to support investment in natural and social capital, enhanced data collection and analysis to illustrate economic returns from that investment and creating inclusive governance frameworks to support policy and legislation that incentivize information sharing and private sector investment in sustainable outcomes (World Economic Forum, 2024).

Investment in data collection, publication, and analysis to understand linkages between tourism and natural and cultural resources and the full costs and benefits of tourism. Many of the amenities that attract visitors to coastal and marine destinations are open-access public goods, generating no direct economic impacts, but serving as key drivers for market-based activities that generate income and employment (NOAA, 2023). A deep body of research illustrates that maintaining or enhancing the quality of coastal and ocean ecosystems creates significant contributions to economic growth, employment and poverty reduction while enhancing resilience to climate change, natural disasters and economic shocks (Patil et al., 2016). Damage to coastal and ocean systems creates real economic costs. Eroded or littered beaches [S4.C5a, S4.C6.sub2], degraded reefs [S4.C5d] and polluted seawater [S4.C6.sub5] are known to be less attractive to tourists (Qiang et al., 2020; Schuhmann et al., 2016) and loss of coastal ecosystems puts tourism assets at risk (Barbier, 2015; Spalding et al., 2014).

Despite these well-known findings, coastal and marine ecosystems continued to be modified, damaged and degraded by human activities associated with market-based returns (Atwood et al., 2017; Riegl et al., 2019). Part of this dichotomy lies in the fact that market-based metrics such as arrivals, spending, jobs and revenues are widely publicized and easily understood, while measures of ecosystem health and function lack clear and appropriate monetary signals, creating a situation where private and public interests are naturally inclined to prioritize market values. This information gap inhibits sustainable management, as policy makers must operate with incomplete understanding of connections between traditional economic activity and natural and cultural capital (Thorburn et al., 2021).

Measuring tourism's impacts on natural and cultural resources is an integral part of monitoring and controlling those impacts (Papathanassis, 2023). Investments in comprehensive collection and analysis of

economic, social and environmental data can facilitate empirical assessment of the relationships between market activity and environmental and cultural sources of human wellbeing [S5B.C3] such as ecosystem health and extent, maintenance of local knowledge and traditions, and equitable distribution of the economic benefits from tourism. Avenues for data collection to support enhanced monitoring, assessment and prediction of ecosystem health include advanced mooring systems that facilitate collection of real-time data on seawater quality, biodiversity, climate variability, and ocean hazards. Smart tourism apps can help measure and manage ecological footprints and carrying capacities, assess visitor satisfaction, enhance operational efficiency and reduce waste (Pencarelli, 2020; Wang et al., 2016; Yu et al., 2018). Smart technology can also facilitate bi-directional exchange of information with visitors, further engaging them in destination sustainability by guiding and informing decisions regarding purchases, experiences and movement. An example of the power of digital tools and improved access to data is the use of mandatory GPS trackers to monitor local seafood in Jamaica's tourism sector, where consumers are increasingly demanding supply chain transparency and traceability (Northrop et al, 2023). Digital data-gathering mechanisms like apps empower local fishers [S5A.C1b] while giving consumers confidence in premium-priced, sustainably labelled seafood [S5A.C1e].

Coupling traditional measures of economic impacts from tourism with measures of non-market impacts such as waste generation, water and energy use, crowding, ecosystem health, and qualitative forms of information such as visitor and resident satisfaction can form the foundation for education and capacity building programs designed to help policy makers, tourism operators and civil society understand the real economic value of natural and cultural resources and redefine the notion of tourism success (Frantzeskaki et al., 2019; Schuhmann, 2020). Beyond the provision of a clearer view of tourism's impacts on ecosystems and communities, the measurement and mapping of ecosystem service stocks, flows and values can support evidence-based decision making (Schumacher et al., 2020; Spalding et al., 2021) for investment planning and for designing policies that direct resources toward their highest and best use (Papageorgiou, 2016; Schuhmann, 2020). Empirical evidence regarding the economic losses created by tourism can also help destinations negotiate and implement tourist fees (e.g., cruise passenger fees) commensurate with costs imposed on local resources and infrastructure.

Echoing the recommendations of the Ocean Decade Vision 2030 (Calewaert et al., 2024) and the IOC-UNESCO State of the Ocean 2024 (O'Brien et al., 2024) this pathway may require increased investment in data literacy, information technology readiness, updating and modernization of national statistical offices and systems, data collection and sharing, and analysis efforts that span disciplinary and geographical boundaries. Natural capital accounting methods such as the UN SEEA system and Ocean Accounts[45] provide structure for such data using a framework that is compatible with traditional national income accounts used by statistical offices and finance ministries. Creating and maintaining such accounts can

45 Ocean accounts are integrated, standardized records that provide a comprehensive view of a country's environmental conditions, economic activities, and social conditions related to ocean resources. Ocean accounts facilitate tracking of economic progress, allowing countries to go "beyond GDP," measuring not just market output but also the value of ecosystem services, the condition of natural assets, and the impact of human activities on the ocean environment. For more information, see the Global Ocean Accounts Partnership, https://www.oceanaccounts.org/

foster and improve collaboration and coordination across government entities, help identify gaps and deficiencies in data and statistics related to national priority issues (e.g., energy efficiency, water use, emissions, protected area management), help measure and manage risks and opportunities related to nature, and improve stakeholder engagement (Fenichel et al., 2023; Ingram et al., 2024; King et al., 2024; Perkiss et al., 2022). By mapping tourism's linkages with coastal and marine ecosystems, Ocean Accounts also demonstrate the sector's vested interest to support ocean conservation safeguarding its own future prosperity and can be used to identify sustainable scenarios and pathways (Gacutan et al., 2022).

High-quality, immersive nature-positive and authentic community-based tourism. A broad body of empirical evidence shows that immersion in nature and culture can stimulate place attachment, sustainable behaviors and willingness to return (Chen and Rahman, 2018; Kil et al., 2012; Wilkins et al., 2018; Zhang et al., 2023) and that tourists are willing and able to give back (Adam, 2021; Wearing and McGehee, 2013). Developing and promoting opportunities for high-quality, immersive nature-positive and authentic community-based tourism (CBT) experiences can foster connections between visitors and marine environments, attract longer-staying visitors who spend within the local economy, strengthen visitor awareness of local conservation issues, and enhance resiliency by counteracting tourism seasonality, while creating opportunities for employment, entrepreneurship, and economic empowerment (Leotaud et al., 2024; Lewis-Cameron and Brown-Williams, 2022; Vergori and Arima, 2020). Well-designed experiences can cultivate visitors' ocean literacy and environmental consciousness that extends beyond the travel period (Ballantyne et al., 2018), generating ripple effects as tourists return home with new perspectives on ocean conservation, potentially influencing consumption patterns and political support for marine protection (Zeppel & Muloin, 2008; Walker & Moscardo, 2014). For coastal communities facing climate threats, sustainable tourism initiatives can serve as a vehicle for climate adaptation education, helping both residents and visitors understand changing ocean conditions while building collective resilience against environmental uncertainties (Hall, 2019; Cinner et al., 2018).

Examples of nature-positive community-based opportunities include the Dominican Republic Sustainable Community Tourism initiative which links communities with tourists emphasizing proper management of natural resources, appreciation of cultural heritage, equitable distribution of benefits from tourism, and local community development through empowerment, entrepreneurship, and self-management.[46] Tourist scuba divers in Fiji can join with local nonprofits and engage in citizen science or participate in more active pursuits such as coral restoration, creating a triple win – improved data and knowledge, action that advances conservation, and enhanced tourist satisfaction and willingness to return.[47] Blue Safari Seychelles allows visitors to help protect marine ecosystems through data collection of encounters with species, tree planting, beach clean-ups, and underwater debris collection.[48] Travelers pay a USD 25 per day conservation charge, earmarked for ecological programs and initiatives (Thorburn et al., 2021). Other examples are shown in Table 1.

[46] https://www.godominicanrepublic.com/
[47] https://www.fijimarinas.com/citizen-science/
[48] https://bluesafari.com/

Opportunities to inform visitors regarding the importance of environmental and cultural assets and the purpose of sustainability initiatives can further engage visitors and stimulate responsible behavior (Aini & Syuraini, 2023; Downs et al., 2022; Leotaud et al., 2024). Codes of conduct such as the Palau Pledge[49] incentivize tourists to interact with the local community and culture and participate in regeneration projects (Herrmann, 2022; Levitan-Haffar, 2022). The Palau Pledge is stamped in all tourists' passports, which they must sign before passing through customs (Government of Palau, 2024). An emerging area is improving access to information regarding the environmental impacts of trip decisions and enabling tourists to make carbon-offset contributions into blue carbon investments such as mangrove restoration or choose lower-emitting flights and accommodation based on carbon calculators and carbon data transparency initiatives, such as Skyscanner and Google.

Challenges to implementing nature-positive and community-based tourism include scaling due to reliance on small enterprises and carrying capacities of sensitive cultural sites and ecosystems, maintenance of natural and cultural integrity and avoiding the commodification of culture and heritage. To ensure long-term success and community buy-in it is essential for residents to be fully engaged in the co-development of these initiatives. Inclusive capacity building and training in sustainable practices targeting local management and/or ownership of commercial tourist enterprises can further empower residents.

Table 1: Nature -positive and community-based tourism initiatives

Active	
Preservation	Shoreline and marine clean-up efforts; invasive species removal
Regeneration	Mangrove planting; seagrass propagation; coral restoration; tree planting; dune restoration; marsh restoration; restoration of tidal flows and natural hydrology
Citizen science	Encounters with species; species counts; water quality or clarity assessments; litter counts
Nature- and culture-based adventures	Wildlife and habitat viewing; fishing; diving & snorkeling; cooking and cuisine
Passive	
Tours and visits	Museums, coastal ecosystems; historic & heritage sites; visual and performing arts
Local goods and services	Markets for local art & crafts, products and services; health and wellness
Non-intrusive access to nature	Boardwalks, bridges, wildlife viewing structures; species identification and other interpretive signage

49 https://palaupledge.com [https://perma.cc/3JRM-CJ3R]

Immersive learning experiences	Cultural interpretation of natural environments and species, storytelling, history & heritage; importance of ecosystems; endemic biodiversity

Adapted from Thorburn et al. (2021) and Leotaud et al. (2024).

Multi-use planning and diversification for infrastructure, services and operators can provide backstop income and employment opportunities during periods of tourism disruption and enhance destination resilience to natural hazards and economic shocks. Public investments in infrastructure improvements targeting energy efficiency, maintenance of water and waste, and protection of ecosystems and biodiversity have been shown to provide positive economic and environmental returns (Paramati et al., 2018). Opportunities for tourism diversification include niche markets such as ecotourism, cultural and heritage tourism and community-based tourism (Leotaud et al., 2024). Increasing focus on service quality for business travelers, and perks or incentives to extend visits beyond the work period can offset losses from the decline in demand for business travel, generate additional economic impacts and create new opportunities for return visitation. Examples include remote work visa programs and travel bubbles that target digital nomads (Sánchez-Vergara et al., 2023). Investments in local capacity building such as training marine tourism operators to monitor protected sites and collect data regarding ecosystem health and function can also enhance economic resilience to tourism downturns and empower tourism stakeholders as stewards of the natural environment (Day, 2008). A key challenge is that diversifying tourism value chains and decreasing economic dependence on tourism requires structural reform.

Enhanced use of economic instruments to incentivize transition toward sustainable outcomes and create fiscal space for investments in natural and cultural capital: Coastal and ocean tourist destinations can use an array of fiscal policy tools to harness the power of monetary incentives and direct financial resources toward activities that generate long-term economic returns through regeneration and resilience, pollution reduction and improving the sustainability of tourist attractions. Taxes, fees, subsidies, and payments for environmental services have been shown to be effective in funding protected area management, green energy, nature-based solutions, decarbonizing supply chains, waste and emissions reductions and water use efficiency, without constraining economic and social development or deterring visitation (Olmstead and Stavins, 2009; Sun and Feng, 2023; von Saltza and Kittinger, 2022).

Tourist fees can serve the dual purpose of revenue generation and visitor management. A large body of empirical evidence suggests that visitors are willing to pay fees that improve resource quality or offset management costs when the purpose is clearly communicated (Edwards, 2009; Font et al., 2004; Rivera-Planter and Muñoz-Piña, 2005). Collection points for visitor fees also create a conduit for bidirectional exchange of information, enabling enhanced visitor management and the education of tourists on codes of conduct, the importance of natural systems, history, culture and traditions, environmentally and culturally responsible behaviors, and facilitating collection of information related to tourist activities, spending, preferences and satisfaction.

Governments can also incentivize private sector sustainability initiatives through monetary and operational subsidies such as favorable tax treatment and fast-tracking permitting for tourism projects that promote renewable energy, green products and services, locally sourced inputs, high-quality/low-volume experiences, and community benefits (Leotaud et al., 2024; World Economic Forum, 2014). Special

events, visitor concessions for off-season trips and visits to less popular sites and attractions can also be used for visitor management and reducing the impacts of seasonality (Connell et al., 2015). Quota or reservation systems can also be used for high-demand or sensitive sites. Destinations must first measure and understand capacity limits in terms of adverse impacts on ecosystems, cultural integrity, water and energy resources, infrastructure, community wellbeing, safety and visitor satisfaction.

4.7 Conclusion

The above review of the nature and extent of coastal and ocean tourism and its impacts on human and environmental wellbeing highlights a coupling of dependence and impact. Economic and social gains from coastal and ocean tourism rely on the ability of coastal and marine ecosystems to provide benefits to visitors and local communities. Yet, mounting evidence suggests that continued growth of the sector poses threats to the natural and cultural resources upon which tourism depends.

Transitioning coastal and ocean tourism toward more sustainable outcomes will require a shift among tourism stakeholders to view the value and success of tourism more holistically, complementing traditional market-based measures of economic activity with measures of environmental, cultural and community costs and benefits. This shift will require purposeful public and private sector investments. Investments in data collection and analysis can close information gaps, allowing for a more comprehensive view of tourism's value and impacts, facilitating evidence-based planning and decision making and providing the foundation for education and capacity building programs. Support for nature-positive and community-based tourism opportunities can create economic gains and empower both visitors and local communities to be agents of change. Multipurpose infrastructure and diversification of product and service offerings can improve economic efficiency and enhance destination resilience to natural hazards and economic shocks. Enhanced use of economic instruments can incentivize sustainable behaviors and create revenue streams to support investments in natural and cultural capital.

References

Adam, I., 2021. Tourists' perception of beach litter and willingness to participate in beach clean-up. *Marine Pollution Bulletin*, *170*, p.112591.

Aini, W. and Syuraini, S., 2023. The Implementation of Community Participation Guidebook Development as an Effort in Environmental Preservation of Air Manis Beach in Padang City. *Journal of Nonformal Education*, *9*(1), pp.77-86.

Åkerman, J., Kamb, A., Larsson, J. and Nässén, J., 2021. Low-carbon scenarios for long-distance travel 2060. *Transportation Research Part D: Transport and Environment*, *99*, p.103010.

Albalate, D. and Bel, G., 2010. Tourism and urban public transport: Holding demand pressure under supply constraints. *Tourism management*, *31*(3), pp.425-433.

Almroth, B.C. and Kershaw, P., 2024. Status and trends of plastic pollution, including strategies on how to reduce them. *STATE OF THE OCEAN REPORT*, p.18.

Alvarez, S., Brown, C. E., Diaz, M. G., O'Leary, H., & Solís, D., 2024. Non-linear impacts of harmful algae blooms on the coastal tourism economy. *Journal of Environmental Management*, *351*, 119811.

Amrhein, S., & Langer, M. (2025). Resistance and power dynamics in tourist destinations: a study of Mallorca's anti-touristification protests through Bourdieu's theory of practice. Journal of Sustainable Tourism, 1-18.

Artal-Tur, A., Navarro-Azorín, J.M. and Ramos-Parreño, J.M., 2021. Estimating the impact of cruise tourism through regional input–output tables. In *Tourism Research in Ibero-America* (pp. 70-80). Routledge.

Atwood, T.B., Connolly, R.M., Almahasheer, H., Carnell, P.E., Duarte, C.M., Ewers Lewis, C.J., Irigoien, X., Kelleway, J.J., Lavery, P.S., Macreadie, P.I. and Serrano, O., 2017. Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, *7*(7), pp.523-528.

Back, K.J., 2024. ESG for the hospitality and tourism research: Essential demanded research area for all. *Tourism Management*, 105, p.104954.

Barbier, E.B., 2015. Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosystem Services*, *11*, pp.32-38.

Berdalet, E., Pavaux, A. S., Abós-Herràndiz, R., Travers, M., Appéré, G., Vila, M., ... & Lemee, R., 2022. Environmental, human health and socioeconomic impacts of Ostreopsis spp. Blooms in the NW Mediterranean. Harmful Algae, 119, 102320.

Bichler, B.F., 2021. Designing tourism governance: The role of local residents. *Journal of Destination Marketing & Management*, *19*, p.100389.

Bichler, B. F., & Lösch, M., 2019. Collaborative governance in tourism: Empirical insights into a community-oriented destination. Sustainability, 11(23), 6673.

Bresson, G. and Logossah, K., 2011. Crowding-out effects of cruise tourism on stay-over tourism in the Caribbean: Non-parametric panel data evidence. *Tourism Economics*, *17*(1), pp.127-158.

Brida, J.G., Gómez, D.M. and Segarra, V., 2020. On the empirical relationship between tourism and economic growth. *Tourism Management*, *81*, p.10)4131.

Bushell, R. and Bricker, K., 2017. Tourism in protected areas: Developing meaningful standards. *Tourism and Hospitality Research*, *17*(1), pp.106-120.

Butler, R. W., & Dodds, R. (2022). Island tourism: Vulnerable or resistant to overtourism. Highlights of Sustainability, 1(2), 54-64.

Butt, N., 2007. The impact of cruise ship generated waste on home ports and ports of call: A study of Southampton. *Marine Policy*, *31*(5), pp.591-598.

Calewaert, J.-B., Sierra-Correa, P. C.,de Boer, G., Crosman, K., Kågesten, G., Taconet, M., Busumprah, P. T., Alvarez-Fanjul, E., Shepherd, I., Schaap, D., Hall, S., Zinkann, A.-C. , Haddad, T., Jegat, V., Smit, M., Sun, M., Suzuki, T., Visbeck, M., Xingyuan, R. & McMeel, O. (2024). Ocean Decade Vision 2030 White Papers – Challenge 8: Create a Digital Representation of the Ocean. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.8.). https://doi.org/10.25607/bxhy-ra59

Canavan, B., 2016. Tourism culture: Nexus, characteristics, context and sustainability. Tourism management, 53, pp.229-243.

Catalano, M., Forni, L. and Pezzolla, E., 2020. Climate-change adaptation: The role of fiscal policy. *Resource and Energy Economics*, *59*, p.101111.

Cattano, C., Turco, G., Di Lorenzo, M., Gristina, M., Visconti, G., & Milazzo, M., 2021. Sandbar shark aggregation in the central Mediterranean Sea and potential effects of tourism. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *31*(6), 1420-1428.

Cazenave, A. and Mitchum, G., 2024, Sea level rise *STATE OF THE OCEAN REPORT*, p.52.

Chaudhry A. K., Sachdeva P., 2021. Microplastics' origin, distribution, and rising hazard to aquatic organisms and human health: Socio-economic insinuations and management solutions, *Regional Studies in Marine Science*, 48, 102018.

Chen, H. and Rahman, I., 2018. Cultural tourism: An analysis of engagement, cultural contact, memorable tourism experience and destination loyalty. *Tourism management perspectives*, *26*, pp.153-163.

Chen, J.M., Petrick, J.F., Papathanassis, A. and Li, X., 2019. A meta-analysis of the direct economic impacts of cruise tourism on port communities. *Tourism Management Perspectives*, *31*, pp.209-218.

Choi, J., Jeon, H., & Asperin, A. (2024). Popularity Paradox in Venice, Italy: A Battle of Priorities. Journal of Hospitality & Tourism Cases, 21649987241281375.

Cisneros-Montemayor, A.M., Townsel, A., Gonzales, C.M., Haas, A.R., Navarro-Holm, E. E., Salorio-Zuniga, T., Johnson, A.F., 2020. Nature-based marine tourism in the Gulf of California and Baja California

Peninsula: economic benefits and key specie *Nat. Resour. Forum* 44 (2), 111–128. https://doi.org/10.1111/1477-8947.12193

Coldwell, W., 2017. First Venice and Barcelona: now anti-tourism marches spread across Europe. The Guardian, 10, 2017.

Connell, J., Page, S.J. and Meyer, D., 2015. Visitor attractions and events: Responding to seasonality. *Tourism management*, *46*, pp.283-298.

Cooper, J. A. G., O'Connor, M. C., & McIvor, S., 2020. Coastal defences versus coastal ecosystems: a regional appraisal. Marine Policy, 111, 102332.

Coste, A., M. Cali, N. Cantore, and D. Heine, 2018. "Staying Competitive: Productivity Effects of Environmental Taxes." In Fiscal Policies for Development and Climate Action, edited by M.A. Pigato, 65. Washington, DC: World Bank. https://elibrary.worldbank.org/doi/epdf/10.1596/978-1-4648-1358-0_ch2

CLIA, 2024. State of the Cruise Industry Report, Cruise Lines International Association, May, 2024. https://cruising.org/-/media/clia-media/research/2024/2024-state-of-the-cruise-industry-report_updated-050824_web.ashx

de Schipper, M. A., Ludka, B. C., Raubenheimer, B., Luijendijk, A. P., & Schlacher, T. A., 2021. Beach nourishment has complex implications for the future of sandy shores. Nature Reviews Earth & Environment, 2(1), 70-84.

Day, J., 2008. The need and practice of monitoring, evaluating and adapting marine planning and management—lessons from the Great Barrier Reef. *Marine policy, 32*(5), 823-831.

Domènech, A., Gutiérrez, A. and Anton Clavé, S., 2020. Cruise passengers' spatial behaviour and expenditure levels at destination. *Tourism Planning & Development*, *17*(1), pp.17-36.

Downs, C.A., Cruz, O.T. and Remengesau Jr, T.E., 2022. Sunscreen pollution and tourism governance: Science and innovation are necessary for biodiversity conservation and sustainable tourism. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *32*(5), pp.896-906.

Dwyer, L., 2003. Trends underpinning tourism to 2015: An analysis of key drivers for change. International Journal of Tourism Sciences, 3(2), pp.61-77.

Dwyer, L., & Kim, C., 2003. Destination competitiveness: Determinants and indicators. *Current Issues in Tourism*, 6(5), 369-414.

Edwards, P.E., 2009. Sustainable financing for ocean and coastal management in Jamaica: The potential for revenues from tourist user fees. *Marine Policy*, *33*(2): 376-385.

Epler Wood, M., 2017. Sustainable Tourism on a Finite Planet: Environmental, Business and Policy Solutions. London: Routledge. https://doi.org/10.4324/9781315439808.

Epler Wood, M., M. Milstein, and K. Ahamed-Broadhurst, 2019. Destinations at Risk: The Invisible Burden of Tourism. Bristol, UK: EplerWood International and Travel Foundation; New York: Cornell University, Centre for Sustainable Global Enterprise. https://www.thetravelfoundation.org.uk/invisible-burden/

Fan, D.X., Liu, A. and Qiu, R.T., 2019. Revisiting the relationship between host attitudes and tourism development: A utility maximization approach. *Tourism Economics*, *25*(2), pp.171-188.

Fenichel, E.P., Milligan, B., Porras, I., Addicott, E.T., Árnasson, R., Bordt, M., Djavidnia, S., Dvarskas, A., Goldman, E., Grimsrud, K. and Lange, G.M., 2023. National accounting for the ocean and ocean economy. In The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy (pp. 279-307). Cham: Springer International Publishing.

Fisher, D., & Stewart, E. J., 2017. Tourism, time, and the last chance. Tourism Analysis, 22(4), 511-521.

Font, X., Cochrane, J. & Tapper, R., 2004. Pay per nature view: understanding tourism revenues for effective management plans. Report for WWF, Leeds Metropolitan University, Leeds, UK.

Frantzeskaki, N., McPhearson, T., Collier, M.J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Van Wyk, E., Ordóñez, C. and Oke, C., 2019. Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making. *BioScience*, *69*(6), pp.455-466.

Frent, C., 2016. An overview on the negative impacts of tourism. Revista de turism-studii si cercetari in turism, (22).

Forrester, G.E., Flynn, R.L., Forrester, L.M. and Jarecki, L.L., 2015. Episodic disturbance from boat anchoring is a major contributor to, but does not alter the trajectory of, long-term coral reef decline. *PloS one*, *10*(12), p.e0144498.

Gacutan, J., Galparsoro, I., Pınarbaşı, K., Murillas, A., Adewumi, I.J., Praphotjanaporn, T., Johnston, E.L., Findlay, K.P. and Milligan, B.M., 2022. Marine spatial planning and ocean accounting: Synergistic tools enhancing integration in ocean governance. Marine Policy, 136, p.104936.

Garcés-Ordóñez, O., Díaz, L. F. E., Cardoso, R. P., & Muniz, M. C., 2020. The impact of tourism on marine litter pollution on Santa Marta beaches, Colombian Caribbean. *Marine pollution bulletin*, *160*, 111558.

Garza, N. and Ovalle, M.C., 2019. Tourism and housing prices in Santa Marta, Colombia: Spatial determinants and interactions. *Habitat International*, *87*, pp.36-43.

Gascon, M., Zijlema, W., Vert, C., White, M.P. and Nieuwenhuijsen, M.J., 2017. Outdoor blue spaces, human health and well-being: A systematic review of quantitative studies. *International journal of hygiene and environmental health*, *220*(8), pp.1207-1221.

Ghaderi, Z., Tavakoli, R., Yarahmadi, F., Bagheri, F. and Almuhrzi, H.M., 2024. Islamic views on local tourism engagement in conservative societies: an insight from Oman. Current Issues in Tourism, pp.1-17.

González-Reverté, F., & Guix, A. S. (2024). The social construction of anti-tourism protest in tourist cities: a case study of Barcelona. International Journal of Tourism Cities, (ahead-of-print).

Gössling, S., Scott, D., & Hall, C. M. (2020). Pandemics, tourism and global change: a rapid assessment of COVID-19. *Journal of Sustainable Tourism*, 29(1), 1-20

Gouveia, A.X. and Eusébio, C., 2019. Assessing the direct economic value of cruise tourism in a port of call: The case of Funchal on the island of Madeira. *Tourism and Hospitality Research*, *19*(4), pp.422-438.

Griggs, G., 2024. Beach Nourishment: A Critical Look. *Journal of Coastal Research*.

Gounder, A. and Cox, C., 2022. Exploring the role of tourism dependency on COVID-19 induced economic shock in the Small Island Developing States. *Current Issues in Tourism*, *25*(7), pp.1151-1168.

Grydehøj, A., & Kelman, I. (2017). The eco-island trap: Climate change mitigation and conspicuous sustainability. Area, 49(1), 106-113.

Guidino, C., Campbell, E., Alcorta, B., Gonzalez, V., Mangel, J.C., Pacheco, A.S., Silva, S., Alfaro-Shigueto, J., 2020. Whale watching in northern Peru: an economic boom? *Tourism Mar. Environ.* 15 (1), 1–10. https://doi.org/10.3727/ 154427320X15819596320544.

Hampton, M.P., and J. Jeyacheya. 2020. "Tourism-Dependent Small Islands, Inclusive Growth, and the Blue Economy." *One Earth* 2 (1): 8–10. https://www.sciencedirect.com/science/article/pii/S2590332219302763.

Henderson, C. J., Gilby, B. L., Schlacher, T. A., Connolly, R. M., Sheaves, M., Maxwell, P. S., ... & Olds, A. D., 2020. Landscape transformation alters functional diversity in coastal seascapes. Ecography, 43(1), 138-148.

Herrmann, M. 2022. "This Tourism App Unlocks Unique Experiences in Palau through Completing Eco-Friendly Tasks." Forbes, 17 May. https://www.forbes.com/sites/micheleherrmann/2022/05/17/this-tourism-app-for-palau-unlocks-unique-experiences-through-completingeco-friendly-tasks/?sh=c81ac2057020

Hill, K., 2015. Coastal infrastructure: a typology for the next century of adaptation to sea-level rise. Frontiers in Ecology and the Environment, 13(9), 468-476.

Hoarau-Heemstra, H., Wigger, K., Olsen, J. and James, L., 2023. Cruise tourism destinations: Practices, consequences and the road to sustainability. *Journal of Destination Marketing & Management*, *30*, p.100820.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K. and Knowlton, N., 2007. Coral reefs under rapid climate change and ocean acidification. *science*, *318*(5857), pp.1737-1742.

Hughes, N., 2018. 'Tourists go home': anti-tourism industry protest in Barcelona. Social movement studies, 17(4), 471-477.

Ingram, J.C., McKenzie, E.J., Bagstad, K.J., Finisdore, J., van den Berg, R., Fenichel, E., Vardon, M., Posner, S., Santamaria, M., Mandle, L. and Barker, R., 2024. Leveraging natural capital accounting to support

businesses with nature-related risk assessments and disclosures. Philosophical Transactions of the Royal Society B, 379(1903), p.20220328.

Imbsen, C., S. Hartman, P. Bernadett, and B. Lynam, 2021. Towards Destination Stewardship: Achieving Destination Stewardship through Scenarios and a Governance Diagnostics Framework. London: World Travel and Tourism Council. https://wttc.org/Portals/0/Documents/Reports/2021/Destination-Stewardship-Framework.pdf?ver=2021-07-22-091804-637

Ionescu, G.H., Firoiu, D., Pirvu, R. and Vilag, R.D., 2019. The impact of ESG factors on market value of companies from travel and tourism industry. *Technological and Economic Development of Economy*, *25*(5), pp.820-849.

Khadanga M. K., Behera A. K., Swain G. K., Dora D. P., Padhi C. P., Mishra R. K., Pradhan S., Barik S., Mohanty P. K., Mishra P., Patro S., 2022. Evaluation of the status of marine plastic pollution along a tourist beach of Bay of Bengal during lockdown and post lockdown. *Marine Pollution Bulletin*, 182, 113970.

King, S., Agra, R., Zolyomi, A., Keith, H., Nicholson, E., De Lamo, X., Portela, R., Obst, C., Alam, M., Honzák, M. and Valbuena, R., 2024. Using the system of environmental-economic accounting ecosystem accounting for policy: A case study on forest ecosystems. Environmental Science & Policy, 152, p.103653.

Kittinger, J.N., Rotjan, R.D., Hanich, Q., Pasisi, B. and Rambourg, C., 2024. Balancing protection and production in ocean conservation. *npj Ocean Sustainability*, *3*(1), p.24. https://doi.org/10.1038/s44183-024-00062-w

Kil, N., Holland, S.M., Stein, T.V. and Ko, Y.J., 2012. Place attachment as a mediator of the relationship between nature-based recreation benefits and future visit intentions. *Journal of Sustainable Tourism*, *20*(4), pp.603-626.

Koliotasi, A. S., Abeliotis, K., & Tsartas, P. G., 2023. Understanding the Impact of Waste Management on a Destination' s Image: A Stakeholders' Perspective. Tourism and Hospitality, 4(1), 38-50.

Kotrikla, A.M., Zavantias, A. and Kaloupi, M., 2021. Waste generation and management onboard a cruise ship: A case study. *Ocean & Coastal Management*, *212*, p.105850.

Kuba, D., Kuba, M. Z. D., & Sani, K., 2024. Community-Based Management: Marine Tourism Development for Ecological and Economic Sustainability. *Journal of Economic Education and Entrepreneurship Studies*, *5*(3), 467-479.

Lagarias, A., Stratigea, A., & Theodora, Y. (2023, June). Overtourism as an emerging threat for sustainable island communities–Exploring indicative examples from the South Aegean Region, Greece. In International Conference on Computational Science and Its Applications (pp. 404-421). Cham: Springer Nature Switzerland.

Lamb J., Willis B., Fiorenza E., Couch C., Howard R., Rader D., True J., Kelly L. A., Ahmad A., Jompa J., Harvell C. D., 2018. Plastic waste associated with disease on coral reefs. *Science*, 359, 460–462.

Legendre, T.S., Ding, A. and Back, K.J., 2024. A bibliometric analysis of the hospitality and tourism environmental, social, and governance (ESG) literature. Journal of Hospitality and Tourism Management, 58, pp.309-321.

Lehto, X., Davari, D. and Park, S., 2020. Transforming the guest–host relationship: a convivial tourism approach. International Journal of Tourism Cities, 6(4), pp.1069-1088.

Leotaud, N., Laidlow-Ferdinand, A., Clauzel, S., Vaughan, N., 2024. *Towards sustainable blue tourism in the Caribbean: Policy pathways to support community-based coastal and ocean tourism* . Blue Tourism Initiative Diagnostic Study. CANARI: Port of Spain.

Leposa, N., 2020. Problematic blue growth: A thematic synthesis of social sustainability problems related to growth in the marine and coastal tourism. *Sustainability Science*, *15*, pp.1233-1244.

Lester, S.E., White, C., Mayall, K. and Walter, R.K., 2016. Environmental and economic implications of alternative cruise ship pathways in Bermuda. *Ocean & Coastal Management*, *132*, pp.70-79.

Levitan-Haffar, M.M., 2022. Can Nature Tourists Police Themselves? Comparing Eco-Pledges in the United States and Palau. *U. Colo. L. Rev.*, *93*, p.801. https://lawreview.colorado.edu/wp-content/uploads/2023/02/11.-Levitan-Haffar.pdf

Lewis-Cameron, A. and Brown-Williams, T., 2022. Rethinking destination success: An island perspective. *Island Studies Journal*, *17*(1), pp.141-156.

Li, C. & Huang, X., 2022. How does COVID-19 risk perception affect wellness tourist intention: findings on Chinese generation z. Sustainability, 15(1), 141. https://doi.org/10.3390/su15010141

Liu, J., Yi, C., Tang, S., Zhang, W., Wen, K., Qin, C., ... & Jiang, A., 2023. Impact of coastal island restoration engineering and subsequent tourism on migratory waterbirds: a 3-year case from Southern China. Restoration Ecology, 31(8), e13974.

Lloret, J., Carreño, A., Carić, H., San, J. and Fleming, L.E., 2021. Environmental and human health impacts of cruise tourism: A review. *Marine pollution bulletin*, *173*, p.112979.

Mafruhah, M., Supriyadi, S., & Rahman, A., 2020. Causality between tourism industry development and the ecological sustainability in the marine environment: A convergence and divergence among stakeholders with MACTOR analysis. *International Journal of Energy Economics and Policy*, 10*(6), 7989. https://doi.org/10.32479/ijeep.7989

Mehvar, N., Khosravi, M., & Zare, M., 2018. Quantifying the economic value of coastal ecosystem services: A review. *Journal of Marine Science and Engineering*, 6*(1), 5. https://doi.org/10.3390/jmse6010005

Mejjad, N., Rossi, A., & Pavel, A. B., 2022. The coastal tourism industry in the Mediterranean: A critical review of the socio-economic and environmental pressures & impacts. *Tourism Management Perspectives, 44*, 101007.

Milano, C., Novelli, M. and Cheer, J.M., 2019. Overtourism and tourismphobia: A journey through four decades of tourism development, planning and local concerns. *Tourism Planning & Development*, *16*(4), pp.353-357.

Milano, C., Novelli, M., & Russo, A. P. (2024). Anti-tourism activism and the inconvenient truths about mass tourism, touristification and overtourism. Tourism Geographies, 26(8), 1313-1337.

Miller, K.M., 2022. Disentangling tourism impacts on small-scale fishing pressure. *Marine Policy*, *137*, p.104960.

Morse M., McCauley D., Orofino S., Stears K., Mladjov S., Caselle J., Clavelle T., Freeman R., 2024. Preferential selection of marine protected areas by the recreational scuba diving industry. *Marine Policy*, 159, 105908.

Mustika, P. L. K., Ichsan, M., & Booth, H., 2020. The economic value of shark and ray tourism in Indonesia and its role in delivering conservation outcomes. Frontiers in Marine Science, 7, 261.

National Oceanic and Atmospheric Administration (NOAA), Office for Coastal Management. 2023. "NOAA Report on the U.S. Marine Economy." Charleston, SC: NOAA Office for Coastal Management. Available at: http://coast.noaa.gov/digitalcoast/training/econreport.html

National Oceanic and Atmospheric Association, 2024. Fast Facts, Tourism and Recreation, NOAA Office of Coastal Management. https://coast.noaa.gov/states/fast-facts/tourism-and-recreation.html#

Nepal, R., & Nepal, S. K. (2021). Managing overtourism through economic taxation: Policy lessons from five countries. Tourism Geographies, 23(5-6), 1094-1115.

New, L., Lusseau, D., & Harcourt, R. (2020). Dolphins and boats: when is a disturbance, disturbing?. Frontiers in Marine Science, 7, 353.

Niella, Y., Udyawer, V., Drew, M., Simes, B., Pederson, H., & Huveneers, C., 2023. Multi-year effects of wildlife tourism on shark residency and implications for management. *Marine Policy*, *147*, 105362.

Nilsson, J. H., & Gössling, S., 2013. Tourist responses to extreme environmental events: The case of Baltic Sea algal blooms. Tourism Planning & Development, 10(1), 32-44.

Northrop, E., Schuhmann, P., Burke, L., Fyall, A., Alvarez, S., Spenceley, A., Becken, S., Kato, K., Roy, J., Some, S. and Veitayaki, J., 2022. Opportunities for transforming coastal and ocean tourism : towards sustainability, regeneration and resilience. *Commissioned by the high-level panel for a sustainable ocean economy (ocean panel). Washington, DC: World Resources Institute*.

Northrop, E., Konar, M., Frost, N., Hollaway, E., 2023. A Sustainable and Equitable Blue Recovery to the COVID-19 Crisis. In: Lubchenco, J., Haugan, P.M. (eds) The Blue Compendium. Springer, Cham. https://doi.org/10.1007/978-3-031-16277-0_19

Novy, J., & Colomb, C., 2021. Urban tourism as a source of contention and social mobilisations: A critical review. Travel and tourism in the age of overtourism, 6-23.

Nunkoo, R., Seetanah, B., Jaffur, Z.R.K., Moraghen, P.G.W. and Sannassee, R.V., 2020. Tourism and economic growth: A meta-regression analysis. *Journal of Travel Research*, *59*(3), pp.404-423.

O'Brien, K., Belbéoch, M., Appeltans, W. and Heslo, E., Open access to ocean data from global to local scales. *STATE OF THE OCEAN REPORT*, p.71.

OECD, 2016. The Ocean Economy in 2030, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264251724-*en*

Olmstead, S.M. and Stavins, R.N., 2009. Comparing price and nonprice approaches to urban water conservation. *Water Resources Research*, *45*(4).

One Planet Network, 2021. "The Glasgow Declaration: A Commitment to a Decade of Tourism Climate Action." Nairobi: One Planet Network Secretariat, United Nations Environment Programme. https://www.oneplanetnetwork.org/sites/default/files/2021-11/GlasgowDeclaration_EN_0.pdf

Ove Hoegh-Guldberg, Eliza Northrop, Oliver S. Ashford, Thierry Chopin, Jessica Cross, Carlos Duarte, Steve Gaines, Tess Geers, Stefan Gössling, Peter Haugan, Mark Hemer, Jennifer Howard, Claire Huang, Andreas Humpe, Gabriella Kitch, David Koweek, Dorte Krause-Jensen, Catherine E. Lovelock, Kathryn Matthews, Patrick Mustain, Finn Gunnar Nielsen, Robert Parker, Joyashree Roy, Tristan Smith, Shreya Some, Ya-Yen Sun, Torsten Thiele and Peter Tyedmers. 2023. "The Ocean as a Solution to Climate Change: Updated Opportunities for Action." Special Report. Washington, DC: World Resources Institute. https://oceanpanel.org/publication/ocean-solutions-to-climate-change

Papageorgiou, M., 2016. Coastal and ocean tourism : A challenging factor in Marine Spatial Planning. *Ocean & coastal management*, *129*, pp.44-48.

Papathanassis, A., 2023. A decade of 'blue tourism'sustainability research: Exploring the impact of cruise tourism on coastal areas. *Cambridge Prisms: Coastal Futures*, *1*, p.e12.

Paramati, S.R., Alam, M.S. and Lau, C.K.M., 2018. The effect of tourism investment on tourism development and CO2 emissions: empirical evidence from the EU nations. *Journal of Sustainable Tourism*, 26(9), pp.1587-1607.

Parretti, P., Canning-Clode, J., Ferrario, J., Marchini, A., Botelho, A.Z., Ramalhosa, P. and Costa, A.C., 2020. Free rides to diving sites: The risk of marine non-indigenous species dispersal. *Ocean & coastal management*, *190*, p.105158.

Pavez, G., MUnoz, L. I. L. Y., Barilari, F., & Sepúlveda, M., 2015. Variation in behavioral responses of the South American sea lion to tourism disturbance: Implications for tourism management. *Marine Mammal Science*, *31*(2), 427-439.

Pencarelli, T., 2020. The digital revolution in the travel and tourism industry. *Information Technology & Tourism*, *22*(3), pp.455-476.

Perkiss, S., McIlgorm, A., Nichols, R., Lewis, A.R., Lal, K.K. and Voyer, M., 2022. Can critical accounting perspectives contribute to the development of ocean accounting and ocean governance?. *Marine Policy*, 136, p.104901.

Peterson, R. R. (2023). Over the Caribbean top: community well-being and over-tourism in small island tourism economies. International Journal of Community Well-Being, 6(2), 89-126.

Peterson, R., & DiPietro, R. B. (2021). Is Caribbean tourism in overdrive? Investigating the antecedents and effects of overtourism in sovereign and nonsovereign small island tourism economies (SITEs). International Hospitality Review, 35(1), 19-40.

Qiang, M., Shen, M. and Xie, H., 2020. Loss of tourism revenue induced by coastal environmental pollution: a length-of-stay perspective. *Journal of Sustainable Tourism*, *28*(4), pp.550-567.

Rangel-Buitrago, N., Galgani, F. and Neal, W.J., 2024. Addressing the global challenge of coastal sewage pollution. *Marine Pollution Bulletin*, *201*, p.116232.

Reinhold, S., Beritelli, P., Fyall, A., Choi, H.S.C., Laesser, C. and Joppe, M., 2023. State-of-the-art review on destination marketing and destination management. *Tourism and Hospitality*, 4(4), pp.584-603.

Ressurreição, A., Cardigos, F., Giacomello, E., Leite, N., Oliveira, F., Kaiser, M.J., Gonçalves, J. and Santos, R.S., 2022. The value of marine ecotourism for an European outermost region. *Ocean & Coastal Management*, *222*, p.106129.

Ressurreição, A. and Giacomello, E., 2013, Quantifying the direct use value of the Condor Seamount. *Deep-Sea Research* II 98: 209-217.

Richardson, R.B. and Witkowski, K., 2010. Economic vulnerability to climate change for tourism-dependent nations. *Tourism Analysis*, *15*(3), pp.315-330.

Riegl, B., Bruckner, A., Coles, S.L., Renaud, P. and Dodge, R.E., 2009. Coral reefs: threats and conservation in an era of global change. *Annals of the New York Academy of Sciences*, *1162*(1), pp.136-186.

Rivera-Planter, M., & Muñoz-Piña, C. 2005. Fees for reefs: Economic instruments to protect Mexico's marine natural areas. *Current Issues in Tourism* 8 (2-3):195–213.

Rogers, C.S. and Garrison, V.H., 2001. Ten years after the crime: lasting effects of damage from a cruise ship anchor on a coral reef in St. John, US Virgin Islands. *Bulletin of Marine Science*, *69*(2), pp.793-803.

Sánchez-Vergara, J. I., Orel, M., & Capdevila, I., 2023. Home office is the here and now. Digital nomad visa systems and remote work-focused leisure policies. *World Leisure Journal, 65*(2), 236-255.

Satnarine-Singh, N., Hosein, R. and Saridakis, G., 2024. Structural change and export diversification: A comparison of CARICOM's position. *The Journal of International Trade & Economic Development*, *33*(6), pp.1163-1189.

Schoo, K.L., Newton, J.A., Widdicombe, S. and Isensee, K., 2024. Status and trends of ocean acidification. *STATE OF THE OCEAN REPORT*, p.21.

Schuhmann, P.W., Bass, B.E., Casey, J.F. and Gill, D.A., 2016. Visitor preferences and willingness to pay for coastal attributes in Barbados. *Ocean & Coastal Management*, *134*, pp.240-250.

Schuhmann, P.W., 2020. Valuation of ecosystem services as a basis for investment in Blue Economies. In *The Caribbean blue economy* (pp. 78-91). Routledge.

Schumacher, J., Bergqvist, L., Van Beest, F.M., Carstensen, J., Gustafsson, B., Hasler, B., Fleming, V., Nygård, H., Pakalniete, K., Sokolov, A. and Zandersen, M., 2020. Bridging the science-policy gap–toward better integration of decision support tools in coastal and marine policy implementation. *Frontiers in Marine Science*, *7*, p.587500.

Scott, N., 2013. Tourism is a fragmented industry and policy area: Myth or reality?. In *Conference Proceedings of the Myths of Tourism Conference*.

Shamir, Z. Z., Shamir, S. Z., Becker, N., Scheinin, A., & Tchernov, D., 2019. Evidence of the impacts of emerging shark tourism in the Mediterranean. *Ocean & Coastal Management*, *178*, 104847.

Slišković, M., Piria, M., Nerlović, V., Ivelja, K.P., Gavrilović, A. and Mrčelić, G.J., 2021. Non-indigenous species likely introduced by shipping into the Adriatic Sea. *Marine Policy*, *129*, p.104516.

Small, M. and Oxenford, H.A., 2022. Impacts of cruise ship anchoring during COVID-19: Management failures and lessons learnt. *Ocean & Coastal Management*, *229*, p.106332.

Spalding, M.D., McIvor, A.L., Beck, M.W., Koch, E.W., Möller, I., Reed, D.J., Rubinoff, P., Spencer, T., Tolhurst, T.J., Wamsley, T.V. and Van Wesenbeeck, B.K., 2014. Coastal ecosystems: a critical element of risk reduction. *Conservation Letters*, *7*(3), pp.293-301.

Spalding, M., Burke, L., & Fyall, A., 2021. Covid-19: Implications for nature and tourism. *Anatolia, 32*(1), 126-127.

Spalding, M.D., Longley-Wood, K., McNulty, V.P., Constantine, S., Acosta-Morel, M., Anthony, V., Cole, A.D., Hall, G., Nickel, B.A., Schill, S.R. and Schuhmann, P.W., 2023. Nature dependent tourism–Combining big data and local knowledge. *Journal of Environmental Management*, *337*, p.117696.

Stojčić, N., Vizek, M., & Glaurdić, J. (2024). Short-term rental expansion and residential displacement in tourism communities: evidence from Croatia. Regional Studies, 58(11), 2115-2128.

Sun, L. and Feng, N., 2023. Research on fiscal policies supporting green and low-carbon transition to promote energy conservation and emission reduction in cities: empirical evidence from China. *Journal of Cleaner Production*, *430*, p.139688.

Tausch, A., 2016. Social cohesion, sustainable development and tourism in small island developing states (SIDS): Alternative models towards sustainability. *Sustainability*, 8(11), 1151.

Tejedo, P., Benayas, J., Cajiao, D., Leung, Y.F., De Filippo, D. and Liggett, D., 2022. What are the real environmental impacts of Antarctic tourism? Unveiling their importance through a comprehensive meta-analysis. *Journal of Environmental Management*, *308*, p.114634.

Thorburn, E., Milne, S. and Deuchar, C., 2021. Developing marine ecotourism for a sustainable blue economy: a literature review.

Topelko, K.N. and Dearden, P., 2005. The shark watching industry and its potential contribution to shark conservation. *Journal of Ecotourism*, *4*(2), pp.108-128.

UNESCO, 2021. Cutting Edge: Bringing cultural tourism back in the game. United Nations Educational, Scientific and Cultural Organization, March 2021. Available at: https://www.unesco.org/en/articles/cutting-edge-bringing-cultural-tourism-back-game

Vergori, A.S. and Arima, S., 2020. Cultural and non-cultural tourism: Evidence from Italian experience. *Tourism Management*, *78*, p.104058.

Vianna, G. M., Meekan, M. G., Rogers, A. A., Kragt, M. E., Alin, J. M., & Zimmerhackel, J. S., 2018. Shark-diving tourism as a financing mechanism for shark conservation strategies in Malaysia. Marine Policy, 94, 220-226.

Vianello, M., 2016. The No Grandi Navi campaign: protests against cruise tourism in Venice. In Protest and resistance in the tourist city (pp. 185-204). Routledge.

von Saltza, E. and Kittinger, J.N., 2022. Financing conservation at scale via visitor green fees. *Frontiers in Ecology and Evolution*, *10*, p.1036132.

von Schuckmann, K., Minière, A. and Cheng, L., 2024. Ocean warming. *STATE OF THE OCEAN REPORT*, p.24.

Waligo, V. M., Clarke, J., & Hawkins, R., 2013. Implementing sustainable tourism: A multi-stakeholder involvement management framework. *Tourism Management,* 36, 342-353.

Wang, X., Li, X.R., Zhen, F. and Zhang, J., 2016. How smart is your tourist attraction?: Measuring tourist preferences of smart tourism attractions via a FCEM-AHP and IPA approach. *Tourism management*, *54*, pp.309-320.

Wang, K.C. M., Lee, K. E., & Mokhtar, M., 2021. Solid waste management in small tourism islands: An evolutionary governance approach. *Sustainability*, 13(11), 5896.

Ward, R.D., Friess, D.A., Day, R.H. and Mackenzie, R.A., 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and sustainability*, *2*(4), p.e01211.

Wearing, S. and McGehee, N.G., 2013. Volunteer tourism: A review. *Tourism management*, *38*, pp.120-130.

Wessel, M., Schmidt-Kessen, M. J., & Hukal, P. (2024). Regulating short-term rental platforms: the effects of local regulatory responses on Airbnb's operations in Europe. Industrial and Corporate Change, 33(5), 1158-1179.

White, M.P., Elliott, L.R., Gascon, M., Roberts, B. and Fleming, L.E., 2020. Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environmental research*, *191*, p.110169.

Wilkins, E.J. and de Urioste-Stone, S., 2018. Place attachment, recreational activities, and travel intent under changing climate conditions. *Journal of Sustainable Tourism*, *26*(5), pp.798-811.

Wong, C. M., Conti-Jerpe, I., Raymundo, L. J., Dingle, C., Araujo, G., Ponzo, A., & Baker, D. M., 2019. Whale shark tourism: impacts on coral reefs in the Philippines. *Environmental management*, *63*, 282-291.

World Economic Forum, 2024. "Bold Measures to Close the Climate Action Gap: A Call for Systemic Change by Governments and Corporations", World Economic Forum, Geneva, Switzerland.

World Tourism Organization, (2023. UNWTO Tourism Statistics Database, Madrid. https://www.unwto.org/tourism-statistics/tourism-statistics-database

WTTC, 2021. Towards Destination Stewardship Achieving Destination Stewardship through Scenarios & a Governance Diagnostics Framework.

WTTC, 2024. World Travel & Tourism Council: Travel & Tourism Economic Impact 2024. https://wttc.org/Portals/0/Documents/Reports/2021/Destination-Stewardship-Framework.pdf?ver=2021-07-22-091804-637

WTTC, 2024b. World Travel & Tourism Council. Climate and Ocean: Quantifying coastal and marine tourism and protecting destinations (A Summary of Key Findings). https://researchhub.wttc.org/product/climate-and-ocean-quantifying-coastal-and-marine-tourism-protecting-destinations

Yan, T., Li, X. D., Tan, Z. J., Yu, R. C., & Zou, J. Z., 2022. Toxic effects, mechanisms, and ecological impacts of harmful algal blooms in China. Harmful Algae, 111, 102148.

Yu, Y., Zhang, Y., & Wang, Y., 2018. Effects on willingness to pay for marine conservation: Evidence from Zhejiang Province, China. *Sustainability*, 10*(7), 2298. https://doi.org/10.3390/su10072298

Yusoff, M. S., Kamaruddin, M. A., Hanif, M. H. M., Norashiddin, F. A., Shadi, A. M. H., Wang, L. K., & Wang, M. H. S., 2022. Solid Waste Management in the Tourism Industry. In Solid Waste Engineering and Management: Volume 3 (pp. 1-54). Cham: Springer International Publishing.

Zamani-Farahani, H. and Henderson, J.C., 2010. Islamic tourism and managing tourism development in Islamic societies: the cases of Iran and Saudi Arabia. *International journal of tourism researc*h, 12(1), pp.79-89.

Zanini, S., 2017. Tourism pressures and depopulation in Cannaregio: Effects of mass tourism on Venetian cultural heritage. *Journal of Cultural Heritage Management and Sustainable Development*, *7*(2), pp.164-178.

Zhang, D., Wang, Q. and Yang, Y., 2023. Cure-all or curse? A meta-regression on the effect of tourism development on poverty alleviation. *Tourism Management*, *94*, p.104650.

Zhang, H., Cai, L., Bai, B., Yang, Y. and Zhang, J., 2023. National forest park visitors' connectedness to nature and pro-environmental behavior: The effects of cultural ecosystem service, place and event attachment. *Journal of Outdoor Recreation and Tourism*, *42*, p.100621.

Section 5

Chapter 5: Use of genetic resources and biotechnology

Authors:

Muriel Rabone*[1]; Sophie Arnaud Haond; Robert Blasiak*[1]; Angelika Brandt; Tyler Rae Chung; Luciana Fernandes Coelho; Jane Collins; Natalia Erazo; Marcel Jaspars; Jessica Lavelle; Muriel Rabone*[2]; Randi Rotjan; Changwei Shao; Mat Upton; Helena Vieira; Tanya Wagenaar; Robert Blasiak*[2]

*[1] Convening author; robert.blasiak@su.se

*[2] Joint cConvening author, m.rabone@nhm.ac.uk

*[1] Joint cConvening author; robert.blasiak@su.se

1. Key Findings

- Marine genetic resources (MGRs) hold immense potential but remain largely understudied, with most areas beyond national jurisdiction (ABNJ) and the deep sea still unexploredMarine genetic resources (MGRs) have vast potential but are still understudied; most areas beyond national jurisdiction (ABNJ) and the deep sea remain unexplored.
- Improvements Advancements in the MGRs research and development pipeline have contributed to increasinged interest in biodiscovery in the marine environment, including the deep sea; marine microbes, particularlyincluding microbiomes, are a key focusmarine microbes (including as microbiomes) are a particular focus.
- MGRs, including the fair and equitable sharing of benefits, is one of the main elements addressed under the BBNJ Agreement. Engagement by the scientific community will be crucial for its implementation, including to achieve cooperation in activities with respect to MGRs of ABNJ, marine scientific research, capacity building and the transfer of technology, and optimizing interdisciplinary approaches.
- Equitable access and use are of central importance for the future of genetic resources and biotechnology, and need to guide efforts to address existing knowledge and capacity gaps.
- There is a need to harmonize and ensure coordination across the CBD, its Nagoya Protocol, the DSI COP decision 16/2[50] and the BBNJ Agreement on issues of benefit sharing.
- Equitable access and use are of central importance for the future of genetic resources and biotechnology, and need to guide efforts to address existing knowledge and capacity gaps.

[50] https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-02-en.pdf

2. Introduction

A remarkable diversity of life is found in the ocean, which is home to species from 33 of the 34 major animal phyla (Sigwart and others, 2021a). Living organisms have evolved in the ocean for three billion years longer than they have on land, and have adapted to thrive in complex habitats, some of which are characterised by extreme temperature, salinity and the absence of light. Extreme conditions and habitat heterogeneity ~~of the deep sea~~ drive adaptation and evolutionary novelty, for example hydrothermal vents and abyssal plains in the deep sea (Le Bris and Gaill, 2007; Sun and others, 2020). The vast genomic diversity of marine ecosystems therefore offers a reservoir of genetic resources and biological innovations, with marine organisms producing a wide variety of specific and potent bioactive substances (Blasiak and others, 2021, Arrieta and others, 2010).

Marine genetic resources (MGRs) are defined as "any material of marine plant, animal, microbial or other origin containing functional units of heredity of actual or potential value" (UN 2023)[51]. Marine biotechnology (also termed 'blue' biotechnology) is the discovery and usage of MGR for a range of potential applications, ~~Uses of MGRs~~ including ~~advancing~~ human and animal health, improving industrial processes, climate change mitigation, bioremediation and managing invasive species (Blasiak and others, 2020; Harden-Davies and others, 2020; Jaspars and others, 2016; *see also Section 3, Chapter 2, marine genetics*). Another application is biomimetics, as MGRs can inspire novel materials and structural design innovations (Blasiak and others, 2022). Around 42,000 marine bioactive compounds have been extracted, identified, and characterized in recent decades (Carroll and others, 2023). Several studies have found higher bioactivity in marine organisms compared to terrestrial ones (Royal Society, 2017; Saravanan and Debnath, 2013; Appleby, 2016), but a recent study also found marine compounds to be closely related to terrestrial counterparts (Voser and others, 2020). While roughly one in 5,000-10,000 tested terrestrial compounds leads to applications, this rises to one in 2,550 for marine compounds, potentially due to high levels of bioactivity in some species (Royal Society, 2017; Gerwick and Moore, 2012).

This potential, however, has yet to translate into a step-change in research into MGRs and marine biodiversity (Sigwart and others, 2021a). Marine biodiversity, particularly in the deep sea, has been little explored. In regions of the ~~the~~ Pacific for example, an estimated 80-90% of deep-sea species are new to science (Rabone and others, 2023, Kennedy and others, 2019). Only 0.001% of the deep sea has been observed or surveyed (Danovaro and others, 2017). Marine biodiscovery has focused on a relatively small group of organisms and habitat types. While 1,639 marine species have genetic sequences associated with patents (Zhivkoplias and others, 2024), there are currently ~250,000 known marine species in the World Register of Marine Species

[51] https://www.un.org/bbnjagreement/sites/default/files/2024-08/Text%20of%20the%20Agreement%20in%20English.pdf

database (WoRMS, 2024), with new species discovered at a rate of ~2,300 annually. Only a handful of medicines have been derived from MGRs to date[52], representing a tiny fraction of the discovery potential. Many new discoveries are expected, including new species (metazoans or microbes), antimicrobial defences, mechanistic pathways, immune strategies, or chemical compounds, all with potential applications in medicine and biotechnology.

3. Recent Trends and Developments since last World Ocean Assessment

Ongoing advancements in MGRs research and development have contributed to increased interest in marine-derived medicines (Francesch and others, 2024; Zhivkoplias and others, 2024; Harden-Davies, 2020; Jaspars and others, 2016). The exploration of MGRs has been facilitated in recent years by improved and lower-cost sequencing technologies and bioinformatics tools. Since the World Ocean Assessment II, there have been particular advances in sequencing techniques, including in-situ sequencing platforms, synthetic biology, metagenomics, and environmental DNA/metabarcoding (Francesch and others, 2024; Govindarajan and others, 2022). Other key developments include the use of artificial intelligence and automation in sampling/collection (Rabone and others, 2025). These advancements in MGRs research can support conservation processes and environmental monitoring, as well as biodiversity discovery efforts (Lewin and others, 2020).

A total of 1,425 new bioactive compounds were reported from marine organisms in 2021 alone (Carrol and others, 2023). In addition, there has been increasing patenting activity of products derived from MGRs. In 2024, the Marine Bioprospecting Patent database identified 4,779 patent filings that reference marine genes from 1,639 different marine species (Zhivkoplias and others, 2024). A focus on deep-sea species for biodiscovery has been growing (Zhivkoplias and others, 2024). Marine microbes, including host-associated microbiomes of metazoans like sponges, show great potential as genetic resources (Berdy, 2005), and new studies have revealed previously unreported levels of biodiversity and novel function of the global ocean microbiome (Chen and others, 2024; Vohsen and others., 2024; Schubotz., 2024). New techniques for rapid biodiscovery are also emerging, including use of in situ cultivation and metagenomics tools (Bogdanov and others, 2024). Novel applications include bioremediation by genetically modified bacteria (Saijad and others, 2024). Large-scale initiatives to map the ocean genome are being undertaken. These include the Ocean Genome Atlas Project (OGAP), which has the goal of developing a database representing at least 80% of extant marine species, ATLASea, which aims to sequence the genomes of over 4,000 marine species in French Exclusive Economic Zones, and the recently developed KMAP Global Ocean Gene Catalog 1.0 containing more than 308 million gene groups (Laiolo and others, 2024).

[52] (https://www.marinepharmacology.org/approved)

4. Pressures and Impacts

Ocean systems are being degraded due to multiple (and frequently cumulative) anthropogenic pressures and impacts (Crona and others, 2021; Vieira and others, 2023). Fisheries, ~~and~~ aquaculture, ~~as well as other activities, and the~~and development~~Fisheries and aquaculture as well as the development~~ of coastal areas have impacted genetic diversity and populations of certain species, directly impacting coastal habitats, particularly in tropical areas rich in biodiversity such as mangrove forests (Thomas and others, 2017, IUCN, 2024), coral reefs (Morrison and Aalbersberg, 2022) and seagrass habitats (Herrera and others, 2022). ~~Another noted impact from aquaculture is the exposure of wild populations to genetically modified species, e.g. transgenic salmon escaping and outcompeting wild populations and resulting in genetic drift (Dunham and Su, 2020; Gilbey and others, 2021; Karlsson and others, 2016).~~ Climate change has ~~also~~ impacted ~~marine ecosystems~~ diversity and distribution of marine species through processes of ocean warming, acidification and deoxygenation (Levin and others, 2018; see also Section 4 Chapter 3 Climate Change). Rapidly changing environmental conditions due to all these factors and others have resulted in ecosystem and habitat degradation and loss. In addition to the manifold negative impacts for humanity from degraded ecosystems, countless species and potentially invaluable MGRs (including ones that could help address challenges in planetary and human health), may be lost before they are even discovered. Addressing ocean health is therefore doubly crucial for conservation of marine biodiversity and MGRs (See Section 5B).

5. Sustainability Pathways

Maintaining a balance between the utilisation of marine ecosystems and their resilience to such utilisation is crucial. This can be aided by global efforts to address biodiversity knowledge gaps (Laiolo and others, 2024; Rabone and others, 2023; Rogers and others, 2023), the application of genetic/genomic monitoring tools, cooperative interdisciplinary marine scientific/biodiscovery research (Rabone and others, 2025), more holistic approaches to valuing MGRs (Krusberg and others, 2024), ~~and the interdisciplinary exploration of~~ sustainability pathways and ocean futures (Pereira and others, 2023). ~~Marine genetic resources~~MGRs and marine biotechnology have often been conceptualised as “future” or “emerging” elements of an ocean economy that generated over USD 1.9 trillion in revenues in 2019 alone (Claudet and others, 2021; Virdin and others, 2021). Developing pathways for equitable and sustainable use of MGRs now is therefore crucial (Pereira and others, 2023; Krusberg and others, 2024). The following section introduces aspirational pathways towards 2050, and a possible future in which MGRs are accessed and used in a fair and inclusive manner, ~~that contributes~~contributing a broad range of monetary and non-monetary benefits and improved conservation outcomes (Claudet and others, 2021; Martin and others, 2022). Proceeding along this pathway will require steps across several interconnected topics as described below.

Governance: The Convention on Biological Diversity (CBD) and the Nagoya Protocol on Access and Benefit Sharing provide a framework for the fair and equitable sharing of MGRs within national jurisdictions and exclusive economic zones (EEZs). The recent work at CBD COP16 (decision 16/2) [53] establishes a multilateral mechanism for benefit sharing from Digital Sequence Information (DSI) within national jurisdiction. The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) Agreement, adopted in 2023, provides a legal framework for equitable access and benefit sharing of MGRs, including the regulation of not only physical MGRs but also the knowledge and DSI derived from them (see Section 3 and Section 5B Chapter 5). The equitable use and access of MGRs provided for in the BBNJ agreement requires: (1) its ratification and entry into force (Ardron and others, 2024), (2) provision of sufficient resources, including capacity, to enable implementation of the Agreement by all States (Harden-Davies and others, 2024); (3) support for the efforts of the preparatory commission to ensure rapid implementation upon entry into force of the BBNJ Agreement. By 2030, the BBNJ Agreement will have entered into force and the subsidiary bodies it established will have achieved consensus on modalities and levels of benefit sharing. The first commercial product from MGRs from ABNJ post ratification of the BBNJ agreement demonstrates flagship benefit sharing, ~~facilitated by the BBNJ subsidiary bodies. A~~where all phases of research and~~product~~ development, commercialisation and ~~beyond~~ sales are fully BBNJ compliant and achieve transparency. By 2040, the legal clarity established by the agreement and its clearing house mechanism will have facilitated a new era of exploration and marine biodiscovery in the deep sea. Alongside legally binding regulations, new norms of inclusivity have become increasingly embedded throughout marine scientific endeavours, with each research expedition composed of scientists from diverse backgrounds (de Vos and others, 2023; Wang and others, 2024; Amon and others, 2022). By 2050, a growing library of examples of novel biotechnologies associated with MGRs is publicly available alongside benefit-sharing agreements that have built capacity around the world, contributed to improved conservation outcomes, and illustrate that the legal frameworks governing MGR have developed into effective, fit-for-purpose instruments.

Economy/markets/technology: If ~~-~~States around the world have access to marine biotechnology applications and can actively participate in their development by ~~20250~~2025, ~~it is likely that~~ under the guidance of the UN Decade of Ocean Science for Sustainable Development (2021-2030), a coordinated international effort ~~will have been~~will be made to build scientific, technical, and computing capacity (Blasiak and others, 2020)~~.~~. T~~t~~o ensure fair and equitable access to MGRs, including their utilisation for marine conservation~~. Through such a concerted global effort~~, a network of regional centres of excellence could be~~-~~ established~~-~~, catalysing~~-~~ knowledge exchange ~~and peer-to-peer learning~~. In this scenario, if companies embrace equity and inclusivity as norms of corporate practice, they ~~might not only~~would publicly announce and share access and benefit-sharing agreements in line with the Nagoya Protocol and BBNJ agreement. Additionally, ~~companies could enter into~~ long-term industry partnerships with regional centres of excellence could be developed with aims to advance the fair and equitable sharing of benefits from MGRs.

[53] https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-02-en.pdf

By 2040, this network of regional centres could have generated not only commercial benefits, but also helped build distributed capacity to employ genomic/genetic technologies for a wide range of applications. These might include setting conservation priorities, monitoring, and establishment of networks of marine protected areas.

As the range of benefits associated with marine biotechnologies becomes more widely known, there might be a shift from purely economic valuations to more holistic approaches. These would align with the findings of the Values Assessment framework of the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services, which show a broad scope of the values related to nature including broad and specific values, i.e., intrinsic (nature for nature), instrumental (nature for society) and relational (nature for culture) ~~These would align with the Values Assessment framework of the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services~~ (Krusberg and others, 2024; IPBES, 2022; Balvanera and others, 2022). ~~It is conceivable that valuation paradigms for MGRs could extend beyond monetary and non-monetary assessments, becoming part of public and legal discourse (Krusberg and others, 2024).~~ As~~If~~ the multiple benefits of marine biotechnology become ~~widely known~~part of public discourse, policymakers might incentivise use of marine bioresources for biotechnology. In turn, industry could channel resources from successful commercialization efforts into foundations that support scientific research and conservation. By 2050, marine biotechnology might be considered a pillar of the sustainable and equitable blue economy, assessed not only in terms of revenues, but also its contribution to ~~sustainable development and~~ ocean conservation and sustainable development.

6. Social Components

The advancement of marine biodiscovery is increasingly being recognised as a valuable tool ~~for improving global health (Salicrup and Fedorková; 2006) and can also~~to help ~~to~~ achieve certain Sustainable Development Goals (SDGs). There are myriad potential societal benefits from the exploration of~~for~~ and utilization of MGRs, including improving global health (Salicrup and Fedorková; 2006) through addressing the control of zoonoses, the looming antimicrobial resistance (AMR) crisis and even pandemic preparedness (see Section 5B: One Health). Maintaining a balance between the sustainable use and resilience of marine ecosystems, including utilisation of marine resources, is critical. To achieve this balance, coordination of scientific research activities, governance and management of global supply chains where ocean resources are involved is needed.

One potential benefit from exploration for and exploitation of MGRs is in addressing the looming AMR crisis, where infections become less treatable with current antibiotics, resulting in ~~longer hospital stays,~~ growing morbidity and mortality and significant economic losses (Naghavi and others, 2024; Murray and others, 2022). An estimated 1.14 million people died of an antimicrobial resistant infection in 2021, and new antibiotics for some of the most significant AMR pathogens could save 11 million lives between now and 2050 (Naghavi and others, 2024). Most ~~of the~~

antibiotics currently in use are derived from ~~natural product chemicals produced by~~ soil bacteria, but there is significant potential for new antibiotics in marine environments (Barbosa and others, 2020; Tortorella and others, 2018), especially ~~niches found at great depths~~the deep sea, given the extreme ~~environments found in these locations~~conditions and the potential they are from undiscovered chemical classes and therefore have activity against the current AMR pathogens. This is also true for the most promising alternative to antibiotics, phage-therapy (Gordillo and others, 2019), with large reservoirs of bacteriophage viruses in marine environments (Breitbart and others, 2019). ~~A likely benefit of finding new marine derived natural product antibiotics is that they may be from undiscovered chemical classes and have activity against the current AMR pathogens. Many of the marine natural products discovered to date are derived from~~ Another potential source is the bacteria that form elements of the microbiomes of sponges and other marine animals. The recovery of bacteria from these environments allows for the investigation of their genomes, which can reveal the presence of biosynthetic gene clusters (BGCs) responsible for ~~the~~ production of bioactivity~~e natural products~~. Some marine derived bacteria have been shown to carry more than 30 such BGCs, indicating the level of potential ~~for bioactivity~~ (Hesketh-Best and others, 2023).

A sustainable blue economy is one that provides social and economic benefits for current and future generations through its ability to ~~restore,~~ protect, ~~and~~ maintain and restore diverse and productive marine ecosystems~~.~~. The global blue economy has been estimated at USD 2.5 trillion a year (WWF/UNEP 2021). Marine biotechnology offers significant growth potential globally due to ~~rich marine biodiversity,~~ increasing demand for sustainable resources, and recent technological advancements including in molecular techniques (Zhivkoplias and others, 2024). It also has the potential to create new employment opportunities in the marine sector from academia to industry (OECD, 2013). I~~n this regard, i~~t has been estimated that the global marine biotechnology sector creates 200,000 employment opportunities annually (Rademaekers and others, 2015). The marine biotechnology industry can therefore play an important role in the sustainable development and economic growth of a State (Querellou and others, 2009) through its potential to address social, economic and environmental challenges.

The quantification of the marine biotechnology sector's economic value is a complex task, due to the lack of a robust economic activity classification system globally for these enterprises. Nevertheless, estimates of the global market value of blue biotechnology range between EUR 2.5 and ~~-~~EUR 3.9 billion in 2021 (MRFR Report, 2024). In terms of applications, the medical and pharmaceutical sectors are at the forefront of marine biotechnology development worldwide, and vaccine development is expected to contribute substantially to the sector's future growth. These trends reflect the increasing interest of consumers towards products based on marine compounds, together with the fact that pharmaceuticals and medical applications tend to have high added value (EU Blue Economy Report, 2024). Other high value applications from MGRs include nutraceuticals and cosmeceuticals, biomaterials and medical devices, as well as climate and agricultural mitigation applications~~.~~ (Blasiak and others, 2021). Revenues from just five marine drugs (Adcetris, derived from the marine ~~mollusk~~mollusc *Dorabella auricularia* and used to treat

Hodgkin Lymphoma; Halaven, derived from the *Lissodendoryx* marine sponge and used to treat breast cancer that has spread to other parts of the body; Lovaza, made from omega-3 fatty acids of fish oils and used to lower very high triglyceride levels; Prialt, derived from the cone snail *Conus magus* and used to treat severe chronic pain in adults; and Yondelis, derived from the marine tunicate *Ecteinascidia turbinata* and used to treat soft tissue sarcoma) were found to total over USD 1 billion per annum (Blasiak and others, 2022), with Halaven generating annual sales of USD 333 million in 2020 alone (Ottaviani, 2020). The Caribbean sponge, *Tectitethya crypta*, has yielded Zovirax, an anti-viral treatment for herpes (Guilloux; 2018), with annual global sales estimated in 2019 to be USD 92 million (OPTUMRx; 2019); as well as Cytarabine (Ara-C), an anti-cancer compound (Lloyd-Evans; 2005) with global sales estimated to reach USD 571.7 million by 2030 (Globe Newswire; 2023). In addition to the use of MGRs in disease treatment, these resources also find application in industry. Sales of pfu DNA, developed from *Pyrococcus furiosus* and Vent Polymerase, developed from *Thermococcus litoralis*, were estimated in 2013 to account for 30% of a USD 500 million per annum (Juniper, 2013). These polymerase enzymes are derived from archaea found in hydrothermal vents and are widely used in research applications and the biotechnology industry, for their particularly high fidelity in copying DNA, especially in PCR (Juniper, 2013). ~~In light of the demonstrated value of MGRs, ocean governance frameworks will need to address monetary benefits from future commercialisation.~~

Benefits of MGRs go far beyond monetary valuations (Krusberg and others, 2024). Beyond biotechnology, research on genetics/genomics such as within species diversity and population connectivity provides crucial insights for ecology and evolution (Jeffery and others, 2022). Because of the unique conditions and environment in which MGRs survive, they can provide essential information about life on Earth and its evolution (A/AC.276/6, 2013) and improve our knowledge of marine biodiversity and the role it plays in the provision of ecosystem services (A/62/66, 2007). Such information is key for conservation and environmental management, for example understanding species ranges, dispersal potential and population connectivity is crucial for design of marine protected areas (Hunter and others, 2024). Information on MGRs therefore is crucial to the conservation and sustainable use of marine biodiversity (Rabone and others, 2019). Non-monetary benefits of marine scientific research and data and sample sharing combined with capacity building allows knowledge transfer and addressing of global inequities in research, while simultaneously building scientific knowledge and addressing knowledge gaps, with outcomes for conservation (Harden-Davies and others, 2020, 2022, Rabone and others, 2019, 2025).

One primary concern related to utilizing MGRs is the potential impact on marine ecosystems, particularly if products are developed that require continuous supply of biological materials (Krusberg and others, 2024). To date, however, marine biotechnology has depended on the collection of samples of small size to discover new molecules which are subsequently often produced through partial or total synthesis to avoid the need for further harvesting that may be unsustainable due to low natural abundance or other environmental concerns. Such collection efforts are comparable to those employed by taxonomists and are subject to the same norms of

best practice to minimise ecosystem harm (Hope and others, 2018). For example, biodiscovery from microbes can be carried out in a sustainable manner if the bacteria can be cultured in the laboratory as this eliminates the need to repeatedly sample a potentially sensitive environment (Krusberg and others, 2024). One exception is the harvesting of marine species such as krill for the production of high purity polyunsaturated fatty acids for heart medication (Caffrie and others, 2023). Krill and other species are also targeted by mesopelagic fisheries for nutraceuticals but there are concerns on sustainability (Field and others, 2023).

Equity

Diverse narratives of a blue economy have emerged, but a crucial element to most framings is that equity is a key characteristic and guiding motivation for transitioning to a sustainable and fair blue economy (Cisneros-Montemayor and others, 2021; Österblom and others, 2020). In the context of MGRs, fair and equitable sharing of benefits associated with use are set forth in both the Nagoya Protocol of the Convention on Biological Diversity and the BBNJ Agreement. Despite regulatory expectations and emerging norms of best practice (Blasiak and others, 2019; Rabone and others, 2019; 2025; Harden-Davies and others, 2022), realizing the aspirational vision of an equitable blue economy in section 5 presents significant challenges. Specifically, there are imbalances in capacity that may present challenges for equitable sharing of benefits, as imbalanced capacity can lead to fewer opportunities for participation in all stages of the ocean biodiscovery process, from accessing the open and deep ocean to conducting laboratory research (Krusberg and others, 2024; Sigwart and others, 2021; Zhivkoplias and others, 2024).

Currently, the ability to conduct research on MGRs is not equal across States (Broggiato and others; 2018). It has been demonstrated that the unequal access to MGRs is driven as much by disparities in molecular biology and biotechnology expertise as by limited access to oceanographic assets, such as ships and deep-water vehicles (Arnaud-Haond and others, 2011). The expertise to conduct discovery research for bioactive marine natural products does exist in some centres in the Global South, where the richest biodiversity is found and a correlated increased discovery of novel chemical matter is to be expected (Harden-Davies and others, 2020b). However, investment is required to strengthen capacity and retain trained staff in these Global South centres and achieve fair and equitable sharing of benefits that could come from this biodiscovery work. This skewed access may limit States from participating in marine biodiscovery and reaping its benefits (Harden-Davies and Snelgrove; 2020). In light of the potential benefits, developing States in particular have been motivated to seek their “just returns” from the utilisation of MGRs, including those located in areas beyond national jurisdiction (Hassanali, 2022). As such, during BBNJ negotiations, it was considered crucial that the outcome resulted in a mechanism to facilitate fair and equitable benefit-sharing that would enable entities from developing States to participate in, and benefit from, marine biodiscovery, thereby levelling the playing field (Morgera; 2018).

One recent example of equitable and inclusive MGR development is a project based in the Republic of Kiribati, a small island developing state that obtained their first-ever patent (U.S. 11,878,057) in a collaboration with U.S.-based researchers. The discovery of novel deep-sea bacteria (Gauthier and others, 2021) was made without any major impact to the environment, requiring no additional sampling beyond normal exploration efforts. Furthermore, the subsequent experiments and inventions do not require any further visitation to, or extraction from, the deep-sea, since the bacteria are able to be cultured in the lab. These novel bacteria were discovered in filtered water and tissue samples of benthic organisms, and were then cultured in in a lab environment, where they can be maintained in ~~perpetuity~~long-term storage. Innovations and inventions from these novel, lab-cultured bacteria were patented with named inventors from both Kiribati and the U.S. (Rotjan and others, 2024). The U.S.-based institutions covered the full legal and filing fees for the patent, but the majority ownership of the patent rests with the Government of Kiribati. While no monetary benefits have yet been realized, the patent itself may be beneficial for improved conservation outcomes, since this discovery and subsequent invention were motivated by the conservation status of the Phoenix Islands Protected Area, which at the time was fully protected and was the largest and deepest World Heritage Site. Though this site has currently relaxed protections, future conservation efforts here and elsewhere will be strengthened by the realization that cutting-edge research can lead to new, non-exploitative industry pathways that involve and include equitable partnership. The balance between production and durable ocean protection is essential for enabling MGRs pathways that have low environmental impact and high potential for economic value (Kittinger and others, 2024).

Gender

Gender is an important consideration of use of marine genetic resources and biotechnology, especially in terms of achieving equity and sustainable development goals (Österblom and others, 2023; see also Section B chapter 6). However, gender data is scarce for most regions, and in particular for emergent sectors like marine biotechnology. It has been mostly looked at from the traditional sectors perspectives (Grygorian and others 2025, in press). Firstly, looking at participation in marine scientific research, women account for 33% of ocean science researchers and 37% of ocean science personnel (UNESCO 2021 and 2022). Similar persistent gender bias patterns have been reported for EU marine sciences and conservation (Giakoumi and others, 2021, Lima and Rheuban, 2022). Fundamental issues of women's safety at sea while conducting scientific work (including within industrial sectors of fisheries/oil and gas exploration) have started to be addressed in the literature (Amon and others, 2022; Johannsen and others, 2022; Maia and others, 2024). Multiple factors contribute to a challenging work environment for women at sea, including rarity of women-led expeditions, cultural factors arising from traditionally male bias in maritime activities, safety issues resulting from equipment being designed for men and even fundamentals of ship design (Johannsen and others, 2022). ~~There is the high likelihood that there is underreporting even within such high proportions (Johannsen and others, 2022).~~ Implementing frameworks to address fundamental equality issues including ~~for access to ocean expedition~~work environments at sea particularly for women in the Global South are ~~clearly needed~~crucial (Amon and others, 2022, Johanssen and others, in press).

Gender inequality in marine biotechnology has been noted in the literature (Kitada and others, 2015) but there is little available data for gender status and gaps in MGRs and marine biotechnology. There have been calls to mainstream gender equality in legislation and policy frameworks to promote the creation of better employment opportunities for women across the blue economy (UN Women, 2020; Rahaman and others, 2024). However, these are not yet widespread or implemented across geographies nor sectors in ocean related activities, including those directly linked to MGRs as marine biotechnology for example, where data is scarce. Recommendations are being put forward at UN level and OECD to address gender equality in marine scientific research, and acknowledge the contributions of women in marine conservation efforts (UNESCO, 2024). Examples of women's participation in the blue economy in developing countries include women-led small scale local fisheries and aquaculture in sub-Saharan Africa for example, seaweed farming in Zanzibar, with outcomes both positive and more equivocal, noting the need to support women's active participation (Brugere and others, 2020). Enhancing women's roles in sustainable innovative uses of MGRs would further contribute to a more equitable blue economy; together with calls for addressing the root causes of gender inequalities and collaborating with men and boys to challenge stereotypes, and create conducive environments for women-led initiatives in the maritime industry and ocean space (UNESCO 2024/COP 28).

Traditional and Indigenous Peoples' Knowledges

~~Traditional~~ Kknowledge from Indigenous Peoples, traditional and local communities (IPLCs) associated with the management of marine resources, understanding species' behaviour and use of marine species for medicinal purposes dates to ancient times with references in Indian, Chinese, Greek and Arabic texts (Voultsiadou and Vafiis 2007; Gopal and others, 2008). Traditional knowledge has been and continues to be vital to the conservation and sustainable use of the ocean and marine resources,— and there is a growing focus on integrating traditional knowledge into ocean governance and management (Pena-Neira and Coelho, 2025). However, the link between scientific discovery associated with MGRs and traditional knowledge is less clear, in large part due to a disconnect between scientists undertaking biodiscovery research and the IPLCs -that hold the traditional knowledge. The IPLCs -as holders of traditional knowledge -lack access -to MGRs with Western scientists having much greater capacities to explore and utilize MGRs (Armitage and others, 2020). In addition, Western science and traditional knowledge follow different epistemologies in terms of knowledge production. While the former relies -on rigorous methodological approaches and generalizations, the latter is localized and tied to the experiences, observations, and practices passed down through generations, often tied to cultural, ecological, medicinal, social, agricultural and spiritual practices (Hockings and other, 2019). This disconnect raises ethical and legal challenges in -between access and benefit sharing as researchers may lack awareness of associated traditional knowledge and communities may face challenges in accessing information, organizing and navigating Access and Benefit Sharing (ABS) negotiations. Furthermore, inadequate legal frameworks exist for recognizing IPLCs knowledge systems and protecting the intellectual property rights of traditional knowledge holders. This is particularly

challenging as traditionally –knowledge is often communally held and across geographical boundaries, especially in the case of marine species.

Studies have shown that marine species used in traditional medicine belong to groups –rich in bioactive natural products, namely sponges, cnidarians, molluscs, echinoderms and tunicates, pointing to the potential of traditional knowledge on marine species in the discovery of– novel bioactive compounds (Herbert and others, 2003). A recent example of traditional knowledge and MGRs is the oyster *Crassostrea (Magallana) saidii* - a species first identified by traditional knowledge and maintained as a separately managed fishery for over 120 years before it was formally described (Sigwart and others., 2021b). The local fishers could distinguish the "new" species from a co-occurring congener consistently and easily but scientists could not; the fishers' identifications were 100% accurate, as confirmed by -DNA barcoding (Sigwart and others, 2021b). At the same time there is a potential difference in terms of traditional and scientific knowledge in relation to MGR as traditional knowledge systems comprise not only of medicinal-use knowledge but also social-spiritual dimensions of traditional medicine that cannot be readily translated into scientifically evaluated and medically approved patent medicines (Williams and Whiting, 2016; Hau'Ofa, E., 2008). The governance of traditional knowledge associated with MGRs employs a zonal approach. The Convention on Biological Diversity (CBD) and it's Nagoya Protocol govern benefit sharing linked to MGR originating from areas within national jurisdiction (AWNJ~~),,~~), Conversely, the BBNJ Agreement governs such matters pertaining to MGR of ABNJ. Benefit sharing under the CBD may involve bilateral agreements between IPLCs of provider states and resource recipients. This approach facilitates direct benefit flows to TK holders.~~.~~ To further harmonise legal frameworks governing MGR, such as the Nagoya Protocol and BBNJ Agreement, and to support the fair and equitable sharing of benefits arising from MGR, it may be pertinent to promote the connection ~~betwewn~~between traditional knowledge and scientific research and foster more inclusive biodiscovery and innovation (Rabone and others, 2025; Pena-Neira and Coelho, 2025).

7. Governance

Key legal frameworks for the fair and equitable benefit sharing of MGRs and digital sequence information (DSI) of such resources irrespective of where their utilization occurs include the Convention on Biological Diversity (CBD) and the Nagoya Protocol, in ~~areas within national jurisdiction (~~AWNJ~~)~~, and the BBNJ agreement for MGRs of ~~areas beyond national jurisdiction (~~ABNJ~~)~~. Over the past decade, a number of challenges linked to effective implementation of the CBD have been identified (Laird and others, 2020; Prathapan and others, 2018; Scholz and others, 2022, 2024). While many States have ratified the Nagoya Protocol, challenges linked to capacity and enforcement mean that many countries have not yet implemented relevant administrative procedures (Scholz and others, 2024). The bilateral structure of Nagoya necessitates navigation of the legislation on a country-by-country basis which can be burdensome for users (Laird and others, 2020). Work is ongoing under the auspices of the CBD to address some of these challenges, particularly in the context of the Kunming-Montreal Global Biodiversity Framework

which was adopted at CBD COP 15 in December 2022. In relation to DSI, there has been a shift toward a more harmonised approach to benefit sharing with adoption of the multilateral mechanism on DSI and creation of the 'Cali Fund' – a global benefit sharing fund (CBD, 2024; Sett and others, 2024~~Scholz and others, 2022~~).

Adopted in June 2023 and opened for signature in September 2023, the BBNJ Agreement addresses a package of objectives geared towards achieving the conservation and sustainable use of biodiversity beyond national jurisdiction (DOALOS Fact Sheet 2, 2024). The objectives relevant to MGRs include fair and equitable benefit-sharing, capacity-building, knowledge-generation, and marine technology transfer (Article 9 of the BBNJ Agreement[54]). The Agreement applies to activities with respect to the collection and use of MGRs and DSI sourced from ABNJ, subject to utilization, after the entry into force ~~of the Agreement~~, excluding fishing and fish or other living marine resources known to have been taken in fishing and fishing-related activities from areas beyond national jurisdiction (Article 10~~(1) of the BBNJ Agreement~~). In addition, the Agreement can be applied to the utilisation of MGRs and DSI sourced before the entry into force of the Agreement, unless a Party expresses an exception in writing (Article 10(1) ~~of the BBNJ Agreement~~). Such activities can be carried out in ABNJ by all Parties, regardless of their geographical location, and by natural and ~~juristic~~ juridical persons under their jurisdiction (Article 11(1) ~~of the BBNJ Agreement~~). No State may claim or exercise sovereignty over MGRs of ABNJ (Article 11(4) ~~of the BBNJ Agreement~~) and collection of in situ MGRs will not constitute the basis of any claim to the marine environment or its resources (Article 11(5) ~~of the BBNJ Agreement~~). Relevant activities must be carried out with due regard for the rights and legitimate interests of coastal States in AWNJ, as well as other States active in ABNJ (Article 11(3) ~~of the BBNJ Agreement~~). The interests of all States must be taken into account, particularly the interests and needs of developing States (Article 11(6) ~~of the BBNJ Agreement~~). In addition, such activities must be carried out for exclusively peaceful purposes (Article 11(7) ~~of the BBNJ Agreement~~) and for the benefit of humanity (Article 11(6) ~~of the BBNJ Agreement~~).

Specific notification requirements have been created with respect to the collection and utilisation of these resources. Parties are required to take the necessary legislative, administrative or policy measures to ensure that information is provided to the CHM at different stages of the process (DOALOS Fact Sheet 2, 2024). Article 11(2)(a)-(j) lists the information that must be provided six months prior or as early as possible before the in situ collection occurs, after which time a BBNJ Standardised Batch Identifier (SBI) is generated (Article 12(3) of the BBNJ Agreement). This is essentially a "tag" that follows MGRs and DSI through the research and commercialisation journey. Although this is a high level "tag" that refers for instance to a whole research cruise, its utility rests on the fact it can be used to identify research, development and commercialisation activities on MGRs and associated DSI, making this a "light touch" end-user traceability mechanism (Lawson~~,~~

[54] References to 'Article' hereafter refer to the BBNJ Agreement

2012 and others, 2025; Rabone and others, 2025) whereby “a unique identifier is associated with the collected MGR and is passed between subsequent users” (DOSI, 2022).

After in situ collection has taken place, Parties are required to ensure that information regarding, inter alia, where collected MGRs and DSI will be deposited, the geographical location from where MGRs were collected, and, to the extent possible, the findings from the activities undertaken, are provided to the CHM together with the SBI as soon as it becomes available, but no later than one year from the in situ collection date (Article 12(5) of the BBNJ Agreement). Once use of MGRs and DSI occurs, including commercialisation, Parties must ensure that information regarding, inter alia, publications, patents granted, and products developed; modalities for the management of access to collected MGRs and DSI; and details of the sales of relevant products, are also provided to the CHM together with the SBI (Article 12(8) of the BBNJ Agreement).

Regarding benefit-sharing, the BBNJ agreement uniquely makes a direct link between benefits and how they should be used by providing that benefits, both monetary and non-monetary, must be shared in a fair and equitable way in order to contribute to the conservation and sustainable use of marine biodiversity of ABNJ (Article 14(1) of the BBNJ Agreement). Regarding non-monetary benefit-sharing, the Agreement provides extensive examples of the forms non-monetary benefit-sharing can take (see Article 14(2)(a)-(h) of the BBNJ Agreement). Parties are also required to take reasonable measures to ensure MGRs and DSI are deposited in publicly-accessible repositories and databases as soon as they become available, but no later than three years from when the collection took place (Article 14(3) of the BBNJ Agreement). Reasonable conditions can be placed on access to MGRs and DSI, such as the need to protect the physical integrity of the MGRs and reasonable maintenance and access costs (Article 14(4) of the BBNJ Agreement; DOALOS Fact Sheet 2, 2024). Furthermore, opportunities for access on fair and most favourable terms, including on concessional and preferential terms, may be provided to researchers and research institutions from developing States (Article 14(4) of the BBNJ Agreement). Concerning monetary benefit-sharing, the Agreement provides that such benefits must be shared through the financial mechanism established under the Agreement (DOALOS Fact Sheet 2, 2024). Initially, developed Parties will be required to make annual contributions into a special fund, the rate of contribution of which is set at 50% of that Party’s assessed contribution to the budget adopted by the Conference of the Parties (COP) (Article 14(6) of the BBNJ Agreement). Subsequent modalities for, inter alia, milestone payments, payments related to the commercialisation of products, and a tiered fee based on a Party’s level of activity, will be decided by the COP, taking into account the recommendations of the access and benefit-sharing committee established under the Agreement (Article 14(7) of the BBNJ Agreement). These payments are to be made through the special fund established by Article 52 of the Agreement (DOALOS Fact Sheet 2, 2024).

Currently, States are working towards becoming Parties to the Agreement and preparing for its implementation. The Agreement will enter into force 120 days after the date of deposit of the 60th instrument of ratification, approval, acceptance or accession (Article 68(1) of the BBNJ Agreement). In the context of timeframes, swift ratification of the BBNJ agreement is essential to meet the Kunming-Montreal Biodiversity Framework's goal of protecting 30% of the marine environment by 2030 (Blasiak and Jouffray, 2024).

8. References

Amon, Diva. J, and others. Safe working environments are key to improving inclusion in open-ocean, deep-ocean, and high-seas science. Marine Policy, 137, pp.104947, 2022

Appleby, Thomas, and others. The marine biology of law and human health Journal of the Marine Biological Association of the United Kingdom, vol. 96, No. 1, pp. 21, 2016

Arrieta, Jesus .M, and others. What lies underneath: conserving the oceans genetic resources. Proceedings of the National Academy of Sciences, vol. 107, No. 43, pp. 18318-18324, 2010

Ardron, Jeff. A, and others. Considerations concerning state ratification of the BBNJ Agreement. In F. Humphries (Ed.) Decoding marine genetic resource governance under the BBNJ Agreement. Springer. Chapter 10. (PREPRINT), 2024

Armitage, Derek, and others. Governance principles for community-centered conservation in the post-2020 global biodiversity framework. Conservation Science and Practice, vol. 2. 2020

Arnaud-Haond, Sophie, and others. Marine Biodiversity and Gene Patents. Science, vol. 331, No. 6024, pp. 1521-1522, 2011.

-Arnaud-Haond, Sophie, and others. “Mind the gap between Biological Samples and Marine Genetic Resourcesin Areas Beyond National Jurisdiction: Lessons from Lans”, in *New Knowledge and Changing Circumstances in the Law of the Sea.* (The Netherlands, Brill, Nijhoff,2020).

Balvanera, P., Pascual, U., Christie, M., Baptiste, B., Guibrunet, L., Lliso, B., Monroy-Sais, A. S., 7 Anderson, C. B., Athayde, S., Barton, D. N., Chaplin-Kramer, R., Jacobs, S., Kelemen, E.,

Kumar, R., Lazos, E., Martin, A., Mwampamba, T. H., Nakangu, B., O'Farrell, P., … González-Jiménez, D. (2022). Chapter 1: "The role of the values of nature and valuation for addressing the biodiversity crisis and navigating towards more just and sustainable futures", In: Methodological Assessment Report on the Diverse Values and Valuations of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.P. Balvanera, U. Pascual, C. Michael, B. Baptiste, and D. González-Jiménez (eds.). https://doi.org/10.5281/zenodo.6418971~~Balvanera, P., Pascual, U., Christie, M., Baptiste, B., Guibrunet, L., Lliso, B., Monroy-Sais, A. S., Anderson, C. B., Athayde, S., Barton, D. N., Chaplin-Kramer, R., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Martin, A., Mwampamba, T. H., Nakangu, B., O'Farrell, P., … González-Jiménez, D. ("The role of the values of nature and valuation for addressing the biodiversity crisis and navigating towards more just and sustainable futures", *Methodological Assessment Report on the Diverse Values and Valuations of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,* Vessuri Hebe, Robert. T. Watson, Mace Georgina, and others, eds. *(IPBE, secretariat, Bon, Germany, 2022).*~~

Barbosa, Filipa, and others. Targeting antimicrobial drug resistance with marine natural products. International journal of antimicrobial agents, vol. 56, No. 1, pp. 106005, 2020.

Beattie, Andrew. J, and others. Ecology and bioprospecting. Austral ecology, vol. 36, No. 3, pp. 341-356, 2011.

Bérdy, János. Bioactive microbial metabolites. The Journal of Antibiotics, vol. 58, No. 1, pp.1-26, 2005

Blasiak, Robert, and others. A forgotten element of the blue economy: marine biomimetics and inspiration from the deep sea. *PNAS nexus*, vol. 1, No. 4, ppgac196, 2022.

Blasiak, Robert, and others. Corporate control and global governance of marine genetic resources. Science advances, vol. 4, No. 6, pp. eaar5237, 2018.

Blasiak, Robert, and others. "Developments in the exploration for and use of marine genetic resources". In World Ocean Assessment II. (United Nations, 2021).

Blasiak, Robert, and others. Scientists should disclose origin in marine gene patents. Trends in ecology & evolution, vol. 34, No. 5, pp. 392-395, 2019.

Blasiak, Robert, and others. and others. The ocean genome and prospects for conservation and equity. Nature Sustainability, vol. 3, No. 8, pp. 588-596, 2020.

Blasiak, Robert, and Jouffray Jean-Baptiste.. When will the BBNJ Agreement deliver results? Nature Partner Journal. Ocean Sustainability, vol 3. art. 21, pp. 21, 2024

Bogdanov, Alexander, and others.. Small molecule in situ resin capture provides a compound first approach to natural product discovery. Nature Communications, vol. 15, art. 5230, 2024

Breitbart, Mya, and others. others. Phage puppet masters of the marine microbial realm. Nature Microbiol, vol.3, No. 7, pp. 754-766, 2018

Broggiato, Arianna. Marine Genetic Resources Beyond National Jurisdiction – Coordination and Harmonisation of Governance Regimes. Environmental Policy and Law, vol. 41. No. 1, pp. 39, 2011.

Broggiato, Arianna, and others. Fair and Equitable Sharing of Benefits from the Utilization of Marine Genetic Resources in Areas Beyond National Jurisdiction: Bridging the Gaps between Science and Policy. Marine Policy, vol. 49, pp. 177, 2014.

Broggiato, Arianna, and others. Mare geneticum: balancing governance of marine genetic resources in international waters. The International Journal of Marine and Coastal Law, vol. 33, No. 1, pp. 3-33, 2018.

Caffrey Cliodhna, and others. Cardiovascular diseases and marine oils: a focus on omega-3 polyunsaturated fatty acids and polar lipids. Marine Drugs, vol. 21, No. 11, pp. 549, 2023.

Calado Ricardo, Leal Miguel Costa, Gasper Helena, Santos Susana, Nunes Maria Leonor, and Vieira Helena. and others. “How to Succeed in Marketing Marine Natural Products for Nutraceutical, Pharmaceutical and Cosmeceutical Markets”, in *Grand Challenges in Marine Biotechnology*, Rampelotto P. H. et al eds. (Cham, Springer International Publishing, 2018).

Carroll Anthony R, and others. Marine Natural Products. Natural Product Reports, vol. 40, No. 3, pp. 275–325, 2023.

CBD. Digital sequence information on genetic resources. Decision 16/2, 2024.

Chen Jianwei, and others. Global marine microbial diversity and its potential in bioprospecting. Nature, vol. 633, pp. 1-9, 2024.

Cisneros-Montemayor Andrés. M, and others. Enabling conditions for an equitable and sustainable blue economy. Nature, vol. 591, No. 7850, pp. 396-401, 2021.

Claudet Joachim, and others. Transformational opportunities for an equitable ocean commons. Proceedings of the National Academy of Sciences, vol. 118, No. 42, pp. e2117033118, 2021.

Coelho, LF, Harden-Davies, H., forthcoming. Marine genetic Resources in Areas Beyond National Jurisdictions: A New Regime. Cambridge Handbook on the Law of the Sea.

de la Concepción, Richard Tur. Negotiating fair and equitable sharing of benefits in the BBNJ agreement: Role of the Group of 77 and China. Marine Policy, vol. 163, pp. 106085, 2024

.

Cordier, Tristan, and others. Patterns of eukaryotic diversity from the surface to the deep-ocean sediment. Science Advances, vol. 8, No. 5, pp. eabj9309, 2022.

Crona, Beatrice, and others. Sharing the seas: a review and analysis of ocean sector interactions. Environmental Research Letters, vol. 16, No. 6,pp. 063005, 2021.

Danovaro, Roberto, and others. The deep-sea under global change. *Current Biology*, vol. 27, No. 11, pp. R461-R465, 2017.

de Vos, Asha, and others. Towards equity and justice in ocean sciences. npj Ocean Sustainability, vol. 2, art. 25, pp. 25, 2023.

DOALOS “Marine genetic resources, including the fair and equitable sharing of benefits”(2024) Fact Sheet 2 https://www.un.org/bbnjagreement/sites/default/files/2024-07/BBNJAgreementFactsheet2MGRs.pdf (accessed on 20/03/2025).

Fjeld, Kristian, and others. Mesopelagics–New gold rush or castle in the sky? Marine Policy, vol. 147, pp. 105359, 2023.

Francesch, Andres M, and others. Pharmaceuticals from marine sources: past, present and future. The Pharmaceutical Journal, vol. 313, No. 7987, 2024.

Gauthier, Anna E, and others. Deep-sea microbes as tools to refine the rules of innate immune pattern recognition. Science Immunology, vol. 6. No. 57, pp. 1-15, 2021.

Gerwick, W. H. & Moore, B. S. Lessons from the past and charting the future of marine natural products drug discovery and chemical biology. Chem. Biol. 19, 85–98 (2012).

Giakoumi, Sylvaine, and others. Persistent gender bias in marine science and conservation calls for action to achieve equity. Biological Conservation, vol. 257, pp. 109134, 2021.

Gjerde, Kristina M, and others. Getting beyond yes: fast-tracking implementation of the United Nations agreement for marine biodiversity beyond national jurisdiction. npj Ocean Sustainability, vol. 1 art. 6, pp. 6, 2022.

Global Acute Myeloid Leukemia (AML). Therapeutics Strategic Research. 2023. https://www.globenewswire.com

Gopal, Radhika, and others. Marine organisms in Indian medicine and their future prospects. Natural Product Radiance, vol. 7, No. 2, pp. 139-145, 2008.

Gordillo Altamirano, Fernando. L, and Barr, Jeremy. J. Phage Therapy in the Postantibiotic Era. Clinical Microbiol Reviews, vol. 32, No. 2, 2019.

Govindarajan, Annette. F, and others. Improved biodiversity detection using a large-volume environmental DNA sampler with in situ filtration and implications for marine eDNA sampling strategies. *Deep Sea Research Part I: Oceanographic Research Papers*, vol. *189*, pp. 103871, 2022.

Guilloux Bleuenn, Marine Genetic Resources, R&D and the Law 1: Complex Objects and Use. ISTE Ltd and Wiley, 2018.

Harden-Davies, Harriet, and others. “First to finish, what comes next? Putting Capacity Building and the Transfer of Marine Technology under the BBNJ Agreement into practice. Nature Partner Journal. *Ocean Sustainability, vol* 3, art. 3, 2024

Harden-Davies, Harriet “The exploitation of deep-sea biodiversity: components, capacity and conservation”, in Natural Capital and Exploitation of the Deep Ocean, Maria, Baker, Eva Ramirez-Llodra, and Paul Tyler, eds. *(*Oxford, Oxford Academic,2020).

Harden-Davies, Harriet and Snelgrove Paul. Science Collaboration for Capacity Building: Advancing Technology Transfer Through a Treaty for Biodiversity Beyond National Jurisdiction. Frontiers in Marine Science, vol 7, No. 40, 2020a.

Harden-Davies, Harriet, and others. . *Science in Small Island Developing States: Capacity Challenges and Options relating to Marine Genetic Resources of Areas Beyond National Jurisdiction*. Report for the Alliance of Small Island States. University of Wollongong, Australia. 2020b.

Hassanali, Kahlil. Negotiating the BBNJ Agreement: Exploring the Caribbean Community's Engagement from a Blue Economy Perspective with Special Focus on Environmental Impact Assessment Provisions. Doctoral Thesis, World Maritime University, Sweden, pp. 55-56, 2022.

Harris, L, Preet, G, Desai, R, Hasan, AH, Copley, J, Bribiesca-Contreras, G, Astakala, RV, Jaspars, M, Glover, A, Global distribution of novel bioactive compounds from deep-sea organisms: exploring the influence of phylogeny and environment, (in prep)

Hau'Ofa, Epeli. We are the ocean: Selected works. Honolulu, Hawaii: University of Hawaii Press, 2008

Herbert, David. G, and others. Invertebrate animals as a component of the traditional medicine trade in KwaZulu-Natal, South Africa. African Invertebrates, vol. 44, No. 2, pp. 1-18, 2003

Herrera, and others, 2022 Front. Mar. Sci., 22 April 2022 Sec. Marine Fisheries, Aquaculture and Living Resources

Volume 9 - 2022 | https://doi.org/10.3389/fmars.2022.781713

Hesketh-Best, Poppy. J, and others. Whole genomes of deep-sea sponge-associated bacteria exhibit high novel natural product potential. Federation of European Microbiology Societies Microbes, vol. 4, art. p. xtad005, 2023.

Hockings, Marc, Lilley Ian, Matar Diane. A, Dudley Nigel, and Markham Robert. "Integrating science and local knowledge to strengthen biosphere reserve management", in UNESCO Biosphere Reserves. (Routledge, 2019).

Hope, Andrew. G, and others. Collection of scientific specimens: benefits for biodiversity sciences and limited impacts on communities of small mammals. BioScience, vol. 68, No. 1, pp. 35-42, 2018.

Hunter, Margaret. E, and others. A new era of genetic diversity conservation through novel tools and accessible data. Frontiers in Ecology and the Environment, vol. 22, No. 4, 2024.

IPBES (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds.). IPBES secretariat, Bonn, Germany.

Jaspars, Marcel, and others. The marine biodiscovery pipeline and ocean medicines of tomorrow. Journal of the Marine Biological Association of the United Kingdom, vol. 96. No. 1, pp. 151-158, 2016.

Jeffery, Nicholas. W, and others. Application of omics tools in designing and monitoring marine protected areas for a sustainable blue economy. Frontiers in Genetics, vol13, 2022.

Johannesen, Ellen, and others. The sea change needed for gender equality in ocean-going research. Marine Technology Society Journal, vol. 56, No. 3, pp. 18-24, 2022.

Juniper, Kim. Technological, Environmental, Social and Economic Aspects. In IUCN Information Papers for the Intersessional Workshop on Marine Genetic Resources, 02-03 May 2013, pp. 15-21, 2013.

Momoko, Kitada., Erin Williams., and Lisa Loloma Froholdt, eds. Maritime women: global leadership, vol. 3, Springer. Berlin, 2015.

Kittinger, John. N, and others. Balancing protection and production in ocean conservation. Nature Partner Journal Ocean Sustainability, vol. 3, No. 1, pp. 24, 2024.

Krusberg, Tilde, and others. A review of marine genetic resource valuations. Nature Partner Journal pj Ocean Sustainability, vol. 3, No. 46, 2024.

Laiolo, Elisa, and others. Metagenomic probing toward an atlas of the taxonomic and metabolic foundations of the global ocean genome. Frontiers in Science, vol. 1, p.1038696, 2024.

Lancelot, Yves. P, and others. Proceedings of the Ocean Drilling Program,, Leg 129 Preliminary Report: Old Pacific Crust. Program. Texas A & M University, vol. 129, 1990

Langlet, Arne and Dunshirn Paul. Traceability Options for Marine Genetic Resource from Areas Beyond National Jurisdiction. In the High Seas Alliance Policy Brief, 2023

Leary, David, and others. Marine Genetic Resources: A Review of Scientific and Commercial Interest. Marine Policy, vol. 33, No. 2, 2009.

Le Bris, N. and- Gaill, F. How the annelid *Alvinella pompejana* deals with an extreme hydrothermal environment. Reviews in Environmental Science and Biotechnology, vol. 6, No. 1-3, pp. 197-221, 2007

Lewin, Harris. A, and others. The earth BioGenome project 2020: Starting the clock. Proceedings of the National Academy of Sciences, vol. 119, No. 4, p.e2115635118, 2022.

Lima, Ivan. D and Rheuban, Jennie. E. Gender differences in NSF Ocean Sciences awards. Oceanography, vol. 35, No. 1, pp. 68-75, 2022.

Lloyd-Evans, L. P. M. A Study into the Prospects for Marine Biotechnology Development in the United Kingdom: Volume 1 – Strategy. Report Commissioned by the Foresight Marine Panel, 2005.

Lindequist, Ulrike. Marine-derived pharmaceuticals–challenges and opportunities. Biomolecules & therapeutics, vol. 24, No. 6, pp. .561, 2016.

Maia, Michele. C, ans others. Harassment and bullying aboard: Impacts of gender inequality on ocean professionals. Marine Policy, vol. 160, p.105946, 2024.

Market Research Future (MRFR).Global blue biotechnology market research report: Forecast to 2032, 2024.

Adrian Martin, Patrick O'Farrell, Ritesh Kumar, Uta Eser, Daniel Faith, Erik Gomez-Baggethun, Zuzana V. Harmáčková, Andra-loana Horcea-Milcu, Jliana Mercon, Martin Quaas, Julian Rode, Ricardo Rozzi, Nadia Sitas, Yuki Yoshida, Tobias Nyumba Ochieng, Ann-Kathrin Koessler, Natalia Lutti Hummel, Lelani Mannetti, Gabriela Arroyo-robles. "The role of diverse values of nature in visioning and transforming towards just and sustainable futures", in *Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy*

Platform on Biodiversity and Ecosystem Services, Christie, M, Balvanera P, Pascual U, Baptiste B, and Gonzáles-Jiménez D, eds. (Bonn, Germany, IPBES secretariat, 2022).

Melvin, Emily. C, and others. (Un)claiming Rights, Resources, and Ocean Spaces: Marine Genetic Resources and Area-Based Management Tools in High Seas Governance Negotiations. Nature and Space, vol. 6, No. 3, pp. 1662-1667, 2023.

Millicay, Fernanda. Marine Genetic Resources of Areas Beyond National Jurisdiction and Intellectual Property Rights. InNew Knowledge and Changing Circumstances in the Law of the Sea, Tomas Heidar eds. *Publication on Ocean Development,* vol. 92, 2020.

Morgera, Elisa. Equity and Benefit Sharing from Marine Genetic Resources in Areas Beyond National Jurisdiction, IIED Briefing Papers, 2018.

Morrison, John. R, and others Aalbersberg, W. G. L. “Anthropogenic Environmental Impacts on Coral Reefs in the Western and South-Western Pacific Ocean”, in Coral Reefs of the Western Pacific Ocean in a Changing Anthropocene,- Zhang, J, Yeemin, T, Morrison, R.J., Hong, G.H. eds. (Cham, Springer, vol. 14. 2022)

Murray, Christopher J, and others. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. The lancet, vol. 399, No. 10325, pp. 629-655, 2022.

Naghavi, Mohsen, and others. Global burden of bacterial antimicrobial resistance 1990–2021: a systematic analysis with forecasts to 2050. The Lancet, vol. 404, No. 10459, pp. 1199-1226, 2024.

Organisation for Economic Cooperation and Development. “The Ocean Economy in 2030”, (Paris, OECD Publishing,2016).

Organisation for Economic Cooperation and Development, “Marine Biotechnology: Enabling Solutions for Ocean Productivity and Sustainability”, OECD Science, Tchnology and Innovation Policy Paper, No. 43. (Paris, OECD Publishing, 2013).

Organisation for Economic Cooperation and Development. ” “Marine biotechnology: Definitions, infrastructures and directions for innovation”,. OECD Science, Technology and Industry Policy Papers, No. 43. (Paris, OECD Publishing, 2017)

OPTUMRx “Zovirax” (2019)

Österblom, Henrik, –Wabnitz Colette. C, and Tladi Dire. “Towards ocean equity”, in *The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy*, Jane Lubchenco and Peter M. Haugan, eds. (Cham, Springer International Publishing, 2023)

Ottaviani, Daniela. Economic Value of Ecosystem Services from the Deep Seas and the Areas Beyond National Jurisdiction. FAO Fisheries and Aquaculture Circular, No. 1210 (Rome, 2020).

Papon, Nicolas, and others. Marine drugs: Biology, pipelines, current and future prospects for production. Biotechnology Advances, vol. 54, p.107871, 2022.

Pena-Neira, Sergio. & Coelho Luciana -Fernadndes. “Traditional Knowledge associated with marine genetic resources in Areas Beyond National Jurisdiction”, *in Decoding marine genetic resource governance under the BBNJ Agreement,* Fran, Humphries, eds. (Cham, Springer, 2025).

Pereira, Laura. M, and others. The living infinite: Envisioning futures for transformed human-nature relationships on the high seas. Marine Policy, vol. 153, p.105644, 2023.

Prunier, Jérôme. G, and others. Genetic erosion reduces biomass temporal stability in wild fish populations. Nature Communications, vol. 14, art. 4362, 2023.

Querellou, Joel and others. Marine Biotechnology: A New Vision and Strategy for Europe. *Marine Board, ESF Position Paper 15, 2009.*

Rabone, M., Horton Tammy, Humphries Frances, Lyal Christopher. H, Muraki Gottlieb Hiroko, Scholz, Amber. H, Vanagt Th~~m~~omas and Jaspars, Marcel. “BBNJ Agreement: Considerations for

Scientists and Commercial End Users of MGRS at Research, Development and Commercialisation Stages", in *Development and Commercialisation Stages* (*Springer*). 2025

Rabone, Muriel, and others. How many metazoan species live in the world's largest mineral exploration region? Current Biology, 33, 1-14. 2023

Rabone, Muriel, and others. Access to Marine Genetic Resources (MGR): raising awareness of best-practice through a new agreement for Biodiversity Beyond National Jurisdiction (BBNJ). Frontiers in Marine Science, vol. 6, p.520, 2019.

Rademaekers, Koen, and others. Deep-Seabed Exploitation: Tackling Economic, Environmental and Societal Challenges, *Study prepared for the European Parliamentary Research Service, 2015.*

Md, Saidur Rahaman, Leo Paul Dana and Nishath Anjum. "Empowering Women in Building a Sustainable Blue Economy", in Handbook of Sustainable Blue Economy. (Cham, Springer Nature Switzerland, 2024).

Rotjan, Randi. D., and others, Immunomodulatory lipopolysaccaride compositions, New PCT Application No.: PCT/US2021/062898, filed December 10, 2021, Based on U.S. Provisional Application Nos. 63/124, 340 filed December 11, 2020, US Patent 11,878,057Awarded January 2024.

Royal Society. Future ocean resources: Metal-rich minerals and genetics – evidence pack Issued: May 2017 DES4703 ISBN: 978-1-78252-260-7, 2017.

Noreen, Sajjad, Ayesha Sultan, Gulzar Muhammad, Aiza Azam, Muhammad Arshad Raza, Muhammad Ajaz Hussain, and Liaqat Ali. "Application of Genetically Modified Microorganisms for Remediation of Petrol Discharges and Related Polluted Sites", in *Genetically Engineered Organisms in Bioremediation*. (CRC Press, 2024)

Salicrup, Luis. A, and Fedorková Lenka. Challenges and Opportunities for Enhancing Biotechnology and Technology Transfer in Developing Countries.Biotechnology Advances, vol. 24, No. 1, pp. 69-79, 2006.

Saravanan and Debnath “Patenting Trends in Marine Biodiversity: Issues and Challenges” (2013) 7(4) *Pharma Utility* 5.

Salimi, Parisa. Alidoost, and others. . A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. Marine Biodiversity Records, vol. 14, art. 11, 2021.

Scholz, Amber Hartman, and others. Multilateral benefit-sharing from digital sequence information will support both science and biodiversity conservation. Nature Communications, vol. 13. Art. 1086, 2022.

Schubotz, Florence, and others. Going deep on marine lipid metabolism. Science, vol. 385, No. 6714, pp. 1167-1168, 2024.

Sett, Scarlett, and others. Harmonize rules for digital sequence information benefit-sharing across UN frameworks. Nature communications, vol. 15, art. 8745, 2024.

Sigwart, Julia. D, and others. . Unlocking the potential of marine biodiscovery. Natural Product Reports, vol. 38, No. 7, pp. 1235-1242, 2021a.

Wong, and others. Global controversy in oyster systematics and a newly described species from SE Asia (Bivalvia: Ostreidae: Crassostreinae). Marine Biodiversity, vol. 51, art. 83, pp. 1-16, 2021b.

St Clair, Madeline A. Sexual Harassment in Marine Science Report, 2021.

Sun, Jin, and others. The Scaly-foot Snail genome and implications for the origins of biomineralised armour. Nature Communications, vol. 11, art. 1657, 2020.

Thambisetty, Siva, and others. The Expert Briefing Document: A Developing Country Perspective on the Making of the BBNJ Treaty.*LSE Law, Society and Economy Working Paper No. 30/2023, 2023.*

Thomas, Nathan, and others. Distribution and drivers of global mangrove forest change, 1996–2010. PloS one, vol. 12, No. 6 p.e0179302, 2017.

International Union Conservation of Nature. Red List of Mangrove Ecosystems. 2024. https://iucn.org/resources/conservation-tool/iucn-red-list-ecosystems/red-list-mangrove-ecosystems

Tortorella, Emiliana, and others. Antibiotics from deep-sea microorganisms: current discoveries and perspectives. Marine drugs, vol. 16, No. 10p.355, 2018.

United Nations Women. Women's economic empowerment in fisheries in the blue economy of the Indian Ocean Rim: A baseline report.2020. https://www.unwomen.org/en/digital-library/publications/2020/10/womens-economic-empowerment-in-the-indian-ocean-rim

UNEP "Digital Sequence Information on Genetic Resources" Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity (19 December 2022) CBD/COP/DEC/15/9 at par 16.

UNEP "Marine and Coastal Biological Diversity: Status and Trends of, and Threats to, Deep Seabed Genetic Resources Beyond National Jurisdiction, and Identification of Technical Options for their Conservation and Sustainable Use" Note by the Executive Secretary submitted to the SBSTTA at its 11th Meeting (22 July 2005) UNEP/CBD/SBSTTA/11/11 at par 21.

UNGA "Intersessional workshops aimed at improving understanding of the issues and clarifying key questions as an input to the work of the Working Group in accordance with the terms of reference annexed to General Assembly resolution 67/78" Summary of proceedings prepared by the Co-Chairs of the Working Group (10 June 2013) A/AC.276/6.

UNGA "Oceans and the Law of the Sea" Report of the Secretary-General submitted to the UNGA at its 66th Session (22 March 2011) A/66/70

UNGA "Oceans and the Law of the Sea" Report of the Secretary-General submitted to the UNGA at its 62nd Session (12 March 2007) A/62/66.

Vieira, Helena, and others. Current and Expected Trends for the Marine Chitin/Chitosan and Collagen Value Chains. Marine Drugs, vol. 21, No. 12:605, 2023.

Vohsen, Samuel. A, and others. Discovery of deep-sea coral symbionts from a novel clade of marine bacteria with severely reduced genomes. Nature Communications, vol. 15, art. 9508, 2024.

Voser, Tanja. M, and others. How different are marine microbial natural products compared to their terrestrial counterparts? Natural Product Reports, vol. 39, No. 1, pp. 7-19, 2022.

Voultsiadou, Eleni, and –Vafiis, Dimitris. Marine invertebrate diversity in Aristotle's zoology. Contributions to Zoology, vol. 76, No. 2, pp. 103-120, 2007.

Vierros, Marjo. K, and others. "Who Owns the Ocean? Policy Issues Surrounding Marine Genetic Resources. *Association for the Sciences of Limnology and Oceanography*, vol. 25, No. 2, 2016.

Virdin, J, and others. The Ocean 100: Transnational corporations in the ocean economy. Science Advances, vol. 7, No. 3:p.eabc8041, 2021.

Voser, Tanja. M, and others. How different are marine microbial natural products compared to their terrestrial counterparts? Natural Product Reports, vol. 39, No. 1, pp. 7-19, 2022.

Williams, Philip G. Panning for Chemical Gold: Marine Bacteria as a Source of New Therapeutics. Trends in Biotechnology, vol. 27, No. 1, pp. 45, 2009.

Williams, Vivienne. Linda and Whiting, Martin John. A picture of health? Animal use and the Faraday traditional medicine market, South Africa. Journal of Ethnopharmacology, vol. 179, pp. 265-273, 2016.

Zewers, Kirsten. E. Bright Future for Marine Genetic Resources, Bleak Future for Settlement of Ownership Rights: Reflections on the United Nations Law of the Sea Consultative Process on Marine Genetic Resources.Loyola University Chicago International Law Review, vol. 5, No. 1, pp. 151 -156, 2008.

Zhivkoplias, Erik, and others. Growing prominence of deep-sea life in marine bioprospecting. Nature Sustainability, vol. 7, pp. 1-11, 2024.

Section 5A

Chapter 6: Shipping

Authors

Ida-Maja Hassellöv (coordinating), James J. Winebrake, Intan Suci Nurhati, Fani Sakellariadou, Sindhura Polepalli, Zhen Sun, Momchil Terziev, Mariana Graciosa Pereira, K. M. Azam Chowdhury, Magnus Chidi Onuoha, Bjørn Einar Grøsvik, Monica Lundh, Scott MacKinnon

Keynotes points

- Maritime shipping is ~~crucial to global GDP~~vital to the global economy, handling over 8~~0per~~0 per cent of global trade by volume~~,~~. Developing economies, particularly in Asia, play a significant role in this sector.~~with developing economies, especially in Asia, playing a major role.~~ The industry's economic expansion has led to substantial environmental impacts, reinforcing the urgency of sustainable solutions.~~Shipping's economic growth has had a significant environmental impact, underscoring the need for sustainability.~~
- Shipping is a major source of environmental pollution~~Shipping contributes to environmental pollution~~, including chemical, biological, and energy-related contamination, as well as greenhouse gas emissions~~including chemical-, biological-, and energy pollution, and greenhouse gas emissions~~. In addition to the ship-generated pressures, port activities also negatively affect marine ecosystems and coastal communities, intensifying issues like eutrophication and habitat disturbance, and has an adverse impact on human rights.
- The shipping sector's decarbonization is crucial, with GHG emissions from ships contributing ~3 per cent of global emissions. Strategies like Zero and Near-Zero (ZNZ) fuels~~alternative fuels~~ (e.g., LNG, methanol, hydrogen), improved ship designs, and policy frameworks are aimed at reducing emissions, but the associated costs, expansion of infrastructure, and fuel cycle emissions remain ~~challengeing~~challenging.
- Shipping affects human health through emissions that e.g. impact coastal communities, and the maritime sector faces issues like crew safety, occupational health, and gender equity. Regulatory frameworks (e.g., low-sulfur fuel standards) aim to reduce human health risks, though unintended environmental tradeoffs exist.
- Global regulations, primarily developed by the IMO, are central to governing shipping's environmental impact. Conventions like MARPOL and BWM set standards to reduce pollution and invasive species spread. Continued updates and enforcement are essential for sustainable ocean management and climate goals.

Introduction

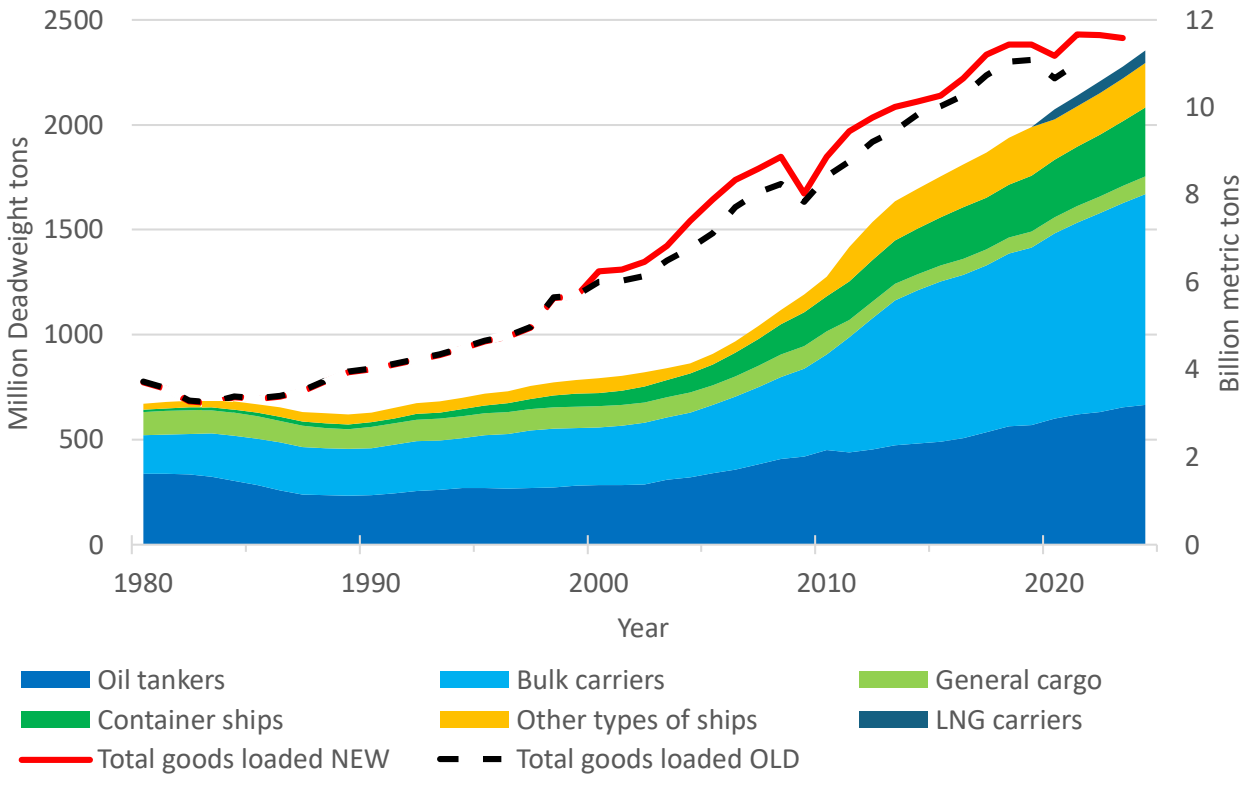
Maritime shipping refers to the transportation of goods and passengers via sea. This sector, which includes both vessels and landside support infrastructure (i.e., seaports), plays a dominant role in the ocean economy's contribution to global Gross domestic product GDP, and its importance in advancing the sustainable development agenda cannot be

understated (UNCTAD 2023). This chapter discusses environmental pressures due to a growing number of vessels active on the world's oceans, as well as potential pathways and policies that can lead towards a more sustainable shipping sector. Further, the human dimensions of shipping, such as safety, occupational health, and human rights are addressed.

International shipping activities reflect global economic and geopolitical situations. The impacts of the 2008-2011 financial crisis, and then the 2020-2023 COVID-19 pandemic, marked the first and second WOA respectively [Section 5B, Chapter 7: Pandemics including COVID-19 impacts, Easton White]. As the global economy recovers from the pandemic, international shipping has rebounded with ~~a~~ several dampening effects in 2022-2025 ~~in the second quarter of 2022 e.g. linked to the war in Ukraine~~, thereby demonstrating the impact of geopolitical events on shipping and the marine environment ~~– a link illustrated most recently by the rerouting of ships from the Suez Canal due to the war in Gaza~~ [Section 4, Chapter 1: Drivers, Mike Elliot].

Globally, shipping accounts for over 8~~0per~~0 per cent of the international trade volume, making it an important part of every nation's economic growth (UNCTAD 2024). Together with other ocean economic activities, maritime transport, ports and warehouses, have been growing globally for the past twenty-five years often outpacing the growth of the global economy (OECD 2024).

The annual amount of goods loaded has doubled over the past three decades with over 11 billion metric tons moved by over 105,000 ships, with 92 per cent of the growth attributed to dry cargo (carried by bulk carriers, container ships, and general cargo ships) (UNCTAD 2024, Figure 5A. 6.1). This shipping activity occurs across the world's oceans (Figure 5A.6.2) and through a complex network of seaports and routes with over 4.6 million port calls in 2023~~3~~ (~~Figure 5A.6.2~~UNCTAD Statistics Data Hub, https://unctadstat.unctad.org/datacentre/dataviewer/US.PortCallsArrivals). Those seaport activities accounted for 13 per cent of the global value added of ocean industries and are projected to increase to 16 per cent (exceeding USD ~~3~~ 3 trillion) by 2030 (UNCTAD 2023). Developing economies dominate international shipping with Asian seaports accounting for 5~~0per~~0 ~~cent~~ and 3~~0per~~0 per cent of goods discharged and loaded, respectively (UNCTAD 2023).


2500
2000
1500
1000
500
0
Million Deadweight tons
12
10
8
6
4
2
0
Billion metric tons
1980
1990
2000
2010
2020
Year
Oil tankers
Bulk carriers
General cargo
Container ships
Other types of ships
LNG carriers
Total goods loaded NEW
Total goods loaded OLD

1

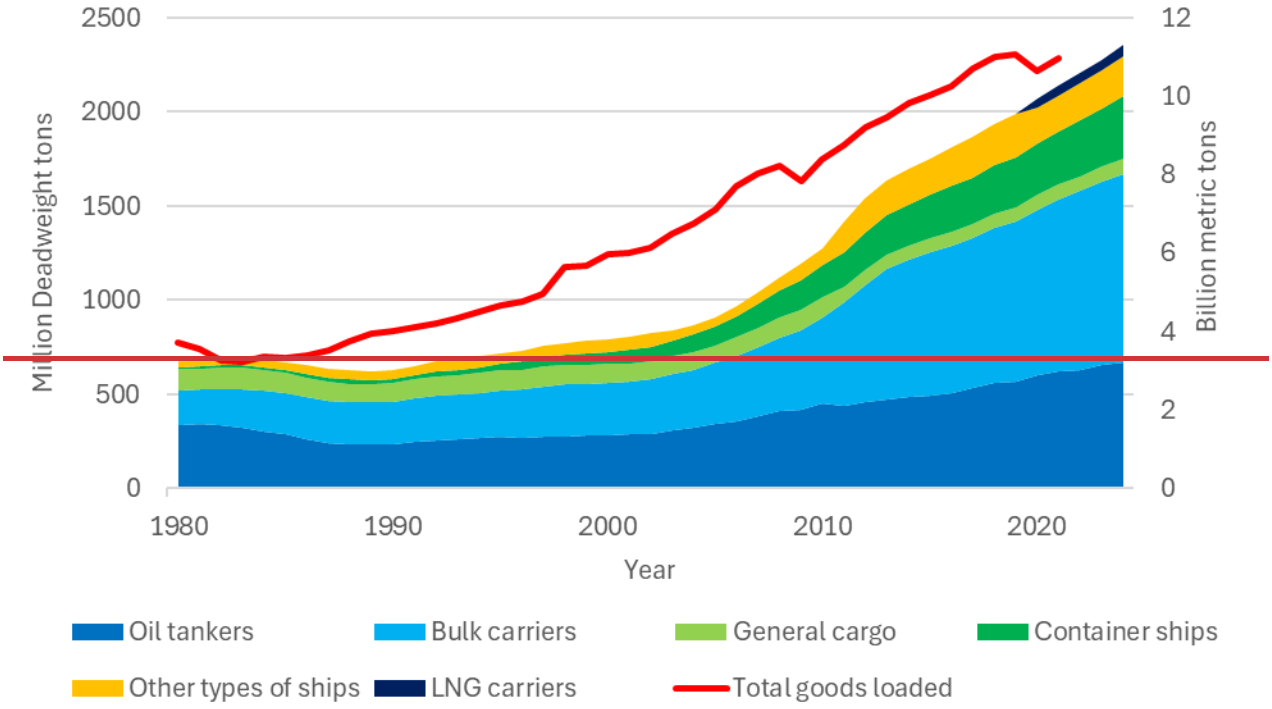


Figure 5A.6.1 Upward trend in the development of international maritime trade as annual goods loaded worldwide (Billions of Tons) and the World shipping fleet by vessel type (Millions of Dead Weight Tons). In 2025, UNCTAD changed their methodology applied for data from the year 2000, why both the new and the old data available are included. Data source: UNCTAD 2024.

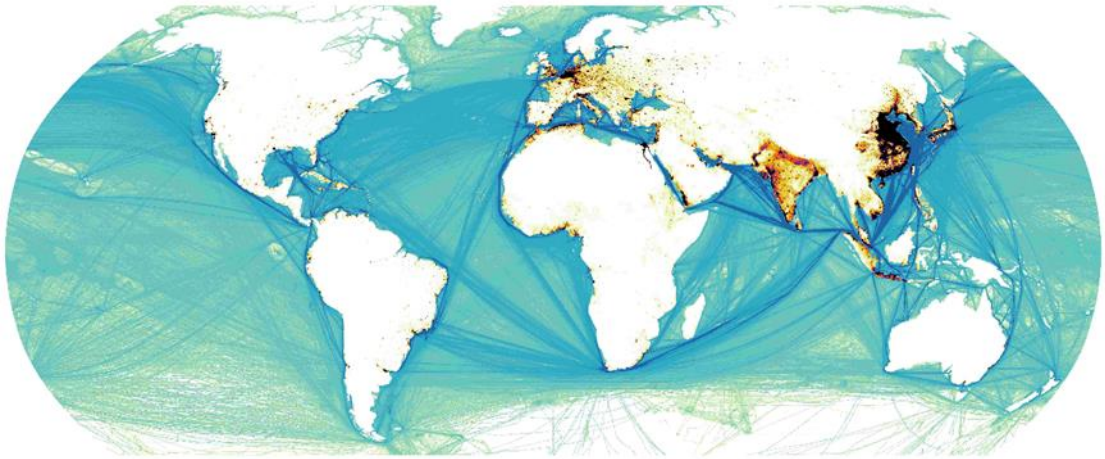


Figure 5A.6.2. Emissions over water from world shipping routes (bolder lines corresponding to major routes), and the related human health impacts on land (Sofiev, Winebrake et al.

2018). American sulfur emission control areas have been effective in reducing human health impacts in North America. Reproduced with permission, CC BY 4.0.

Environmental pressures from shipping and related port activities include chemical-, biological- and energy pollution, and physical disturbance from anchoring and dredging. Climate change introduces additional pressures by shifting marine habitats sometimes into shipping lanes and opening new shipping routes in the Arctic. WOA II reported that while shipping activities continue to increase, there have been fewer shipping accidents leading to reduced oil pollution into seas [Section 5A Chapter 3b: Non-renewables, ~~Karen Breier~~]; additionally, more stringent global or regional regulations to reduce sulfur and nitrogen oxides have led to decreased air pollution into the atmosphere.

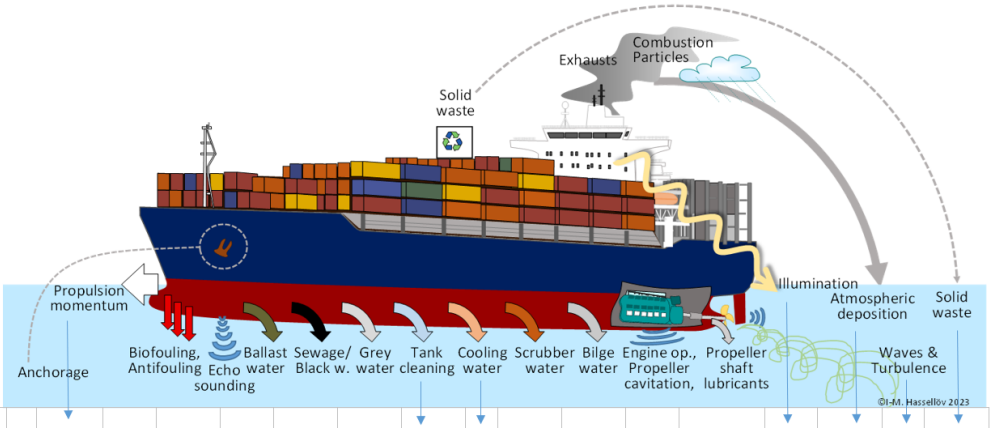
In the current assessment, a comprehensive framework is used to assess environmental pressures and impacts of shipping and their relevant international regulations (Figure 5A.6.3). Besides impacts to natural ecosystems, shipping emissions also impact human health (Sofiev, Winebrake et al. 2018) [Section 5B, Chapter 2: The Ocean and Human Health~~, Michael Moore~~]. The pressures and impacts may be further exacerbated by illegal activities (e.g. dumping, trafficking, piracy) and geopolitical instability (e.g. increased shipwrecks in areas of war, sanctions resulting in a shift towards an increased fleet of substandard vessels, fraudulent registration of ships).

Since the publication of WOA II in 2021, efforts have continued to enhance the sustainability of the shipping sector. These efforts include development of international and regional regulations and the advancement of technological solutions such as emission abatement (Inal, Charpentier et al. 2022), hybrid sources of renewable energy (e.g. solar, wind fuel cells), Zero and Near-Zero (ZNZ) fuels~~alternative fuels~~ (e.g. LNG, methanol) (Pan, Sun et al. 2021), hull and engine design, and lifecycle cost management. Advances have also been made in shipbuilding, where recycling and the promotion of a "circular economy" in shipping has taken hold. The "Blue Ports ~~-~~Initiative" establishes a strategy for seaports to integrate economic efficiency with social responsibility and environmentally friendly practices into port activities, operations and management. Assessments on how the shipping sector may contribute to the sustainable development agenda are presented in Sustainability ~~Sustainability Pathways~~. Regional and international shipping regulations since WOA II are presented in Sector relevant governance~~Sector relevant governance~~.

Environmental pressures and impacts of shipping activities

The positive impacts of shipping are well known and include economic growth, job creation, and new investments in research and development (OECD 2016). However, ships have an array of subsystems (see columns in Figure 5A.6.3) that exert pressures on the marine environment (see rows in Figure 5A.6.3) (Jalkanen, Johansson et al. 2021, Shu, Wang et al. 2022, Ytreberg, Hansson et al. 2022). This section discusses these pressures in four primary categories: chemical pollution, biological pollution, greenhouse gas emissions, and energy pollution (including hydrodynamics, noise, and light). Although the

focus is on impacts from vessels in this chapter, it is recognized that additional impacts from seaports are important to consider with respect to the degradation of coastal areas and soil pollution.



Pressure																	
Collision (birds, mammals, ice habitats)		X															
Non-indigenous species (NIS)			X		X	X	X										X
Contaminating compounds					X	X	X	X	X	X	X		X		X		
Nutrient and organic enrichment						X	X	X		X					X		X
Acidifying compounds								X		X					X		
PM & marine litter, incl. microplastics			X			X	X			X	X				X		X
Artificial light pollution														X			
Noise and energy pollution	X	X		X								X				X	
Physical Seabed Disturbance	X															X	
Shipping regulatory framework			AFS		BWMC	MARPOL Annex IV	MARPOL Annex IV*	MARPOL Annexes I, II & V		MARPOL Annex VI	MARPOL Annex I		MARPOL Annex I		MARPOL Annex VI		MARPOL Annex V

Figure 5A.6.3 Ship activities' pressures on the marine environment. PM in the pressure categories denotes particulate matter. Grey water is often mixed with sewage, implying that Annex IV, indicated with * in the table, will indirectly apply. Modified from Jalkanen et al. (2021), CC BY 4.0.

Chemical pollution

Ships continue to emit large amounts of sulfur and nitrogen oxides into the environment, which cause acidification and human health impacts. This has been mitigated in recent years with the use of low sulfur fuels and pollution control technologies, although these reductions often come with climate change tradeoffs (Sofiev, Winebrake et al. 2018, Yuan, Song et al. 2024). In the case of exhaust gas cleaning systems (scrubbers) another tradeoff is increased contaminant load to the marine environment (Lunde Hermansson, Hassellöv et al. 2021). Today, the approximately 5000 ships equipped with scrubbers, allowing for continued use of cheap heavy fuel oil, account for 25 per cent of the global bunker consumption and a major share of metals and organic contaminants from shipping (Lunde Hermansson, Hassellöv et al. 2024), in addition to particulate matter (PM) entering the marine environment (Anders, Bauer et al. 2025, Gondikas, Mattsson et al. 2025). Ships also leach metals and other chemicals into the marine environment through antifouling paint, and cooling water where sacrificial anodes are used. Indeed, these are the largest sources of copper and zinc from ships (Amara, Miled et al. 2018). Organotin

compounds and cybutryne in ship antifouling paints have been prohibited since 2008 and 2023, respectively, by the Anti-Fouling Systems (AFS) Convention (MEPC 2021c). Despite the ban in 2008, due to slow degradation and previous high pollution levels, TBT (tributyltin) is still found at very high levels in many harbours and hot spots throughout Europe, Asia, and North and South America (Beyer, Song et al. 2022). Metals and organic contaminants also occur in treated and untreated bilge water and propeller shaft lubricants. For example, in the Baltic Sea, maritime shipping is estimated to be a major contributor of copper (almost 40per0 per cent of total load when compared to all other sources, such as riverine run off, atmospheric deposition and point sources on land), vanadium (12 per cent), phenanthrene (9 per cent) and anthracene (8 per cent) (Ytreberg, Hansson et al. 2022). Studies have indicated that shipping can be a significant contributor of contaminants in other estuarine and coastal areas with intense ship traffic and limited water exchange (Aghito et al. 2025, Calgaro et al. 2025).

Nitrogen oxides in ship exhausts deposited on the sea surface, will together with nitrogen and phosphorus in ship-generated food waste, untreated sewage and greywater, contribute to eutrophication (Raudsepp, Maljutenko et al. 2019). The resulting excess biomass, together with directly discharged organic matter from food waste and sewage sludge, will be deposited on the sea floor, where it can cause oxygen depletion (Diaz and Rosenberg 2008, Wilewska-Bien, Granhag et al. 2016).

Plastic litter is recognized as a major environmental problem. Despite the fact thatEven though dumping of plastic material as wastes has been prohibited by the London Convention and London Protocol, and discharge of plastic as garbage is regulated by MARPOL Annex V, shipping and fisheries industries are still recognized as marine sources of plastic litter. Further work to increase the availability and adequacy of port reception facilities for the collection of plastics are vital to tackling this issue, and as a result IMO adopted a Marine Litter Strategy in 2021. There is emerging, but inconclusive, evidence that antifouling paints may be an important source of microplastics in the sea (Dibke, Fischer et al. 2021). In summary, shipping contributes to cumulative pressure of contaminants, eutrophying and acidifying substances to the marine environment *[Section 4 Chapter 6: Pressures 2) Pier Dunstan, Cumulative effects]*. Chemical pollution due to shipping also threatens a broad range of human rights, including the rights to to a clean, healthy and sustainable environment, life, health, life, food, water and sanitation, and safe and healthy working conditions (Orellana et al. 2024).

Biological pollution

Ships are the primary vector spreading non-indigenous marine species (NIS) on hulls, in niche areas, or in the ballast water of ships (Bailey, Brown et al. 2020)[Section 4 Chapter 6: Pressures 1) Thomas W. Theriault, Invasive species]. Ballast water treatment systems are using mechanical, physical, chemical, biological or combined treatments (Sayinli, Dong et al. 2022), and have been regulated by the Ballast Water Management (BWM) Convention (IMO 2004) since 2017. Hull biofouling also increases the surface roughness of a ship's hull (i.e., frictional resistance, shear stress, and the vessel's weight), thereby increasing fuel consumption and resulting emissions to maintain the speed profile. Shipping is suggested

to have a more pronounced effect on marine invasions than climate-driven environmental changes (Sardain, Sardain et al. 2019).

Greenhouse gas emissions (GHGs)

Shipping accounts for about 3 per cent of global GHG emissions, with a projected increase between 90 ~~per cent~~ and 130~~per~~0 per cent of 2008 levels by 2050, following increased maritime trade under a business-as-usual scenario (IMO 2020a). These emissions are considered to contribute significantly to global warming and climate change, causing significant impacts on the environment. A number of approaches, technical and economic, are being taken to address these emissions such as a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity, and a pricing mechanism for maritime GHG emissions (MEPC 2023d).

One major impact of global warming is the reduction of Arctic sea-ice extent and thickness, thereby reducing ice-albedo and leading to even more global warming and concomitant ice reduction (Intergovernmental Panel on Climate Change (IPCC) 2022). With reduced ice, more ships are expected to travel to the Arctic during certain months of the year (Corbett, Lack et al. 2010). Ships navigating in the Arctic Waters are required to comply with the International code for ships operating in polar waters (Polar Code) and related regulations relating to the safety of navigation, the protection of the marine environment and the manning and training for seafarers (MEPC 2015). By 2050, Polar Class 6 (PC6) and non-ice class vessels will likely have access to more route options through the Northwest Passage (NWP), Northern Sea Route (NSR) and the Transpolar Sea Route (TSR) (Smith and Stephenson 2013, Melia, Haines et al. 2016, Theocharis, Pettit et al. 2018). Use of Arctic shipping routes will reduce travel time, consumption of fossil fuels and the associated carbon dioxide and other emissions; for example, using the NWP can reduce carbon dioxide emissions by 49 per cent to 78 per cent compared to conventional shipping routes (Schøyen and Bråthen 2011). However, other ship emissions, such as black carbon, may create near-term environmental and climate concerns as these Arctic routes are opened (Corbett, Lack et al. 2010, Corbett, Winebrake et al. 2010). Shipping activities in Arctic waters should be carefully managed to protect the Arctic's sensitive marine ecosystem and consider the interests of Indigenous peoples.

Energy pollution

Energy from ship propulsion may physically affect the marine environment. Depending on the water depth, the speed of the vessel, and the distance from the ship's course (Huang, Li et al. 2023), ship-generated waves can account for large portions of the total wave energy in confined waterways and coastal areas, where ships also produce a localized depression in the water that can drive strong currents (Dempwolff, Melling et al. 2022). The waves may cause morphological changes in nearby coastal slopes, damage infrastructures (Grue 2017) *[Section 4, Chapter 6: Pressures 2) Luciana S. Esteves, Erosion and sedimentation]*, and disturb the biodiversity of marine habitats (Gabel, Lorenz et al. 2017). Propeller action is the main source of turbulence, which can extend over considerable distances and contribute to oceanic mixing (Nylund, Hassellöv et al. 2023). In coastal,

methane rich, environments ship passages may trigger substantial methane emissions from the bottom water to the atmosphere i.e. fluxes of 11.1 mmol m^{-2} day^{-1}, 20 times higher than the surrounding background flux, were reported from the Neva Bay shipping lane (Nylund, Mellqvist et al. 2025). Due to the propeller's significant impact on ship efficiency, extensive research focuses on its optimization. ~~(Nylund, Hassellöv et al. 2023)~~

Ship-generated underwater noise, primarily from the ship hull, engines, and propeller may interfere with the ability of marine animals (e.g., whales, sea turtles, fishes) to navigate to preferred habitats to find food and mates; to communicate with each other; and to avoid predators (Jones 2019, Rako-Gospić and Picciulin 2019). It has been suggested that airborne noise pollution from ships could be reduced by using electric motors, while also improving fuel efficiency, yet a recent study shows that underwater noise is not reduced from a fully electric ship (Andersson, Johansson et al. 2024).

Light pollution from ships, an established but incompletely described type of pressure, can lead to the fragmentation or loss of ecosystems and a decline in biodiversity. Artificial light impacts species orientation, recruitment and reproduction, predation, and communication. It mainly affects the functioning of nocturnal species; symptoms include confusion and attraction or aversion to light sources (Carić and Mackelworth 2014, Davies, Duffy et al. 2014). In addition, seabirds attracted to artificial light lose their way, crash into buildings, run out of food, become exhausted or are caught by predators (Merkel and Johansen 2011). Predicting how fish will react to artificial light is difficult as their ability to perceive light underwater depends on several variables, e.g, the positioning of the light source in water or above, and variation in species-specific response (Marangoni, Davies et al. 2022).

Sustainability pathways

Despite the significant environmental impacts of maritime shipping on the global environment discussed above, there are opportunities to find a more sustainable pathway moving forward, and aligning with Agenda 2030. New technologies (e.g., sewage treatment systems) and operational changes (e.g., slow-steaming and e-navigation) can reduce the amount of contaminants ships emit into the environment. New engine- and hull designs can reduce noise pollution, and new advances in ballast water treatment can reduce the likelihood of invasive species transport. However, because of the critical importance of addressing climate change, this section focuses on sustainable pathways related to the decarbonization of the maritime shipping sector.

Decarbonization pathways

Greenhouse gas emissions from ships represent ~3per cent of global anthropogenic GHG emissions (IMO 2020a), thereby motivating policymakers and industry to focus attention on decarbonizing international shipping (UNCTAD 2023). The IMO and its Member States have taken significant steps toward decarbonization, implementing new policies to reduce GHG emissions from ships (MEPC 2023d). While the long-term effectiveness of these measures are uncertain, Member States adopted an ambitious GHG strategy ~~aiming for~~including at least

40per0 per cent reductions in GHG emissionsthe carbon intensity of international shipping, i.e. the CO_2 emissions per transport work (IMO 2020a), by 2030 compared to 2008 and net zero GHG emissions by 2050 (MEPC 2023b). Achieving these goals is aligned with the United Nations Sustainable Development Goal 13 related to climate change.

The decarbonization of international shipping will require implementation of a variety of technical, operational, and behavioral changes in the international shipping sector (Winebrake and Corbett 2010, IMO 2020a, Kanchiralla, Brynolf et al. 2022). These changes will need to be induced through policy instruments that range from command-and-control directives (e.g., emissions standards or design indices) to market-based approaches (e.g., emissions fees or market-based credit systems). Although current policy instruments focus on the technical and operational aspects of reducing emissions, such as mandating energy efficiency and carbon intensity standards (MEPC 2023b), IMO Member States are also deliberating on economic instruments to complement these technical solutions (MEPC 2023b). Moreover, new technologies are being developed that have the potential to capture and store carbon from ships' exhaust (Kanchiralla, Brynolf et al. 2024). Another key to guide decarbonization is transparent measurement, reporting and verification of ships' fuel consumptions (Singh, Finnegan et al. 2016, Sabine 2024) and in 2016, the IMO launched its Data Collection System (DCS) for this purpose (MEPC 2016).

Finally, whilst the 2006 Stern Review (Stern 2007) estimated that the cost of global inaction on climate change significantly outweighs the expected cost of coordinated global action, tthe cost for decarbonization of the international shipping sector is expected to be substantial and bearing a risk of disproportional negative impacts on the most vulnerable nations, i.e. small island development States (SIDS) and least developed countries. The UNCTAD (2023) reports that "estimates show decarbonizing the world's fleet by 2050 could require $8 billion to $28 billion annually. The infrastructure for 10per0 per cent carbon-neutral fuels could need an even heftier $28 billion to $90 billion each year". If achieved, full decarbonization could double yearly fuel costs, challenging the shipping industry to seek finance frameworks to achieve economic, environmental and social sustainability (Haugan 2024). This section focuses on some of the more prominent decarbonization strategies being explored by the sector and discusses the opportunities and challenges of each with emphasis on the marine environment.

Zero and Near-Zero (ZNZ) fuels Alternative fuels and propulsion technologies

Many promising options exist to use alternative ZNZ fuels as bunker fuel for ships. These fuels have a lower carbon-intensity compared to conventional heavy fuel oil or other diesel-based marine fuels and therefore may have a lower impact on climate when used. The variety of fuels being considered includes fuels such as methanol, natural gas, ammonia, hydrogen, electricity, and biofuels, and the assessment of future fuel mixes is a complex task (Kanchiralla, Brynolf et al. 2024). Yet, the majority of existing life cycle assessment studies of marine fuels show a lack of transparent disclosure of the methodological choices and assumptions, and lack of uncertainty analysis, implying that they cannot provide clear guidance on the potential environmental impacts of marine fuels (Roux, Lodato et al. 2024).

Two primary challenges with introducing these “clean” fuels into the global shipping sector are costs and access. On the cost side, many of these ~~alternative~~ ZNZ fuels are priced considerably higher than conventional fuel oils and so ship operators must be properly incentivized to spend more for these fuels, either through policy mandates or economic incentives. On the access side, many of these fuels have immature landside supply chain and bunkering infrastructure, that may also need extra safety measures, e.g. for hydrogen and ammonia. Vessels will find it challenging to switch to these fuels if there is no guarantee that refuelling options exist across the complex maritime transportation network upon which they travel.

In addition, although many of the ~~low-carbon~~ZNZ fuels such as ~~natural gas and~~ ammonia show significant promise in terms of reducing GHG emissions from vessels, there may be considerable GHG emissions that occur during the extraction, production, and transportation of these fuels to bunkering outlets, as well as from unburned hydrocarbons such as methane that are emitted when used onboard a vessel (i.e., “methane slip”). In addition, ammonia is known to be toxic to marine invertebrates, with growth inhibition, oxidative stress and immunological responses, being the top three types of acute responses, and growth inhibition, nervous system injury and metabolic disorder dominating the chronic responses (Zhang, Li et al. 2023). However, under moderate ammonia stress, ecosystem complexity dampen effects, supporting previously observed scale-dependent toxicity of ammonia on aquatic organisms (Liu, Li et al. 2022). Ammonia as a nutrient pollutant is well known and any spill in areas sensitive to eutrophication will be detrimental [Section 4. Chapter 6: pressures]. Accounting for all these emissions as part of a “total fuel cycle analysis” is important (Kanchiralla, Brynolf et al. 2022). The evaluation of GHG emissions from fuel extraction (or electricity production) to use is called “well-to-wake" (WTW) emissions, and studies have shown that it is critically important to consider WTW emissions when comparing fuels (Winebrake, Corbett et al. 2019, MEPC 2024e, Roux, Lodato et al. 2024).

Nevertheless, opportunities exist for a variety of ~~alternative~~ ZNZ fuels on a WTW GHG basis (Carr, Winebrake et al. 2024). Most promising are fuels that can be produced sustainably (i.e., through renewable means), as well as those that do not need massive infrastructure investments to operationalize. Indeed, the order book for new vessels operating on ~~alternative~~ ZNZ fuels shows over 400 oceangoing vessels investing in methanol, ammonia, and battery-assisted vessels, although it should be noted that these orders represent only a small fraction of the total number of vessels on order (Carr, Winebrake et al. 2024). Continued assessment is needed to demonstrate how these fuels can be produced sustainably and operate effectively in the maritime sector.

Operations and logistics

Another set of options for reducing the carbon-intensity of the shipping sector is through modifications in operations and logistics; or how ships are deployed and used in global transport. Three opportunities that are particularly noteworthy include slow-steaming, just-in-time arrival, and e-navigation systems.

Slow-steaming refers to vessel adjusting their speed on the water as they move goods from origin to destination. Since the use of fuel in a vessel is exponentially proportional to the speed of a vessel, slowing vessel speeds can have a dramatic impact on fuel use and emissions. Reducing speeds by 5~~0per~~0 per cent can lead to a reduction in fuel use by 7~~0per~~0 per cent

(Corbett, Wang et al. 2009). Although promising, there are challenges to slow-steaming as a long-term solution to decarbonization, e.g., slow-steaming leads to slower delivery times that needs to be balanced against the general customer tolerance for longer transit times (Vakili et al. 2023), or may even be unacceptable for certain commodities such as fresh food (Dere, Zincir et al. 2022). Accounting for slower deliveries without loss of service implies adding vessels to the global shipping fleet, which may offset the emissions reductions gains from slow-steaming in the first place. In addition, APEC (2019) highlighted that the complexity of analysis of impacts of slow-steaming for distant economies calls for further studies to ensure that SIDS are not negatively affected by e.g. global strategies for slow-steaming. Nevertheless, for certain commodities, without a best before date, slow-steaming is a viable option for reducing GHG emissions.

Another, existing option to reduce emissions from ships is the concept of "just-in-time arrival". This operational strategy addresses a common problem in the shipping sector, whereby vessels arrive at port but are unable to dock due to congestion, availability, or other factors. When faced with this situation, vessels will anchor outside of port – sometimes for days – burning fuel while they wait for an opportunity to dock and during this period the onboard subsystems will impact the marine environment (Argüello, Krabbe et al. 2022). Just-in-time arrival is designed to address this problem by providing real-time data to vessels under voyage so they may adjust their routes or speeds according to their ability to dock at a destination port. The economic incentives exist to encourage the use of this just-in-time docking, but data exchange systems or port community systems must be made more robust for this practice to be taken up more holistically in the shipping sector, and especially in SIDS (World Bank 2024).There are also counteractive incentives, such as ships sailing and awaiting higher price for their cargo (e.g. LNG price is going up during wintertime), or LNG feeder vessels travelling long periods at sea only to burn boil off gas, i.e. only avoiding the pressure to rise in the LNG tanks not carrying out any real transport work (Hörteborn and Hassellöv 2023).

Lastly, an important tool for making informed decisions regarding the safety and efficiency of ship operations is marine weather data, which comes from various sources such as satellites, buoys, ships, and ground stations (Miloslavich 2024). The maritime industry is undergoing a digital transformation. E-navigation is a key component for smart shipping as it integrates human engagement with navigational advancements and leverages technological achievements to improve safety and security at sea, enhance berth-to-berth navigation and protect the marine environment.

Ship design and retrofitting

Another approach to decarbonizing global shipping is through ship design and retrofitting. Since the early 2000s, the IMO has been working with the shipping industry to improve the efficiency of ship operations. These initiatives have focused on three primary areas: (1) energy efficiency design index (EEDI), which is an increasingly stringent energy efficiency metric per capacity mile (e.g., tonne-mile) based on ship classification; (2) ship energy efficient management plan

(SEEMP), which is a mechanism to achieve greater efficiency in onboard energy management as well as monitoring tools to help monitor energy use (MEPC 2022a); and (3) energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) rating, which went into force in 2022 and 2023, respectively, with a goal of providing a metric for energy efficiency and carbon emissions for existing ships that must be improved annually.

All three approaches are helpful tools for ship builders and operators to seek ways to reduce GHG emissions. These approaches are technology-neutral and do not dictate what energy efficiency or other technologies are required on board a vessel. Instead, these policies provide guidance and targets to the sector that can be met in a variety of ways. Energy saving devices, like wind assisted propulsion systems, air lubrication systems, waste heat recovery devices, or photovoltaic power generation are all options that ship operators may explore (MEPC 2021a).

The costs and benefits of these options are vessel-dependent and sometimes require sophisticated analysis that often include significant uncertainty and validation difficulty due to lack of full-scale data. For example, recent evidence suggests that modelling uncertainties remain higher than the maximum net benefit many energy saving devices typically offer (Ponkratov 2017, Andersson, Shiri et al. 2022, Terziev, Tezdogan et al. 2022). Given the risks involved, ship operators may be reluctant to implement some of these technologies without additional data validation and operational experience at full-scale.

Circular economy ship recycling

Another consideration for sustainable pathways beyond decarbonization is how the sector deals with ships at the end of their operational life considering the concept of “cradle to grave.” By recovering steel, various metals and a wide range of used materials, the need for further extraction of natural resources is minimized. For steel, in particular, which accounts for up to 95per cent of a ship’s weight, recovery through ship recycling can lead to a 70-90per0 per cent reduction in ecological footprint and environmental impact, in comparison with its production from iron ores (Rahman and Kim 2020). However, as many of today’s recycling ships were built in an era with weaker environmental regulations, they can also contain a variety of hazardous and toxic substances including asbestos, metals, PCBs, PAHs, glass wool, biocide antifouling coatings such as TBT, etc. Unsustainable ship recycling operation and wastes disposal poses environmental and health risks (Dey, Ejohwomu et al. 2021). The challenges for sustainability in ship recycling are multidimensional, including corruption to circumnavigate environmental laws, e.g., utilizing Flag of convenience to allow obsolete ships to berth in ship recycling facilities in countries that have not ratified the international conventions. In the global trade fleet, 61per cent of the ships sport such flags, allowing developing countries with less stringent labour and environmental protection legislation to offer long-term low-cost scrapping areas, or scuttling of obsolete ships (Devault, Beilvert et al. 2017). Today, the focus is on the sustainable recycling of ships, minimizing environmental impact and maximizing material recovery (Hiremath, Tilwankar et al. 2015, Zhou, Du et al. 2021) (see section Sector Governance. By taking a holistic approach to the life cycle of a ship, appropriate decisions during the design and construction of a ship (the “design for recycling” concept) and throughout its life cycle can contribute to reducing the environmental impact during the scrapping stage.

Ocean observing and monitoring

Effective and resource-efficient monitoring and ecosystem-based management strategies are essential for the conservation of marine ecosystems. Fixed-wing or mobile rotary-wing Unmanned Aerial Vehicle (UAV) remote sensing platforms can be used to collect multidimensional marine data. These UAVs have been effectively used to monitor the marine environment in situations such as oil spill detection, marine debris identification, algal bloom observation, carbon stock estimation, dissolved organic carbon content, and total suspended sediment assessment. Data on marine physics, chemistry, and biology can be coordinated and collected by underwater gliders equipped with a variety of sensors. Unmanned surface vehicles (USVs) reach various offshore destinations from the nearest shore. Numerous sensors are carried by them for important monitoring of atmospheric and marine environmental variables (Yuan, Li et al. 2023). With the right sensors, maritime autonomous surface ships (MASS) can operate autonomously or remotely to continuously measure ocean parameters. Satellite remote sensing platforms can provide physical oceanography-related monitoring, detect oil spills, contribute to monitoring biological patterns, etc. Ferry Boxes, automated surface water monitoring systems, fitted to the through-flow system of ships, and equipped with various sensors, can collect data on physical, chemical, and biological ocean parameters (IOC-UNESCO 2024). The Voluntary Observing Ship (VOS) program depends on the volunteer participation of crew members and gathers information on weather observations which are valuable for climatologists (https://vos.noaa.gov/). Finally, Automatic Identification System (AIS) data, originally developed for enhanced navigational safety, are today essential both in assessment of environmental pressures of shipping, and to relate sensor data collected by ships (Calewaert 2024, Miloslavich 2024).

Social components

From the perspective of addressing the social elements of sustainable development, two areas are considered: (1) the seafarers (including gender and equity) of the shipping sector on the people immersed in the sector; and (2) the social and human impacts of the shipping sector.

The seafarers

The shipping industry as a whole is facing challenges on recruitment and retention of seafarers (Caesar 2024). As the growth in the shipping industry is predicted to expand, the growing shortage of seafarers will pose even more challenging in the future (Drewry 2024). It is well recognized that shipping is a high-risk occupation with a highpresence of accidents, morbidity and mortality (Slišković and Penezić 2015). Despite the relationships to the sea being important for mariners' identity (Glithero 2024), the physical work environment is also demanding (Oldenburg, Baur et al. 2010). Furthermore, the often harsh operational environments are unpredictable and add more challenges to the work (Ventikos, Papanikolaou et al. 2018) [Section 5B Chapter 7: Pandemics including COVID-19 Impacts. Easton White]. Elements of the psychosocial aspects of work have been given more attention by identifying the challenges of isolation, extended time away from family and friends, bullying, sexism, stress and fatigue to mention a few all of which have a negative impact upon the onboard work environment (Jepsen, Zhao et al. 2017, Jonglertmontree, Kaewboonchoo et al. 2022, Österman and Boström

2022, Toygar, Nart et al. 2023). These are important issues to address to make shipping a more attractive career preference.

There is evidence that seafarers can be treated unfairly. One such example are seafarers serving on vessels under flags of convenience, where the International Transport Workers' Federation (ITF) found the crews were offered, for example, ;substandard working conditions, low wages and forced to work under poor safety conditions (Christodoulou-Varotsi 2012, ITF 2024) [Section 5B Chapter 5: Equity. Nathan Bennett]. Over the years, different initiatives to secure social sustainability in the shipping industry have been taken to improve the conditions for seafarers. The Maritime Labour Convention (MLC) was thus adopted aiming to ensure that seafarers have decent working conditions and job security (ILO 2006). Additionally, the IMO and the European Maritime Safety Agency (EMSA) have recognized the challenges seafarers face and regard the "Human Element", i.e. the complex interplay between people and the systems they work within, as a key discipline to address the social, equity and equality issues related to employment within the industry (IMO 2006, EMSA 2023). The Special Rapporteur on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes has called for a human rights-based approach to this sector by States and businesses (Orellana et al. 2024).

Other interested organisations have identified the importance of wellbeing and psychological safety of the crew onboard. The Oil Companies International Marine Forum (OCIMF) performs inspections onboard tanker vessels to address concerns about sub-standard operational practices (OCIMF 2024). As of 2024, OCIMF inspections have included not only technologies but also human factors and different aspects of the work environment of the crew (OCIMF 2021).

The shipping industry is facing technological developments which will prove to be disruptive causing changes to the sociotechnical system As digitalisation and automation are introduced, the way work is done and will be done will further change (Mallam, Nazir et al. 2020). In preparation of a future with highly automated and autonomous operation of ships, the IMO has conducted regulatory scoping exercises relating to ships with various levels of automation (IMO 2024c). New concepts of operations will require significant modifications to the International Convention on the Safety of Life at Sea (IMO 2024b) and the International Convention on the Standards of Training, Certification and Watchkeeping (IMO 2017) and needs to address the way work is done safely and identifies the future competencies that mariners will need. The existing maritime education and training has been scrutinised for these knowledge gaps for future navigational officers and marine engineers to properly prepare them for roles on increasingly automated and remotely controlled vessels (Jurdzinski 2020, Wang, Wu et al. 2020, Lokuketagoda, Miwa et al. 2023). Fortunately, the disruptions arising from increased levels of automation should create new opportunities for recruitment and retention of the newly trained operators/mariners and should address social inequities for employment in a traditionally male dominated industry.

Human rights, gender and equity

The maritime sector traditionally has been characterised as male dominated. Women represent only 1.28 per cent of the worldwide number of seafarers certified with respect to the

International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). i.e. Captains, Deck Officers, Chief Engineers, Engine Officers, and Radio Officers (BIMCO and ICS 2021). [Section 5B Chapter 6: Gender. Leandra R. Gonçalves] The majority of women seafarers work in non-technical and non-operational sections such as catering and hotel sections on cruise ships and ferries, where women are stereotypically considered to be more suited (Kitada 2022). The same trend is observed in women workers in ports and shore-based maritime industries with significant variations in different countries and regions, and between public or private ownerships (WMU 2019, IMO and WISTA 2021, Kitada 2022, UNCTAD 2023).

Impacts on human health

Atmospheric ship emissions, e.g. sulfur and nitrogen oxides, despite occurring over water, undergo chemical changes in the atmosphere and are transported over land (Figure 5A.6.2) where they can have deleterious effects on human health (Corbett, Wang et al. 2007, Winebrake, Corbett et al. 2009). The social impacts of these effects range from work- and school-days missed to loss of life, due to respiratory ailments or other negative health impacts. In addition, emissions from port activities tend to occur in areas that are heavily populated, often with lower-income populations, and so issues of environmental justice and equity also are a concern.

Due to these human health and environmental concerns related to sulfur emissions, the IMO implemented new low-sulfur fuel standards as of 2020 (IMO 2020b). These standards limit the sulfur content of fuels to 0.5per cent outside of emissions control areas (ECAs) and to 0.1per cent within ECAs. New low-sulfur fuels and scrubbers, are now being implemented to achieve these low-sulfur emissions goals. These new regulations are expected to have significant beneficial impacts on human health (Sofiev, Winebrake et al. 2018); however, unintended tradeoffs also exist. By reducing sulfur particles in the atmosphere, the use of low-sulfur fuels indirectly increases global warming (compared to high-sulfur fuels) due to the radiative forcing effects (Yuan, Song et al. 2024). Moreover, scrubber technology involves the discharge of effluent into the marine environment that includes toxic contaminants (Hassellöv, Koski et al. 2020).

Sector relevant governance

The United Nations Convention on the Law of the Sea (UNCLOS) serves as a 'constitutive' legal framework addressing all issues relating to the ocean (Koh 1982), as complemented by existing and subsequently developed legal instruments and customary international law, as well as a wide range of non-legally binding instruments [Section 3: A global overview of ocean governance, Carina Oliveira and Youna Lyons]. The development and implementation of laws and regulations within this framework on international shipping are also influenced by laws and regulations on the marine environment, fisheries, biological diversity, climate change, human rights, marine science and technology, as well as global political initiatives including the United Nations Sustainable Development Goals. In addressing the triple planetary crisis, shipping laws and regulations will thus evolve alongside other legal instruments such as the United Nations Framework Convention on Climate Change (UNFCCC 1994, and the Paris Agreement adopted thereunder 2015), the Convention on of Biological Diversity (CBD, ~~including the~~and its Kunming-Montreal Global Biodiversity Framework 2022), and the Agreement under UNCLOS on the Conservation and

Sustainable Use of Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ) Agreement) (United Nations 2023).

IMO is the specialized agency within the UN system with the global mandate to establish rules and standards for international shipping on the safety, security and protection of the marine environment (IMO 2014). Special rules and standards have also been adopted by States and regional organizations for certain types of ships and specific regions. Under the auspice of the IMO, States have adopted 59 legally binding conventions and nearly 1,000 non-mandatory codes, guidelines, and recommendations that States have closely implemented (Status of IMO Treaties, 2025). There are eight major conventions with protocols and amendments that directly address the issue of marine pollution from ships. This section provides an overview of the major developments on environmental regulations for shipping at the IMO between 2019 and 2024.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering the prevention of pollution by ships from operational and accidental causes, with six annexes targeting pollution from oil, noxious liquid substances in bulk, harmful substances carried in packaged form, sewage, garbage, and air pollution respectively (see section on Environmental pressures and impacts of shipping activities). Recent amendments include reducing sulfur content in fuel oil to 0.5~~0per~~0 per cent m/m (mass by mass) globally (MEPC 2018b), prohibiting the use and carriage for use as fuel of heavy fuel oil by ships in Arctic waters (MEPC 2021b), and permitting the establishment of regional reception facilities within Arctic waters (MEPC 2022b, c, ~~MEPC 2022~~). Additionally, new Emission Control Areas have been designated for the Mediterranean Sea (MEPC 2023a), the Canadian Arctic and the Norwegian Sea (MEPC 2024a), covering nitrogen oxides, sulfur oxides and particulate matter.

To combat GHG emissions, MARPOL Annex VI has been updated with goal-based technical and operational measures such as the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), the Ship Energy Efficiency Management Plan (SEEMP), the Data Collection System (DCS) and the Carbon Intensity Indicator (CII) rating for ships (IMO 2024a). In 2023, the IMO adopted an updated GHG Strategy (MEPC 2023d) with new indicative checkpoints to reach net-zero GHG emissions by or around 2050. Targeting their entry into force by 2027, discussions continue for the potential adoption of a basket of mid-term measures comprised of both a technical element (a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity) and an economic element (based on a maritime GHG emissions pricing mechanism) following a comprehensive impact assessment process (MEPC 2023d, MEPC 2024b (and related document in the introduction of the report), MEPC 2024c). Further developments include the adoption of guidelines on the life-cycle GHG intensity of marine fuels, and discussions on the development of the IMO Life Cycle Assessment Framework and the terms for conducting the fifth IMO GHG Study (MEPC 2024c).

The International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWM Convention) entered into force in 2017. It is supplemented by a Code for Approval of Ballast Water Management Systems and amendments relating to

forms of BWM certificate and record book, and the use of electronic record books. Under the BWM Convention, there are over 70 type-approved ballast water management systems to prevent harmful organisms from spreading through ballast water (MEPC 2018a)~~.~~. To further address the issue of invasive aquatic species, IMO adopted Guidelines for the control and management of ships' biofouling to minimize their transfer into new marine environments (MEPC 2023e). Concerning the prohibition of the use of harmful anti-fouling coatings on ships, IMO has continued to develop and update guidelines under the International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS Convention), including the controls on cybutryne (MEPC 2021c).

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Hong Kong Convention), expected to enter into force in 2025, will regulate all issues around ship recycling, including the handling of environmentally hazardous substances such as asbestos, heavy metals, hydrocarbons, ozone-depleting substances and others. It will also address concerns about working and environmental conditions in ship recycling facilities.

IMO adopted and implemented strategies to reduce plastic litter from ships (MEPC 2021d), and approved recommendations for the carriage of plastic pellets by sea in freight containers (MEPC 2024d), which address packaging, transport information, and stowage of plastic pellets. This topic has also been under consideration by States in the context of the London Convention and London Protocol concerning marine litter and microplastics, and the end-of-life management of fibre-reinforced plastic vessels and alternatives to at-sea disposal (LC 2024).

Addressing underwater noise, IMO adopted the Revised guidelines for the reduction of underwater noise from shipping to address adverse impacts on marine life (MEPC 2023c) and approved the Action plan for the reduction of underwater noise from commercial shipping and Guidance on the Experience-Building Phase to address barriers to its uptake and implementation (MEPC 2024c).

Between 2019 and 2024, all major IMO environmental conventions received new ratifications, with the largest increase of parties in the BWM Convention (18), followed by the AFS Convention (17), the Hong Kong Convention (17), and MARPOL Annex VI (16). The effectiveness of international shipping regulations depends on the ability of States to fulfil their obligations as required by the instruments to which they are Parties. The current legal framework relies heavily on flag State implementation, supplemented by port State control (PSC) and limited coastal State enforcement measures. IMO adopted unified procedures to guide PSC inspections (IMO 2024e), and collaborates with ten PSC regimes operating globally (IMO, Port State Control). Additionally, IMO has developed various mechanisms to assist IMO Member States to improve their capabilities and overall performance to fully comply with the IMO instruments, including a mandatory IMO Member State Audit Scheme since 2016 (IMO 2013a,b ~~IMO 2013~~). As of October 2024, 92 of 176 IMO Member States and three Associate Members have been audited (IMO 2024d), with an annual report summarizing best practices to enhance implementation (IMO 2024b). Between 2016 and 2022, the IMO Secretariat issues five anonymous consolidated audit summary report

(CASR) on a periodic basis containing lessons learned from the audits. The analysis and lessons contained in the CASRs are reviewed by the relevant committees and fed back into the regulatory process of IMO to help make measurable improvements in the effectiveness of the international regulatory framework for shipping.

References

Aghito, M., Majamäki, E., Hänninen, R., Lunde Hermansson, A., Hassellöv, I.-M., Ytreberg, E., Kolovoyiannis, V., Zervakis, V., Granberg, M., Moldanová, J., Dagestad, K.-F., Breivik, Ø., Hole, L. R. and Jalkanen, J.-P., Marine Pollution Bulletin, Projected changes of the emission and transport of organic pollutants and metals from shipping in European seas 2018–2050. (2025) 211: 117351. DOI: 10.1016/j.marpolbul.2024.117351.

Amara, I., W. Miled, R. B. Slama and N. Ladhari (2018). "Antifouling processes and toxicity effects of antifouling paints on marine environment. A review." Environmental Toxicology and Pharmacology **57**: 115-130.

Anders, L., M. Bauer, S. Jeong, M. Schmidt, H. Hakkim, A. Kalamašņikovs, E. I. Rosewig, J. Schade, R. Irsig, S. Ehlert, J. Bendl, M. R. Saraji-Bozorgzad, B. Giocastro, U. Käfer, U. Etzien, B. Buchholz, T. Adam, M. Sklorz, T. Streibel, H. Czech, J. Passig and R. Zimmermann (2025). "Limited efficiency of wet scrubbers in reducing the environmental impact of ship-emitted particles." Environmental Chemistry Letters **23**(4): 923-929.

Andersson, C., A. T. Johansson, A. Genell and J. Winroth (2024). "Fully electric ship propulsion reduces airborne noise but not underwater noise." Ocean Engineering **302**: 117616.

Andersson, J., A. A. Shiri, R. E. Bensow, J. Yixing, W. Chengsheng, Q. Gengyao, G. Deng, P. Queutey, Y. Xing-Kaeding, P. Horn, T. Lücke, H. Kobayashi, K. Ohashi, N. Sakamoto, F. Yang, Y. Gao, B. Windén, M. G. Meyerson, K. J. Maki, S. Turnock, D. Hudson, J. Banks, M. Terziev, T. Tezdogan, F. Vesting, T. Hino and S. Werner (2022). "Ship-scale CFD benchmark study of a pre-swirl duct on KVLCC2." Applied Ocean Research **123**: 103134.

Argüello, G., N. Krabbe, D. Langlet, I.-M. Hassellöv, C. Martinson and A. Helmstad (2022). "Regulation of ships at anchor: Safety and environmental implications." Marine Policy **140**: 105052.

Bailey, S. A., L. Brown, M. L. Campbell, J. Canning-Clode, J. T. Carlton, N. Castro, P. Chainho, F. T. Chan, J. C. Creed, A. Curd, J. Darling, P. Fofonoff, B. S. Galil, C. L. Hewitt, G. J. Inglis, I. Keith, N. E. Mandrak, A. Marchini, C. H. McKenzie, A. Occhipinti-Ambrogi, H. Ojaveer, L. M. Pires-Teixeira, T. B. Robinson, G. M. Ruiz, K. Seaward, E. Schwindt, M. O. Son, T. W. Therriault and A. B. Zhan (2020). "Trends in the detection of aquatic non-indigenous species across global marine, estuarine and freshwater ecosystems: A 50-year perspective." Diversity and Distributions **26**(12): 1780-1797.

Beyer, J., Y. Song, K. E. Tollefsen, J. A. Berge, L. Tveiten, A. Helland, S. Øxnevad and M. Schøyen (2022). "The ecotoxicology of marine tributyltin (TBT) hotspots: A review." Marine Environmental Research **179**: 105689.

BIMCO and ICS (2021). Seafarer workforce report: The global supply and demand for seafarers in 2021. The Baltic and International Maritime Council, and the International Chamber of Shipping.**:** 106.

Caesar, L. D. (2024). "Emerging Dynamics of Training, Recruiting and Retaining a Sustainable Maritime Workforce: A Skill Resilience Framework." Sustainability **16**(1): 239.
Calewaert, J.-B., Sierra-Correa, P. C., de Boer, G., Crosman, K., Kågesten, G., Taconet, M., Busumprah, P. T., Alvarez-Fanjul, E., Shepherd, I., Schaap, D., Hall, S., Zinkann, A.-C., Haddad, T., Jegat, V., Smit, M., Sun, M., Suzuki, T., Visbeck, M., Xingyuan, R. & McMeel, O. (2024). Ocean Decade Vision 2030 White Papers – Challenge 8: Create a Digital Representation of the Ocean. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.8.). 1-58 pp.
Carić, H. and P. Mackelworth (2014). "Cruise tourism environmental impacts – The perspective from the Adriatic Sea." Ocean & Coastal Management **102**: 350-363.
Carr, E. W., J. J. Winebrake, S. J. McCabe, M. Elling and E. H. Green (2024). Ocean-GoingVessel Decarbonization Technology Assessment. Report for Pacific Environment, May 2024. 148pp.
Christodoulou-Varotsi, I. (2012). "Flag of convenience or not ? Challenging the Flag of Convenience Status of EU Registration States: An Introductory Contribution to a Controversial Debate. https://hal.science/hal-03818065v1/document." Neptunus **18**(2): 1-12.
Corbett, J. J., D. A. Lack, J. J. Winebrake, S. Harder, J. A. Silberman and M. Gold (2010). "Arctic shipping emissions inventories and future scenarios." Atmos. Chem. Phys. **10**(19): 9689-9704.
Corbett, J. J., C. Wang, J. J. Winebrake and E. Green (2007). Allocation and forecasting of global ship emissions. Prepared for the Clean Air Task Force and Friends of the Earth International: Boston, MA, USA.**:** 1-27.
Corbett, J. J., H. Wang and J. J. Winebrake (2009). "The effectiveness and costs of speed reductions on emissions from international shipping." Transportation Research Part D: Transport and Environment **14**(8): 593-598.
Corbett, J. J., J. J. Winebrake and E. H. Green (2010). "An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping." Carbon Management **1**(2): 207-225.
Davies, T. W., J. P. Duffy, J. Bennie and K. J. Gaston (2014). "The nature, extent, and ecological implications of marine light pollution." Frontiers in Ecology and the Environment **12**(6): 347-355.
Dempwolff, L.-C., G. Melling, C. Windt, O. Lojek, T. Martin, I. Holzwarth, H. Bihs and N. Goseberg (2022). "Loads and effects of ship-generated, drawdown waves in confined waterways - A review of current knowledge and methods." Journal of Coastal and Hydraulic Structures **2**: 46.
Dere, C., B. Zincir, O. B. Inal and C. Deniz (2022). "Investigation of the adverse effects of slow steaming operations for ships." Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment **236**(4): 1069-1081.
Devault, D. A., B. Beilvert and P. Winterton (2017). "Ship breaking or scuttling? A review of environmental, economic and forensic issues for decision support." Environmental Science and Pollution Research **24**(33): 25741-25774.
Dey, A., O. A. Ejohwomu and P. W. Chan (2021). "Sustainability challenges and enablers in resource recovery industries: A systematic review of the ship-recycling studies and future directions." Journal of Cleaner Production **329**: 129787.
Diaz, R. J. and R. Rosenberg (2008). "Spreading dead zones and consequences for marine ecosystems." Science **321**(5891): 926-929.
Dibke, C., M. Fischer and B. M. Scholz-Böttcher (2021). "Microplastic Mass Concentrations and Distribution in German Bight Waters by Pyrolysis–Gas Chromatography–Mass

Spectrometry/Thermochemolysis Reveal Potential Impact of Marine Coatings: Do Ships Leave Skid Marks?" Environmental Science & Technology **55**(4): 2285-2295.
Drewry (2024). Manning annual review & forecast 2024/25. Editor: R. Harris. Publisher; Ferenc Pasztor.**:** 1-108.
EMSA (2023). European Maritime Safety Agency. Facts and figures 2023.
Gabel, F., S. Lorenz and S. Stoll (2017). "Effects of ship-induced waves on aquatic ecosystems." Science of The Total Environment **601-602**: 926-939.
Glithero, L. D., Bridge, N., Hart, N., Mann-Lang, J., McPhie, R., Paul, K., Peebler, A., Wiener, C., Yen, C., Kelly, R., McRuer, J., Hodgins, D., & Curtin, F. (2024). Ocean Decade Vision 2030 White Papers - Challenge 10: Restoring Society's Relationship with the Ocean. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.10.). 1-41 pp.
Gondikas, A., K. Mattsson and M. Hassellöv (2025). "A new form of hazardous microparticulate contamination to the marine environment from ships using heavy fuel oil with exhaust gas scrubbers – Characterization and implications for fate, transport and ecotoxicity." Science of The Total Environment **959**: 178263.
Grue, J. (2017). "Ship generated mini-tsunamis." Journal of Fluid Mechanics **816**: 142-166.
Hassellöv, I.-M., M. Koski, K. Broeg, O. Marin-Enriquez, J. Tronczynski, V. Dulière, C. Murray, S. Bailey, J. Redfern, K. de Jong, E. Ponzevera, Maria J. Belzunce-Segarra, C. Mason, Josephine C. Iacarella, B. Lyons, Josean A. Fernandes and K. Parmentier (2020). ICES Viewpoint background document: Impact from exhaust gas cleaning systems (scrubbers) on the marine environment (Ad hoc). ICES Scientific Reports**:** 40.
Haugan, P., Rhodes, A., Hollaway, L., James, P., Abdul Rahman, M., Appiott, J., DeBeauville-Scott, S., Gelcich, S., Gericksky, E., Gonzales-Quiros, R., Harms, E., Heaps, L., Hospes, E., Jeremie, M.-M., Jumbe, A. S., Kostka, W. N., Mokenye, J., Noonan-Birch, R., Park, G., Solis Rivera, V. & Thiele, T. (2024). Ocean Decade Vision 2030 White Papers – Challenge 4: Develop a Sustainable and Equitable Ocean Economy. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.4.). 1-29 pp.
Hiremath, A. M., A. K. Tilwankar and S. R. Asolekar (2015). "Significant steps in ship recycling vis-a-vis wastes generated in a cluster of yards in Alang: a case study." Journal of Cleaner Production **87**: 520-532.
Huang, W., S. Li, Y. Lu, R. Zhang and H. Wang (2023). "A new method for predicting the maximum wave height of ship-generated onshore slopes in restricted channel." Frontiers in Marine Science **10**.
Hörteborn, A. and I.-M. Hassellöv (2023). "Economic incentives and technological limitations govern environmental impact of LNG feeder vessels." Journal of Cleaner Production **429**: 139461.
ILO (2006). International Labour Organization. Maritime Labour Convention, 2006, as amended (MLC 2006). Entry into force: 20 Aug 2013.
IMO (2004). International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWMC). I. M. Organization. London**:** 1-43.
IMO (2006). MSC-MEPC.7/Circ.2 22 May 2006. Strengthening of human element input to the work of IMO.**:** 1 p.
IMO (2013a). Resolution A.1067(28) Framework and Procedures for the IMO Member State Audit Scheme. Assembly 33th session, Agenda item 9, adopted on 4 December 2013. Pp 1-45.

IMO (2013b). Resolution A.1070(28) IMO Instruments Implementation Code (III Code). Adopted on 4 December 2013. Pp 1-15.
IMO (2014). Implications of the United Nations Convention on the Law of the Sea for the International Maritime Organization. Study by the Secretariat of the International Maritime Organization (IMO). LEG/MISC.8, 30 January 2014. Pp 1-139. London, International Maritime Organization: 524.
IMO (2017). International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) including Manilla Amendments, 2017 Edition.
IMO (2020a). Fourth IMO GHG Study 2020. Full Report. London, International Maritime Organization: 524.
IMO. (2020b). "Sulphur 2020 – cutting sulphur oxide emissions." Retrieved October 30th, 2024, from http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx.
IMO. (2024a). "Improving the energy efficiency of ships. Accessed 1 October 2024.", from https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx.
IMO (2024b). International Convention for the Safety of Life at Sea (SOLAS) Consolidated edition 2024, International Maritime Organization.
IMO. (2024c). "International Maritime Organization. Media Centre. Hot Topics. Autonomous shipping." Retrieved November 18th 2024, from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx.
IMO. (2024d). "Member State Audit Scheme. Accessed 1 October 2024.", from https://www.imo.org/en/OurWork/MSAS/Pages/Default.aspx.
IMO (2024e). Resolution A.1185 (33) Procedures for Port State Control. Assembly 33th session, Agenda item 11 and 13, adopted on 6 December 2023.
IMO and WISTA (2021). Women in Maritime Survey 2021. A study of maritime companies and IMO Member States' maritime authorities. International Maritime Organization and Women's International Shipping and Trading Association.
Inal, O. B., J.-F. Charpentier and C. Deniz (2022). "Hybrid power and propulsion systems for ships: Current status and future challenges." Renewable and Sustainable Energy Reviews **156**: 111965.
IOC-UNESCO (2024). State of the Ocean Report. Paris, IOC-UNESCO. (IOC Technical Series, 190). 1-90 pp.
IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge, UK and New York, NY, USA.
ITF. (2024). "International Transport Workers' Federation. Flags of convenience. The scourge of maritime." Retrieved November 18th 2024, from https://www.itfglobal.org/en/sector/seafarers/flags-convenience.
Jalkanen, J. P., L. Johansson, M. Wilewska-Bien, L. Granhag, E. Ytreberg, K. M. Eriksson, D. Yngsell, I.-M. Hassellöv, K. Magnusson, U. Raudsepp, I. Maljutenko, H. Winnes and J. Moldanova (2021). "Modelling of discharges from Baltic Sea shipping." Ocean Science **17**(3): 699-728.

Jepsen, J. R., Z. Zhao, C. Pekcan, M. Barnett and W. M. A. van Leeuwen (2017). Risk Factors for Fatigue in Shipping, the Consequences for Seafarers' Health and Options for Preventive Intervention. Maritime Psychology: Research in Organizational & Health Behavior at Sea. M. MacLachlan. Cham, Springer International Publishing**:** 127-150.

Jones, N. (2019). "Ocean uproar: saving marine life from a barrage of noise." Nature **568**(7751): 158-161.

Jonglertmontree, W., O. Kaewboonchoo, I. Morioka and P. Boonyamalik (2022). "Mental health problems and their related factors among seafarers: a scoping review." BMC Public Health **22**(1): 282.

Jurdzinski, M. (2020). "The Need to Update the Navigation Curriculum as a Consequence of Adoption the e-Navigation Model." Transnav-International Journal on Marine Navigation and Safety of Sea Transportation **14**(3): 541-544.

Kanchiralla, F. M., S. Brynolf, E. Malmgren, J. Hansson and M. Grahn (2022). "Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping." Environmental Science & Technology **56**(17): 12517-12531.

Kanchiralla, F. M., S. Brynolf and A. Mjelde (2024). "Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations." Energy & Environmental Science **17**(17): 6393-6418.

Kitada, M. (2022). Gender and Work within the Maritime Sector. Women, Work and Transport. T. Wright, L. Budd and S. Ison, Emerald Publishing Limited. **16:** 229-248.

Koh, T. T. B. (1982). 'A Constitution for the Oceans', Statements by President Koh at the final session of the Conference at Montego Bay. Pp 1-5.

LC (2024). LC 45/15. Report of the forty-fifth consultative meeting of contracting parties to the London Conventions & eigtheenth meeting of contracting parties to the London Protocol. Agenda item 17. 2-6 October 2023., IMO**:** 79 pp.

Liu, M., Y. Li, H.-Z. Wang, H.-J. Wang, R.-T. Qiao and E. Jeppesen (2022). "Ecosystem complexity explains the scale-dependence of ammonia toxicity on macroinvertebrates." Water Research **226**: 119266.

Lokuketagoda, G., T. Miwa, S. Jayasinghe Arachchillage and S. Ranmuthugala (2023). Training engineers for remotely operated ships of the future, University of Tasmania.

Lunde Hermansson, A., I.-M. Hassellöv, T. Grönholm, J.-P. Jalkanen, E. Fridell, R. Parsmo, J. Hassellöv and E. Ytreberg (2024). "Strong economic incentives of ship scrubbers promoting pollution." Nature Sustainability.

Lunde Hermansson, A., I.-M. Hassellöv, J. Moldanová and E. Ytreberg (2021). "Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers." Transportation Research Part D: Transport and Environment **97**: 102912.

Mallam, S. C., S. Nazir and A. Sharma (2020). "The human element in future Maritime Operations – perceived impact of autonomous shipping." Ergonomics **63**(3): 334-345.

Marangoni, L. F. B., T. Davies, T. Smyth, A. Rodríguez, M. Hamann, C. Duarte, K. Pendoley, J. Berge, E. Maggi and O. Levy (2022). "Impacts of artificial light at night in marine ecosystems—A review." Global Change Biology **28**(18): 5346-5367.

Melia, N., K. Haines and E. Hawkins (2016). "Sea ice decline and 21st century trans-Arctic shipping routes." Geophysical Research Letters **43**(18): 9720-9728.

MEPC (2015). MEPC 68/21/Add.1 Annex 10, p 1-55. Resolution MEPC.264(68) (adopted on 15 May 2015) International code for ships operating in polar waters (Polar Code). IMO.
MEPC (2016). MEPC 70/18/Add.1 Annex 3, p 1-7. Resolution MEPC.278(70) (adopted on 28 October 2016) Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the protocol of 1978 relating thereto Amendments to MARPOL Annex VI (Data collection system for fuel oil consumption of ships), IMO.
MEPC (2018a). Resolution MEPC.300(72). Code for approval of Ballast Water Management Systems (BWMS Code). MEPC 72/17/Add.1 Annex 5. Adopted on 13 April 2018 Pp 1-39. , IMO.
MEPC (2018b). Resolution MEPC.305(73). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto Amendments to MARPOL Annex VI (Prohibition on the carriage of non-compliant fuel oil for combustion purposes for propulsion or operation on board a ship). Adopted on 26 October 2018. Pp 1-3. , IMO.
MEPC (2021a). 2021 GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES FOR CALCULATION AND VERIFICATION OF THE ATTAINED EEDI AND EEXI. International Maritime Organization. MEPC.1/Circ.896. **:** 31pp.
MEPC (2021b). Resolution MEPC.329(76). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto Amendments to MARPOL Annex I (Prohibition on the use and carriage for use as fuel of heavy fuel oil by ships in Arctic waters). Adopted on 17 June 2021 Pp 1-2. , IMO.
MEPC (2021c). Resolution MEPC.331(76). Amendments to the International Convention on the control of harmful anti-fouling systems on ships, 2001. Amendments to Annexes 1 and 4. (Controls on cybutryne and form of the International Anti-fouling System Certificate). Adopted on 17 June 2021 Pp 1-4. , IMO.
MEPC (2021d). Resolution MEPC.341(77). Strategy to address marine plastic litter from ships. Adopted on 26 November 2021 Pp 1-9. , IMO.
MEPC (2022a). MEPC 78/17/Add.1 Annex 8, p 1-34. Resolution MEPC.346(78) (adopted on 10 June 2022) 2022 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP), IMO.
MEPC (2022b). Resolution MEPC.359(79). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto Amendments to MARPOL Annexes I, II and IV (Regional reception facilities within Arctic waters and Form of IOPP Certificate and Supplements). Adopted on 16 December 2022 Pp 1-4. , IMO.
MEPC (2022c). Resolution MEPC.360(79). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto Amendments to MARPOL Annexes V (Regional reception facilities within Arctic waters and Garbage Record Book). Adopted on 16 December 2022 Pp 1-2. , IMO.
MEPC (2023a). MEPC 79/15. Report of the Marine Environment Protection Committe on its seventy-ninth session. Agenda item 15. 8 February 2023. Secretariat., IMO**:** 85 pp.

MEPC (2023b). MEPC 80/17/Add.1 Annex 15, p 1-17. Resolution MEPC.377(80) (adopted on 7 July 2023) 2023 IMO strategy on reduction of GHG emissions from ships, IMO.
MEPC (2023c). MEPC.1/Circ.906. Revised Guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts of marine life. 22 August 2023. Pp 1-21., IMO: 21 pp.
MEPC (2023d). Resolution MEPC.377(80). 2023 IMO Strategy of reduction of GHG emissions from ships. MEPC 80/WP.12. Annex 1. Adopted on 7 July 2023 Pp 1-17. , IMO.
MEPC (2023e). Resolution MEPC.378(80). 2023 Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species. MEPC 80/17/Add.1 Annex 17. Adopted on 7 July 2023 Pp 1-62. , IMO.
MEPC (2024a). MEPC 81/16. Report of the Marine Environment Protection Committe on its eigthy-firsth session. Agenda item 16. 8 April 2024. Secretariat., IMO: 82 pp.
MEPC (2024b). MEPC 82/7/4 Reduction of GHG emissions from ships. Report of the Steering Committee on the comprehensive impact assessment of the basket of candidate GHG reduction mid-term measures (including the outcome of the tenth and eleventh meetings) Note by the Secretariat., IMO.
MEPC (2024c). MEPC 82/17. Report of the Marine Environment Protection Committe on its eigthy-second session. Agenda item 17. 4 October 2024. Secretariat., IMO: 85 pp.
MEPC (2024d). MEPC.1/Circ.909. Recommendations for the carriage of plastic pellets by sea in freight containers. 19 April 2024. 1p., IMO: 82 pp.
MEPC (2024e). Resolution MEPC.391(81). 2024 Guidelines on Life Cycle GHG intensity of marine fuels (2024 LCA Guidelines) MEPC 81/16/Add.1 Annex 10. Adopted on 22 March 2024 Pp 1-67. , IMO.
Merkel, F. R. and K. L. Johansen (2011). "Light-induced bird strikes on vessels in Southwest Greenland." Marine Pollution Bulletin **62**(11): 2330-2336.
Miloslavich, P., O'Callaghan, J., Heslop, E., McConnell, T., Heupel, M., Satterthwaite, E., Lorenzoni, L., Schloss, I., Belbeoch, M., Rome, N., Widdicombe, S., Olalekan Elegbede, I. & Fontela, M. (2024). Ocean Decade Vision 2030 White Papers – Challenge 7: Sustainably Expand the Global Ocean Observing System. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.7.). 1-26 pp.
Nylund, A. T., I.-M. Hassellöv, A. Tengberg, R. Bensow, G. Broström, M. Hassellöv and L. Arneborg (2023). "Hydrographical implications of ship-induced turbulence in stratified waters, studied through field observations and CFD modelling." Frontiers in Marine Science **10**(1273616): 1-20.
Nylund, A. T., J. Mellqvist, V. Conde, K. Salo, R. Bensow, L. Arneborg, J.-P. Jalkanen, A. Tengberg and I.-M. Hassellöv (2025). "Coastal methane emissions triggered by ship passages." Communications Earth & Environment **6**(1): 380.
OCIMF. (2021). "Oil Companies International Marine Forum. SIRE 2.0 Human Factors Update. Enhanced Human Factors Focus Through SIRE 2.0." Retrieved November 18th 2024, from https://www.ocimf.org/news-and-events/news/bulletins/sire-2-0-human-factors-update.
OCIMF. (2024). "Oil Companies International Marine Forum. Ship Inspection Report Programme (SIRE) 2.0. Launched Sept 2nd 2024.", from https://www.ocimf.org/programmes/sire-2-0.
OECD (2016). The Ocean Economy in 2030.
Oldenburg, M., X. Baur and C. Schlaich (2010). "Occupational Risks and Challenges of Seafaring." Journal of Occupational Health **52**(5): 249-256.

Pan, P., Y. Sun, C. Yuan, X. Yan and X. Tang (2021). "Research progress on ship power systems integrated with new energy sources: A review." Renewable and Sustainable Energy Reviews **144**: 111048.
Ponkratov, D. (2017). "Proceedings: 2016 Workshop on Ship Scale Hydrodynamic Computer Simulations." Lloyd's Register, Southampton, United Kingdom.
Rahman, S. M. M. and J. Kim (2020). "Circular economy, proximity, and shipbreaking: A material flow and environmental impact analysis." Journal of Cleaner Production **259**: 120681.
Rako-Gospić, N. and M. Picciulin (2019). Chapter 20 - Underwater Noise: Sources and Effects on Marine Life. World Seas: An Environmental Evaluation (Second Edition). C. Sheppard, Academic Press**:** 367-389.
Raudsepp, U., I. Maljutenko, M. Kouts, L. Granhag, M. Wilewska-Bien, I.-M. Hassellöv, K. M. Eriksson, L. Johansson, J.-P. Jalkanen, M. Karl, V. Matthias and J. Moldanova (2019). "Shipborne nutrient dynamics and impact on the eutrophication in the Baltic Sea." Science of the Total Environment **671**: 189-207.
Roux, M., C. Lodato, A. Laurent and T. F. Astrup (2024). "A review of life cycle assessment studies of maritime fuels: Critical insights, gaps, and recommendations." Sustainable Production and Consumption **50**: 69-86.
Sabine, C., Robinson, C., Isensee, K., Bastian, L., Batten, S., Bellerby, R., Blasiak., R., Laarissa, S., Lira Loarca, A., McGeachy, C., McKinley, G., Melbourne Thomas, J., Ortega Cisneros, K., Qiao, F., Samanta, D., Sanders, R. & Sarma, V. V. S. S. (2024). Ocean Decade Vision 2030 White Papers – Challenge 5: Unlock Ocean-Based Solutions to Climate Change. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.5.). 1-28 pp.
Sardain, A., E. Sardain and B. Leung (2019). "Global forecasts of shipping traffic and biological invasions to 2050." Nature Sustainability **2**(4): 274-282.
Sayinli, B., Y. Dong, Y. Park, A. Bhatnagar and M. Sillanpää (2022). "Recent progress and challenges facing ballast water treatment – A review." Chemosphere **291**: 132776.
Schøyen, H. and S. Bråthen (2011). "The Northern Sea Route versus the Suez Canal: cases from bulk shipping." Journal of Transport Geography **19**(4): 977-983.
Shu, Y., X. Wang, Z. Huang, L. Song, Z. Fei, L. Gan, Y. Xu and J. Yin (2022). "Estimating spatiotemporal distribution of wastewater generated by ships in coastal areas." Ocean & Coastal Management **222**: 106133.
Singh, N., J. Finnegan and K. Levin (2016). MRV 101: Understanding Measurement, Reporting, and Verification of Climate Change Mitigation. Working Paper. Washington DC: World Resources Institute.
Slišković, A. M. and Z. Penezić (2015). "Occupational stressors, risks and health in the seafaring population." Annual Review of Psychology **22**: 29-40.
Smith, L. C. and S. R. Stephenson (2013). "New Trans-Arctic shipping routes navigable by midcentury." Proceedings of the National Academy of Sciences of the United States of America **110**(13): E1191-E1195.
Sofiev, M., J. J. Winebrake, L. Johansson, E. W. Carr, M. Prank, J. Soares, J. Vira, R. Kouznetsov, J.-P. Jalkanen and J. J. Corbett (2018). "Cleaner fuels for ships provide public health benefits with climate tradeoffs." Nature Communications **9**(1): 406.
Terziev, M., T. Tezdogan and A. Incecik (2022). "Scale effects and full-scale ship hydrodynamics: A review." Ocean Engineering **245**: 110496.

Theocharis, D., S. Pettit, V. S. Rodrigues and J. Haider (2018). "Arctic shipping: A systematic literature review of comparative studies." Journal of Transport Geography **69**: 112-128.
Toygar, A., S. Nart and U. Yıldırım (2023). "Work-family conflict and work alienation among seafarers: The mediating role of emotional exhaustion." Marine Policy **155**: 105759.
UNCTAD (2023). Review of Maritime Transport 2023. Towards a green and just transition. UNCTAD/RMT/2023. New York, United Nations Publications**:** 157pp.
UNCTAD (2024). Review of Maritime Transport 2023. Navigating maritime chokepoints. UNCTAD/RMT/2024. New York, United Nations Publications**:** 166 pp.
United Nations (2023). 10. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. In: Chapter XXI Law of the Sea. Adopted 19 June 2023, New York. Pp1-4.
Ventikos, N. P., A. D. Papanikolaou, K. Louzis and A. Koimtzoglou (2018). "Statistical analysis and critical review of navigational accidents in adverse weather conditions." Ocean Engineering **163**: 502-517.
Wang, D., D. Wu, C. Huang and C. Wu (2020). "Marine Autonomous Surface Ship - A Great Challenge to Maritime Education and Training." American Journal of Water Science and Engineering **6**(1): 10-16.
Wilewska-Bien, M., L. Granhag and K. Andersson (2016). "The nutrient load from food waste generated onboard ships in the Baltic Sea." Marine Pollution Bulletin **105**(1): 359-366.
Winebrake, J. J. and J. J. Corbett (2010). Improving the Energy Efficiency and Environmental Performance of Goods Movement. Climate and Transportation Solutions: Findings from the 2009 Asilomar Conference on Transportation and Energy Policy. D. Sperling and J. S. Cannon, Institute of Transportation StudiesUniversity of California, Davis**:** 145-154.
Winebrake, J. J., J. J. Corbett, E. H. Green, A. Lauer and V. Eyring (2009). "Mitigating the Health Impacts of Pollution from Oceangoing Shipping: An Assessment of Low-Sulfur Fuel Mandates." Environmental Science & Technology **43**(13): 4776-4782.
Winebrake, J. J., J. J. Corbett, F. Umar and D. Yuska (2019). "Pollution Tradeoffs for Conventional and Natural Gas-Based Marine Fuels." Sustainability **11**(8): 2235.
WMU (2019). Conference report: Third WMU international women's conference on empowering women in the maritime community. World Maritime University.
Ytreberg, E., K. Hansson, A. L. Hermansson, R. Parsmo, M. Lagerström, J.-P. Jalkanen and I.-M. Hassellöv (2022). "Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea." Marine Pollution Bulletin **182**: 113904.
Yuan, S., Y. Li, F. Bao, H. Xu, Y. Yang, Q. Yan, S. Zhong, H. Yin, J. Xu, Z. Huang and J. Lin (2023). "Marine environmental monitoring with unmanned vehicle platforms: Present applications and future prospects." Science of The Total Environment **858**: 159741.
Yuan, T., H. Song, L. Oreopoulos, R. Wood, H. Bian, K. Breen, M. Chin, H. Yu, D. Barahona, K. Meyer and S. Platnick (2024). "Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming." Communications Earth & Environment **5**(1): 281.
Zhang, T.-X., M.-R. Li, C. Liu, S.-P. Wang and Z.-G. Yan (2023). "A review of the toxic effects of ammonia on invertebrates in aquatic environments." Environmental Pollution **336**: 122374.
Zhou, Q., Z. Du, J. Liu, J. Liang and Y. Jiao (2021). "Factors influencing green ship recycling: A conceptual framework and modeling." Journal of Cleaner Production **322**: 129155.

Österman, C. and M. Boström (2022). "Workplace bullying and harassment at sea: A structured literature review." Marine Policy **136**: 104910.

Section 5A
Chapter 7: Mineral resources

Key findings

- **Pressures**

  Exploration and exploitation of marine mineral resources have occurred in maritime areas within national jurisdiction, driven by demand. Deep-sea mineral exploration has occurred both within and beyond national jurisdiction, but commercial exploitation has yet to begin. Marine mining technologies are evolving rapidly due to growing commercial interest in metal extraction, driven by the global energy transition towards net-zero emissions.

- **Impacts**

  Environmental impact assessments for commercial and project-specific mineral extraction have been conducted for offshore diamonds, phosphorites and a polymetallic sulfide deposit but only limited studies have been conducted for polymetallic nodules or ferromanganese crusts. Environmental impact assessments are closely linked to the design and *modus operandi* of evolving mining technologies and the scientific and technical standards and practices adopted by States, in areas within national jurisdiction and the international community as a whole in areas beyond national jurisdiction.

- **Socio-economic considerations**

  Depending on their economic feasibility, marine mineral resources have the potential to provide a complementary source to mineral resources extracted from land. The combination of marine and land mineral resources has the potential to have an impact on their international market value and their respective environments. There are international legal and economic rights and obligations to States relating to technology transfer and cooperation, and revenue distribution arising from marine mineral resources exploitation in areas beyond national jurisdiction under the United Nations Convention on the Law of the Sea.

- **Governance and sustainability**

  Governance for maritime areas within and beyond national jurisdiction comprise of different legal regimes and different scientific and technical standards and practices, which pose the need for international agreement and consensus. Sustainable exploration and potential exploitation of marine mineral resources depend on scientific and technological innovation, stakeholder participation, environmental management and monitoring, and reliable data to effectively assess social, economic and environmental impacts.

7.1: Introduction

This chapter on mineral resources highlights further developments to chapter 23 of the first World Ocean Assessment [1] with respect to offshore mining industries, and chapter 18 of the second World Ocean Assessment [2] in relation to changes in seabed mining. It provides updates for the distribution of mineral resources and their projected demands. It examines environmental and technological issues relating to ocean mineral exploration and exploitation. It continues with sections relating to sustainable development including socio-

economic aspects and concludes with a final section on governance in the Area and marine regions under areas within national jurisdiction.

The need for a comprehensive international legal framework for the oceans arose from the desire to ensure marine mineral resources for the benefit of all humanity. The latter concept goes back to 1 November 1967, when the Maltese ambassador Arvid Pardo delivered a speech at the General Assembly of the United Nations, in which he proposed that the seabed and subsoil outside national jurisdictions could be considered as *res communis omnium* and the "common heritage of humankind". His speech was reflected on UNGA Resolution 2340 of 18 December 1967, establishing an *Ad Hoc* Committee to Study the Peaceful Uses of the Sea-Bed and the Ocean Floor beyond the Limits of National Jurisdiction and, at a later stage, would be incorporated in UNGA Resolution 2749/1970, the Declaration of Principles Governing the Sea-Bed and the Ocean Floor, and the Subsoil Thereof, beyond the Limits of National Jurisdiction.

With the subsequent resolution 2750/1970, the General Assembly convened the Third United Nations Conference on the Law of the Sea, which took place from 1973 to 1982. The United Nations Convention on the Law of the Sea (UNCLOS) was opened for signature at Montego Bay, Jamaica, on 10 December 1982. It entered into force on 14 November 1994 and is presently in force for 170 parties. UNCLOS and the Agreement relating to the Implementing agreement of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, adopted on 28 July 1994, establish the international legal framework for the rights and responsibilities of States for, among many others, the exploration and exploitation of ocean mineral resources within and beyond regions under national jurisdiction.

The International Seabed Authority (ISA) has already developed regulations for the exploration of polymetallic nodules, polymetallic sulphides, and cobalt-rich ferromanganese crusts. These three international regulations may become useful starting points for the discussion and design of national regulations for area-based management tools, such as Regional Environmental Management Plans (REMPs) and Reserved Areas, which may become integral components of international and national ocean management programmes [3].

7.2: Current Status and Pressures

This section will review the current status of mineral exploration and the pressures and impacts posed by past, present and future demand for world minerals highlighting rising demands and market trends towards net-zero emission goals.

Sand and Gravel

Sand and gravel resources are essential to produce building materials like concrete, as well as for beach nourishment and coastal land reclamation. By volume, these resources are the most extracted marine mineral resource. Annually, between 4 billion and 8 billion tonnes of marine sand and sediments are dredged or mined [1], and their associated environmental impacts, such as increasing erosion, potential reduced protection from storm surges and other extreme events, and damaging habitats for microorganisms that are the basis of marine food webs, have also been analysed [2].

Dredging for marine sand and gravel is conducted on most coastlines around the world, with the exception of a few regions such as Antarctica and much of the west coast of South America. Production rates in some States, such as China, the Netherlands, United Kingdom, and the United States, have remained relatively stable, while States such as India, Indonesia, the Philippines, and United Arab Emirates, saw growth in production over the period from 2012 to 2022. A few countries, such as Argentina, Brazil, Japan and Saudi Arabia, have reportedly reduced their production [3] [4].

Alluvial and placer deposits

Alluvial deposits commonly contain tin, iron minerals, gold, and diamonds. A description of chromite, garnet, platinum and other platinum-group minerals (PGMs) and amber is provided in [5]. An overview of placer deposits, formed by the concentration by gravity of heavy detrital minerals transported by rivers or ocean currents, is provided in [6]. Tin is a critical mineral used in industrial alloying applications such as in bronze and solder. Alluvial tin deposits is best known to be found in Indonesia, but also known in Malaysia, Myanmar and Thailand [7]. A global review of tin resources and reserves by the International Tin Institute shows that the majority of Indonesia's tin reserves, representing nearly 7% of globally reported mining inventory, are located offshore [8].

The potential for iron deposits occur in several marine regions, such as the Black Sea, as well as the coasts of Fiji, Indonesia, Japan, , New Zealand and Philippines. Titanomagnetite iron sand deposits on the west coast of the North Island, New Zealand, are some of the world's largest deposits. Among them, the Taranaki iron sands deposit contains an estimated 3.2 billion tonnes of vanadium-rich titanomagnetite iron sand resource, making it one of the largest known vanadium deposits globally

Marine deposits of alluvial gold are known to occur wherever rivers carrying gold grainsenter the sea. The historical deposit of Nome, Alaska, United States, is being currently exploited alongside their associated riverine alluvial deposits [9]. Other notable examples include the historically mined beach and likely offshore placer deposits in Tierra del Fuego [10].

The best-known marine diamond deposits are located offshore Namibia and South Africa, where operations started in the 1960s and were consolidated as Debmarine in 2002. South

Africa issued its first marine diamond mining concessions in 1994 and has since continued licensing with active miners, such as De Beers, along with Alexkor Ltd, Transhex, Bluewater Diamonds, Nautical Diamonds, and Poseidon Marine. Production steadily increased until at least 2019 using vessels ranging from artisanal, where divers use handheld suction hoses, to large factory vessels [11] [12].

Mineral Precipitate Deposits

Precipitates in this review include polymetallic nodules, ferromanganese crusts, and phosphorites.

Polymetallic nodules contain various metals, with their composition varying in different marine environments. Manganese and iron are the most abundant, while nickel, copper, cobalt, molybdenum, titanium and the rare earth elements can also be present in significant amounts. These metals are used in a wide range of industrial applications, ranging from steel alloys to battery formulations to medical applications.

Recent developments have been primarily focused on three regions of the Area: the Clarion-Clipperton Zone, the Central Indian Ocean Basin and the Northwest Pacific basin [13], and three areas within national jurisdiction: the Cook Islands and Japan (Minamitorishima), both in water depths over 4,000 m; and in relatively shallow depths (~ 20-120 m) the Gulf of Bothnia (Sweden and Finland). The first integrated test mining exercise since the late 1970s was conducted by The Metals Company and their partner Allseas in late 2022 in the Clarion-Clipperton Zone [14].

Ferromanganese crusts contain broadly the same metals as polymetallic nodules but can have high concentrations of metals like cobalt and platinum group elements. Hydrogenetic crusts on seamounts are the best known [15], but crusts can also form on sediments and diagenetically [16]. Crusts are known from the Area: Northwestern Pacific and Rio Grande Rise [17] as well as from areas within national jurisdiction, such as those of the Cook Islands, Japan (Minamitorishima) and Norway [18]. Both China and Japan have recently developed seabed drilling systems to prospect for mineral resources and to perform mining tests within and beyond their respective national jurisdictions. [19] [20] [21].

Marine phosphorite sediments contain potentially economic levels of phosphate, which is used mostly in fertilizer and other chemical applications. The largest terrestrial deposits of phosphate are fossil uplifted marine deposits [22]. While global demand and production of phosphates are increasing, so are moves to be more efficient with the material (e.g. [23]), with reduction in growth rates [24].

The three currently most advanced projects towards exploitation are within the national jurisdictions of Mexico, Namibia, and New Zealand [25]. While all three are interpreted to

have formed from authigenic processes, they vary in water depth (from tens to hundreds of meters of water depth), grain size (from sand to gravels) and resource size (from tens to hundreds of millions of tonnes). In all three projects, the phosphorites are planned to be recovered by a trailing suction hopper dredge and enriched by onboard size screening (e.g., [26]. These three projects stalled at the stage of environmental impact assessment and permit approval [27] [28] [29]. The respective developers are currently exploring alternative options to advance their projects [30] [31] [32].

Hydrothermal deposits

Volcanogenic polymetallic sulfides deposits are formed from the precipitation of sulfide minerals from metals dissolved in hot water that circulates through rocks. These types of deposits are known to occur throughout the geological record [33] with offshore deposits mostly known from active tectonic settings associated with spreading centers and volcanic arcs [34] both within and beyond national jurisdiction. The metal content varies and may include including copper, gold, zinc, lead, and others. Active hydrothermal systems can be important 'hotspots' for marine life and food webs supported by chemosynthetic microbes [35].

Recent developments on the exploration of these deposits include drilling and the development of new mining technologies [36] tested in-situ, notably in Japan and Papua New Guinea [37] [38]. Norway is preparing to issue mining licenses for sulfides and manganese crusts in areas within its national jurisdiction in the first half of 2025, with a view to starting commercial exploitation in 2030.

Sediment-hosted brines were discovered in the 1960s. The zinc-rich Atlantis II, Discovery, Valdivia and Wando deposits in the Red Sea and along the border between Sudan and Saudi Arabia are the largest known marine hydrothermal ore deposits and the only known modern analog of brine pool-type metal deposition [39] [40].

Biogenic deposits

We include rare earth element (REE) deposits but exclude natural gas hydrates.

Rare earth elements (plus scandium and yttrium) are used in a wide range of applications including electronics. REE rich clays are found in different parts of the Pacific [41] [42] [43]. These metals are found in both ferromanganese precipitates and, more significantly, biogenic fluro-apatite. In addition to deposits found in the Area, REE-rich muds have been identified in areas within the national jurisdiction of the Cook Islands and Japan.

The Japan Agency for Marine-Earth Science and Technology completed, in 2017, the pilot test mining programme as part of their 2nd Strategic Innovation Promotion Program [44]. A characteristic of the 'red' REE-rich clay-ooze found in both Japan (Minamitorishima) and the

Cook Islands is that it can be very sticky. JAMSTEC's pilot involved a suspended core and fluidising (or cracking) cutter system, which in theory can penetrate up to 4 meters into the seabed.

Past demand for minerals

The period from 1900 to 1929 was considered a high-demand growth era. The driver of this period was the rapid urbanization of the United States and Western Europe. The initial impetus came from farm mechanization, which created a push-and-pull mechanism. The period from 1929 to 1938, however, was a low-demand growth era. The period was the decade the United States and Western Europe were in the grip of the Great Depression. The period from 1950 to 1975 experienced a return to high demand growth with the years of the postwar boom. The period from 1975 to 2000 was a weaker demand growth era after the postwar boom, and it came to an end by the mid-1970s amid widespread industrial strife and persistent inflation. Thereafter an emerging economies metals demand boom, led by China mining started in the late 1990s to 2000s.[55]

Rising demands for minerals

According to the Global Resources Outlook 2019, metals extraction has increased 3.5 times between 1970-2017.[56] Global domestic extraction of metal ores is projected to grow at a yearly average of 1.7% from 2015 to 2060. It is also projected that 9% of total global resources extraction will be for metal ores in 2060.

Depending on their economic feasibility, deep-seabed minerals could play a role in securing a sustainable supply of metals.[57] Mineral deposits on the seabed tend to contain higher metal contents than those on land.[58] World demand for minerals may be difficutl to be predicted but it will be certainly influenced by three general factors: (i) increasing uses of mineral commodities; (ii) demographic increases; and (iii) economic growth.

Under certain scenarios, variations in economic growth might affect future mineral demand more than demographic increases alone. Per capita consumption of a high number of minerals has increased globally during the last decade, and the biggest differences and changes were related to economic growth.[59]

---

[55] https://www.i2massociates.com/downloads/segn-136-2.pdf

[56] https://www.resourcepanel.org/reports/global-resources-outlook; by International Resources Panel of UNEP

[57] Deep Sea Mining Could Unlock Access to More Critical Minerals (etftrends.com)

[58] Seabed mining is coming — bringing mineral riches and fears of epic extinctions (nature.com)

[59] https://pubs.usgs.gov/circ/2007/1294/circ1294.pdf#page=62

Future scenarios for mineral demand in support of the green energy transition project, including critical minerals[60] will be very high up in 2040 or 2050. Due to this predicted increase in demand, potential risks of imminent supply/demand imbalances are possible. For instance, copper is required for all power generation and transport technologies. Lithium, cobalt and graphite have been used for electric car batteries, as is nickel, which is also used in a number of power generation technologies. Rare earth minerals are needed for offshore wind turbines. Nickel and platinum group metals (PGMs) are important for hydrogen production, and Rare Earth Elements (REEs) play a role in hydrogen, as well as in wind turbines and batteries. Aluminium also plays an important role across a wide range of green technologies.[61]

Market trends

A World Bank report on minerals for climate action in 2020 found that production of metals could increase by nearly 500% by 2050.[62] The global potential market for deep-sea mining driven by the demand for critical minerals is projected to expand from USD 650 million in 2020 to USD 15.3 billion by 2030.[63]

Global mine production of Rare Earth Elements essential for manufacturing technological products is estimated to have increased to 350,000 tons of REO equivalent.[64] This production will have a transversal impact on the economy's primary, secondary, and tertiary sectors.[65]

China's Ministry of Industry and Information Technology raised 2023 quotas for rare-earth mining and separation to 240,000 tons and 230,000 tons of REO equivalent, respectively. In

[60] https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

[61] https://www.unep.org/resources/Global-Resource-Outlook-2024 in page 5: The World Bank (Hund et al. 2020), the UN International Resource Panel (IRP, 2020a), the European Commission (Moss et al. 2013; Bobba et al.2020), the International Energy Agency (IEA 2021IEA 2022 a, b and c), the International renewable Energy Agency (Gielen 2021), the German Raw Materials Agency (Marscheider-Weidemann et al. 2021), the Finnish Geological Survey (Michaux 2021) and various academics, including Grandell (2016); Watari et al. (2018), Elshkaki and Shen (2019), Moreau et al. (2019), Habib et al. (2020), Heijilen et al. (2021), Watari et al. (2021) and Christmann et al. (2022)

[62] https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf

[63] Deep Sea Mining Market should grow to US$15.3 billion by 2030: TMR Study | Global Mining Review

[64] Rare-Earth-Oxide

[65] https://www.mdpi.com/2073-445X/13/8/1220

2023, mine production quotas of rare earth were allocated to 220,850 tons of light rare earths and 19,150 tons of ion-adsorption clays [66].

Towards net-zero emission

The World Energy Outlook 2022 found that mineral requirements for green energy technologies will quadruple by 2030 in the net-zero emission scenario, with particularly high growth for materials for electric vehicles.[67] The required types of mineral resources vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance. Rare Earth Elements are essential for permanent magnets in wind turbines and EV motors. Electricity networks require large amounts of copper and aluminium, with copper being a cornerstone for all electricity-related technologies.

According to the World Energy Outlook Special Report on the Role of Critical Minerals in Clean Energy Transitions revised in 2022, the demand for critical metals collectively is expected to increase almost 20-fold between 2020 and 2050, from less than 10 million tonnes to roughly 150 million tonnes meet the demand of growing low-carbon energy technology under the net-zero emission scenario.[68] Critical minerals and metals required for battery storage are anticipated to see a nearly 40-fold increase, while those required for low-carbon electric power generation are expected to triple. The total market size of critical minerals and metals like copper, cobalt, manganese and various rare earth metals will grow almost sevenfold between 2020 and 2030 in the net zero pathway. One of the most recent assessments for critical minerals involves scenario forecasts for recycling[69] and in some cases growth in primary demand for critical minerals may stabilise or even drop by 2035, although total required inventory will continue to grow into next few decades.

The global infrastructure financing gap is estimated to be around USD 15 trillion by 2040. To provide basic infrastructure for all people over the course of the next two decades, every year the world would need to spend just under USD 1 trillion more than the previous year in the infrastructure sector. The Global Material Resources Outlook by OECD estimates that the biggest increase in resource consumption by 2060 will be in minerals, especially construction materials and metals, particularly in fast-growing economies.[70] According to

[66] https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-rare-earths.pdf

[67] https://www.iea.org/reports/world-energy-outlook-2022

[68] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[69] https://www.iea.org/reports/recycling-of-critical-minerals

[70] https://www.oecd.org/publications/global-material-resources-outlook-to-2060-9789264307452-en.htm

the National Mining Association, the US Department of Defense (DoD) alone uses nearly 750,000 tons of minerals each year.[71]

7.3: Impacts

This section will review potential environmental impacts and technological developments relating to the exploration for and the exploitation of ocean mineral resources and describe the need to achieve a balance among them. This is crucial in order to ensure that if and when exploration and/or exploitation may take place, the social and economic needs of present and future human generations are addressed.

Environmental Issues

The question of whether environmental impacts from proposed deep-sea mineral extraction would be acceptable is still largely unanswered for many seabed mineral types today. Environmental impact assessments (EIA) for the exploitation of marine mineral resources at a commercial scale have only been carried out for offshore diamonds [1], phosphorites [2] and a single polymetallic sulfide deposit, e.g. Solwara 1 [3]. No EIAs have been completed for polymetallic nodules or ferromanganese crusts. Limited environmental impact assessments have been completed to to support pilot testing of nodule mining equipment [4], [5], [6].

Good practice EIAs are structured [7], [8]. They usually start with a scoping exercise, move to a baseline data collection and compilation stage, and then to the project EIA used to justify a permit (or exploitation contract with ISA for example). Environmental impact statements (EIS) might be required for exploration and pilot mining tests before the project EIA is carried out. A project EIA or EIS will usually include a description of the types and scope of activities contemplated , an environmental risk assessment for those activities (usually done according to a framework such as DPSIR (Drivers Pressures State Impact Response) [9], [10]), and the incorporation of peer and public review stages.

It is important to note that a prefeasibility or feasibility study is normally needed for a detailed description of activities (see sub-section below). This would then need to be aligned with the EIA.

The EIA is usually part of a broader framework called an Ecosystem Based Management Framework (EBMF) e.g. UN Environment Program [11]. This widely recognized practice integrates various environmental programmes to assess risk, organise knowledge, inform

[71] https://nma.org/2017/02/03/minerals-and-metals-help-improve-our-national-security/

stakeholders, direct monitoring requirements and activities, and ultimately maintain a healthy ecosystem. In addition to the EIA process, other parts of an EBMF may include:

- Regulatory regime (including overarching principles and more detailed requirements and recommendations within standards and guidelines, e.g. ISA Mining Code [12]);
- Baseline datasets (from marine scientific researchers and other developers);
- Related cases from other developers and mining tests;
- Regional assessments such as strategic environmental assessments [13] and regional environmental management plans [14], including consideration of cumulative impacts [15].
- Stakeholder engagement aspects, including independent review by subject matter experts and public involvement.

The current state of knowledge for seabed minerals districts and projects is considered within the EBMF. For example, contributions to understanding the baseline and possible environmental impacts may start out broad and generic in nature and more rapidly focus as particular projects get closer to being ready for a permit application. Through constructive dialog with stakeholders issues are addressed and flaws can be recognized at an early stage.

Currently there is considerable focus on possible exploitation of polymetallic nodules in the Area , where there are several advanced projects undergoing EIA [15B]. A key issue is that regulations for exploitation have not yet been finalized by the regulator, the International Seabed Authority (ISA). In addition to regulations, important work is still needed to inform supporting standards and guidelines. Some of the current initiatives include [16]:

- As part of an action plan for marine scientific research methodological work for biodiversity assessment
- Development of environmental threshold values (including related to generated plumes and noise);
- Interactions between fishing and mineral resources related activities;
- Biogeochemical modelling to better understand carbon storage and release in the deep sea [17];
- Internalization of environmental costs;
- ISA has constituted an Intersessional Expert Group (IEG) on the development of binding environmental thresholds on (1) toxicity, (2) turbidity and settling of re-suspended sediments and (3) underwater noise and light pollution.

Technological Issues

Any sustained development of seabed minerals depends on cost effective technologies. Particular risks relate to points where novel technology is used.

In theory, technology development (e.g. [18]) can be done independently from project development (e.g. [19]), but in practice the two are often intertwined. Scoping studies and subsequent pre-feasibility studies usually consider alternative technological options, which may be at different levels of technology readiness (TRL). Seabed minerals are planned to be processed on land and where the same issues exist [20].

Significant efforts in exploration and mining tests have already taken place in the previous century, although interests died down after the 1970s [21]. Recently, the interest for extraction of polymetallic nodules has rekindled. The United Nations and, later, ISA has organized technology-focused workshops approximately once every decade since the 1970s [22], [23], [24]. After issuing preliminary economic assessments in 2015 [25] and 2019 [26], Nauru Offshore Minerals Inc and its parent “The Metals Company” plan to issue prefeasibility studies in 2025 for both mining and metallurgical processing [27], [28].

The entire value chain, spanning from seabed to product sales, requires some level of development. Additional effort focussed on reducing environmental impacts, including refinement of available technology[29], [30] and development of new ones e.g. [31]. Some other areas of technological development include:

- Environmental monitoring systems [32], [33]
- Adaptation of existing ships [34]
- Alternative lift system development [29]
- Alternative nodule collection techniques [35], [36]
- “Ship-to-shore" programs including class and safety considerations [37] and the forthcoming ship to shore joint industry programme
- Metallurgical programmes [28]

Technological developments are continuing for other types of deep-sea minerals also. A few examples include:

- One focus of seafloor massive sulfide mining technology development is to reduce environmental impacts including plumes [38]
- Ferromanganese crusts are difficult to cut consistently and at sufficient production ratesgiven variable crust thickness [39], [40]
- REE rich muds are sticky and difficult to liquefy for lifting [41]

Apart from the technological issues related to the start of production, longer term consideration needs to be given to the scale of production. Future possible economies of scale are ideally factored into seabed minerals exploitation permits. These production rates should also be considered in both environmental impact assessments and cumulative

impact assessments. In shallow marine industries, there are examples of progressive increases in scales of operations, such as De Beers marine diamonds operations [42] as well as flatter production profiles such as PT Timah tin e.g. [43].

7.4: Socio-economic considerations

WOA II provided an overview of the economic landscape for seabed mining and social impacts. It is important to note, however, that only exploration activities are taking place at present in areas beyond national jurisdiction. The decision on whether seabed mining may proceed to the exploitation phase rests with Member States of UNCLOS. This section provides an update to the information provided in WOA II.

UNCLOS designates the Area and its resources as the "common heritage of humankind".[72] This principle asserts that any activity in the Area should be for the benefit of all countries, with a focus on equitable sharing, particularly for developing nations.[73] ISA has the mandate to regulate activities in the Area and to ensure that resource exploitation is carried out fairly, promote international cooperation and ensure environmental protection, this implies that economic considerations are an integral part of the negotiation on the exploitation regulations.

In 2015, the Council adopted seven priority deliverables for the development of the exploitation code. The second priority entailed the development of a payment mechanism for exploitation activities, following detailed financial and economic modeling based on proposed business plans. During the next two years, different workshops have been organised to develop a payment system, until in 2018, when the ISA Secretariat commissioned the Massachusetts Institute of Technology (MIT) to develop an economic model for the exploitation of polymetallic nodules, that could be used to model different payment systems & royalties. [74] Results were compared by MIT with three other models received from China, Germany and the African Group. In 2019, the Council agreed to set up an open-ended working group (OEWG) to discuss the financial model and in particular to review the comparative study. In 2020, the ISA Secretariat commissioned two consultants to look into comparable systems on land.[75] In 2022 some member States suggested that the cost associated with environmental externalities should be internalised in the model. In 2023, two studies on the evaluation of natural capital were completed, which are expected

[72] UNCLOS, Art. 136.

[73] UNCLOS, Art. 140 "Activities in the Area shall…be carried out for the benefit of mankind as a whole".

[74] Mine-Site-Cash-Flows_Mn_ore_March5_2023.xlsm (live.com)

[75] Joint-summary-FInalDraft-20201012.pdf

to inform further policy discussions.[76,77] Between 2019 and 2024, the OEWG met on ten different times.

Several financial mechanisms govern how contractors contribute to the economic benefits derived from activities in the Area. While the contractor payment regime is the overall financial structure determining how contractors compensate the international community for extracting resources from the Area, there are other non-monetary benefits to humankind. One specific type of payment within the contractor payment regime consists of royalty payments paid to ISA for the rights to exploit nodules. Various ad valorem royalty fee structures including a fixed, variable and staged, are currently under negotiations percentage.[78] Once commercial mining begins in the Area, the administrative costs of ISA, now covered by ISA member State contributions, will be financed by the revenue generated from royalties. Another portion will flow to support the establishment of an Economic Assistance Fund.[79] This fund will assist developing countries when their economies are adversely impacted by deep-sea bed mining for example a reduction in the mineral price or a decrease of their volume of export. Another portion of the revenue generated from the royalties will flow to towards an environmental compensation fund which is intended to fill any liability gap. The following portion will flow to support the establishment of an Economic Assistance Fund. This fund will assist developing countries when their economies are adversely impacted by deep-sea bed mining. The remaining revenue will be distributed among the Member States with a particular focus on developing States.

In 2022, the African Group assessed the different payment regime options and how they interact with sponsoring state tax systems. In 2023, the Intergovernmental Forum on Mining, Minerals, and Sustainable Development analysed different equalization measures as an addition to the payment regime options to ensure a level playing field between different contractors and sponsoring states.[80,8182] Various options were deliberated during the 29th Session in 2024[83], and these discussions will persist as the Council advances its negotiations in the forthcoming 30th Session (2025).

---

[76] Report-on-Valuation-of-ecosystem-services.pdf

[77] Guidance-on-economic-valuation-Part-II-of-the-report.pdf

[78] *An 'ad valorem' royalty is a percentage of the value of the resource extracted most commonly applied to the gross value of production.*

[79] UNCLOS, Article 151(10)

[80] IGF_Draft_Report_Deep_Sea_Mining_Payment_Regime.pdf (isa.org.jm)

[81] PowerPoint Presentation (isa.org.jm)

[82] Equalization-Measure.pptx

[83] ISBA/C/9/Add.1

Benefit sharing is a crucial element of the legal regime as it addresses the interests and needs of developing States In 2022, the ISA Secretariat published a policy brief outlining its work on benefit sharing which has been under the supervision of the Finance Committee since 2018.[84] The brief draws on findings of ISA technical study 31, which examines the concept and mechanisms for implementing benefit-sharing and also highlights non-monetary benefits.[85]

Alternative approaches to benefit sharing include the establishment of a Seabed Sustainability Fund. The ISA Secretary-General presented a proposal for the fund's establishment to the Finance Committee in 2023 and member States have yet to discuss it.[86,87,88] Some studies suggest that, based on modelling different distributions approaches for the 170 Member States, the economic benefit for an individual country may be limited and also highlight the potential value of the Seabed Sustainability Fund in supporting broader sustainability goals. [89]The draft exploitation regulations frequently reference social impacts, emphasizing all activities in the Area should serve the benefit of humankind. One key mechanism to achieve this is capacity building, which fosters the development of human capital and creates lasting, intergenerational benefits.

Under UNCLOS, ISA has a duty to design and implement mechanisms that support capacity building for developing States. [90] These mechanisms promote technology transfer and expand opportunities for participation in activities in the Area. Experts trained through ISA's programmes contribute by sharing their knowledge and skills with local specialists, strengthening expertise with their home countries.

[84] Policy Brief 01/2022

[85] ISA Technical Study 31

[86] ISBA/29/FC/2

[87] ISBA/29/A/9-IISBA/29/C/20, para 13 and 14

[88] ISBA/28/FC/4

[89] Daniel Wilde, Hannah Lily, Neil Craik, Anindita Chakraborty, Equitable sharing of deep-sea mining benefits: More questions than answers, Marine Policy, Volume 151, 2023, 105572, ISSN 0308-597X, https://doi.org/10.1016/j.marpol.2023.105572.

[90] UNCLOS, Articles 144, 273, 274

A key social component is the legal obligation for contractors to provide training opportunities for personnel from developing States, notably through the Contractor Training Programme.[91] This programme has delivered world-class training in deep sea research and technology development to experts from developing countries. To date, over 350 professionals have benefitted, including 115 women and 118 trainees from least developed countries (LDCs), landlocked developing countries (LLDCs) and small island developing States (SIDS). In 2024, a stocktaking policy brief highlighted ISA's accelerated efforts in this domain emphasizing the essential role of collaborative partnerships.[92]

7.5: Legal and regulatory frameworks for activities relating to marine mineral resources

The Area

In accordance with article 1 of UNCLOS, the "Area" means the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction. UNCLOS recognizes the Area and its resources as the *common heritage of mankind*, and provides that activities in the Area shall be conducted for the benefit of all humankind as a whole.

Activities in the Area are managed by the ISA, an autonomous international organization established under the 1982 UNCLOS and the Agreement related to the implementation of Part XI of the Convention (the 1994 Agreement). The ISA has 170 parties[93] with a seat in the Assembly, the supreme organ and plenary body of the Authority. The Council is the executive body, formed by 36 State parties selected according to a formula that requires representation of special interests, including States with large populations and those that are major importers or net exporters of the commodities to be derived from the Area. Council decisions may result from recommendations by its subsidiary organs: the Legal and Technical Commission and the Economic Planning Commission. As established by the 1994 Agreement, the functions of the Economic Planning Commission have been carried out by the Legal and Technical Commission. The 1994 Agreement also set the functioning of the Finance Committee, whose recommendations shall be considered by the Assembly and the Council. The Finance Committee is tasked to consider the administrative and budgetary implications of proposals involving expenditure from funds of the Authority, and the rules, regulations and procedures on the equitable sharing of financial and other economic

[91] Contractor Training Programme - International Seabed Authority (isa.org.jm)

[92] Policy brief 02/2024

[93] 169 Parties and the European Union.

benefits derived from activities in the Area. As a general rule, decision-making in the organs of the Authority should be by consensus.

The Authority has adopted the regulations on prospecting and exploration for polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts, and is currently discussing the draft regulations, standards and guidelines for the exploitation of these resources. In July 2023, the Council adopted a decision expressing that exploitation should not commence in the absence of regulations, following the announcement by the Republic of Nauru of its intention to submit in 2025 an application for the exploitation of polymetallic nodules in the Area.

The activities developed under the 31 contracts currently in place for exploration for minerals in the Area are monitored through the reports submitted annually by contractors to the Authority. [94]

Recent developments in areas under national jurisdiction

For the context of this section, only two jurisdictions will be considered.

Cook Islands:

The development of deep seabed minerals is viewed as a possible material contributor to diversifying the Cook Islands economy and successive governments have thus maintained an interest in this sector.

The initial Seabed Minerals Act came into force in 2013, leading to the establishment of the Seabed Minerals Authority. In 2019, the Act was repealed with promulgation of a new one that underwent more extensive stakeholder and public review. The Authority manages the industry in consultation with an Advisory Committee of community leaders, and a technical advisory group consisting of relevant government agencies. Some aspects of due governance are managed in that the Seabed Minerals Act works alongside the Environment Act (2003) and the Environment (Seabed Minerals Activities) Regulations 2023 and administered by the National Environment Service, as well as the 2017 Marae Moana Act, administered by the Marae Moana Council, and the fishing oriented Marine Resources Act (2005) administered by Ministry of Marine Resources. The entire Exclusive Economic Zone of the Cook Islands (an area of almost 2.0 million square kilometers) is defined in law as a multiple-use marine park and includes Marine Protected Areas within 50 nautical miles of each of the fifteen islands (~ 14.8 % of the EEZ). All environmental data goes into the public domain as well as the details of exploration licenses and any approved variations.

[94] https://www.isa.org.jm/wp-content/uploads/2024/07/ISA_Status_of_exploration_activities_June_2024.pdf

Following a competitive tender for the exploration of seabed minerals in October 2020, a total of three licenses were issued to Cook Islands-based companies in February 2022. The Exploration Licenses are valid for an initial five-year period and a license holder may apply to have the license renewed subject to statutory requirements.

Norway:

In July 2019, the Norwegian Seabed Minerals Act relating to mineral activities on its continental shelf entered into force. In January 2024, the Norwegian Parliament voted in favor of the Government's proposal to open up an area of approximately 281,000 km^2 for exploration of deep-sea minerals, particularly focused on polymetallic sulphides and ferromanganese crusts. The Seabed Minerals Act stipulates that any targeted area must be subject to an opening decision by the Government, which shall be based on an impact assessment, highlighting which effects a potential opening may have on the three pillars considered on the sustainable development: environmental, economic and social factors. Such impact assessment was finalized in October 2022 followed by the receipt of consultation inputs.

The license regime includes a non-exclusive survey license and an exclusive extraction license. The former is granted for a period up to five years and to a specific area to exploration for and mapping of minerals for commercial purposes. An extraction license gives the licensee the exclusive right to conduct survey for and extract all minerals for commercial purposes in the area covered by the license. An extraction license can be granted for an initial period of up to ten years, with the possibility of applying for a further extension. Unlike the survey license, the extraction license may only be granted to Norwegian entities.

7.6: Sustainability Pathways in the Area and regions under national jurisdiction

Sustainable development aims to meet human needs without compromising future generations' ability to do the same.[95] A key aspect of sustainability under UNCLOS is the precautionary approach, which guides all activities in the marine environment. States and ISA are obligated to use the best available scientific data to prevent significant harm to the marine environment, while promoting the responsible and sustainable use of deep-sea resources.

[95] Our common future

Sustainable exploration and potential exploitation of deep-sea minerals depend on four key pillars: (I) scientific and technological innovation; (II) inclusive stakeholder participation; (III) environmental management; and (IV) reliable data. These pillars are integral to ISA's responsibility for overseeing activities related to deep-sea mineral resources in the Area, ensuring that exploration and exploitation are conducted in a manner consistent with international law, including the precautionary approach.

Advancements in science are key to guiding sustainable development UNCLOS, highlights the mandate to conduct and promote marine scientific research (MSR) in areas under national jurisdiction and the Area.[96] In 2017, the UN General Assembly proclaimed the "Decade of Ocean Science for Sustainable Development (UN Ocean Decade)".[97] In support of the UN Ocean Decade, the ISA adopted its Marine Scientific Research Action Plan in 2020.[98] This plan puts forward six strategic research priorities and has since served as a global framework and agenda to advance deep-sea research.[99] In 2024, a stock-taking report was published that put forward recommendations to shape the future marine research landscape.[100] One example is that the Authority should channel its short-term focus to advance knowledge gaps identified in the REMP process, in order to support the science-policy interface. Projects that have contributed to Joint Programme Initiative

Technological innovation plays a vital role in implementing the precautionary approach in deep-sea resource management by enhancing our ability to prevent harm to marine ecosystems. Advances in technology support the development of sophisticated monitoring and assessment tools, allowing for real-time data collection and more precise evaluations of potential environmental impacts. For example, improved remote sensing technologies, autonomous underwater vehicles (AUVs), and advanced satellite systems can provide detailed insights into the health of deep-sea habitats and ecosystems. However, it is also important to consider the potential risks associated with technological advancements, such as unintended ecological impacts and ethical concerns regarding the use of AI and automation. Significant technological advancements have been made and in April 2024, experts of an ISA scoping workshop identified five priority areas for future development:

[96] UNCLOS, Article 143

[97] A/RES/72/73 para. 292.

[98] ISBA/26/A/17.

[99] ISBA/27/A/4, ISBA/28/A/8, ISBA/29/A/5

[100] Report_Contribution-of-ISA-to-the-scientific-objectives-of-the-UN-Decade.pdf

ocean observation and communication, monitoring, autonomy, automation, robotics, AI and machine learning and mining, energy, and metal processing. [101, 102]

Inclusive stakeholder participation is essential for ensuring transparency and accountability in the governance of marine resources. The ISA actively engages a diverse range of stakeholders to support informed decision-making and strengthen its mandate. This ongoing commitment aligns with the ISA's strategic priorities, which focus on advancing marine resource governance through collaboration and science-based policies.[103,104,105]

Environmental management is essential to sustainable development, balancing the need for resource extraction with the protection of marine ecosystems. Regional Environmental Management Plans (REMPs) are designed as measures to protect the marine environment in specific areas of the Area from the potential harmful effects of activities in the Area. They aim to provide a framework for ensuring environmental protection while enabling the sustainable use of marine resources. Although REMPs are informed by environmental assessments, their development is not solely based on regional environmental impact assessments but also incorporates broader scientific, environmental, and regulatory considerations.[106] The LTC is currently advancing standardized procedures for developing and reviewing REMPs, including environmental goals, management measures, and monitoring processes. To support these efforts, the LTC is also creating technical guidance to complement the standardized procedure.[107,108] One notable success is the REMP of the Clarion Clipperton Zone, where a scientific review identified additional ecologically significant areas that were subsequently granted protection.

Reliable data is essential for informed decision-making and sustainable development in deep-sea mining. It underpins rigorous environmental impact assessments, supports the creation of robust regulatory frameworks, and enables responsible management of deep-sea mineral extraction—thereby safeguarding fragile marine ecosystems and promoting

[101] Sharma et al, 2017, ISA Technical Study 29, ISA Technical Study 30

[102] ISA Website

[103] Stakeholder Engagement - International Seabed Authority (isa.org.jm)

[104] ISBA/24/A/10

[105] ISBA/25/A/15

[106] Regional environmental management plans - International Seabed Authority (isa.org.jm)

[107] ISBA/29/C/10.

[108] ISBA/29/LTC/8.

long-term economic viability. ISA shares non-confidential data of contractors, following the FAIR principle (findable, accessible, interoperable, and reusable). Its DeepData database serves as a central repository for environmental data in the Area, with an average of 5,580 monthly visitors as of April 2024. [109] ISA continues to enhance data quality through partnerships, such as with the World Register of Marine Species (WoRMS) and the Ocean Biodiversity Information System (OBIS) of IOC-UNESCO, and also the Natural History Museum of London and the Pew Charitable Trusts, which led to an in-depth assessment of the quality of biological data.[110] .

[109] https://data.isa.org.jm/isa/map/

[110] Rabone et al., 2024

References Section 7.1

[1] United Nations (Ed.) “The First Global Integrated Marine Assessment: World Ocean Assessment I,” Cambridge University Press, 2017, ISBN: 9781108186148, https://doi.org/10.1017/9781108186148.

[2] United Nations (Ed.) “The Second World Ocean Assessment: World Ocean Assessment II,” Volume II. United Nations Publication: ISBN: 978-92-1-1-130422-0 and eISBN: 978-92-1-1-604006-2. [Online]. Available: https://digitallibrary.un.org/record/3978757?v=pdf.

[3] International Seabed Authority, “A review of the contribution of ISA to the objectives of the 2023 Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdictions,” 2024. ISA: eISBN 978-976-8313-53-9 and ISBN 978-976-8313-52-2. [Online]. Available: https://www.isa.org.jm/wp-content/uploads/2024/06/The_contribution_of_ISA_to_the_BBNJ_objectives.pdf.

References: Section 7.2

[1] United Nations Envrionmental Programme, “UNEP Marine Sand Watch reveals massive extraction in the world’s oceans,” Press Releases. Accessed: Oct. 20, 2024. [Online]. Available: https://www.unep.org/news-and-stories/press-release/unep-marine-sand-watch-reveals-massive-extraction-worlds-oceans

[2] United Nations Environment Programme, “Sand and sustainability: 10 strategic recommendations to avert a crisis,” Geneva, Switzerland, 2022. [Online]. Available: https://wedocs.unep.org/bitstream/handle/20.500.11822/38362/sand_sustainability.pdf

[3] United Nations Envrionmental Programme; and GRID Geneva, “Marine Sand Watch.” Accessed: Oct. 20, 2024. [Online]. Available: https://unepgrid.ch/en/marinesandwatch

[3] United Nations Envrionmental Programme; and GRID Geneva, “Marine Sand Watch.” Accessed: Oct. 20, 2024. [Online]. Available: https://unepgrid.ch/en/marinesandwatch

[4] United Nations Envrionmental Programme and GRID Geneva, “Global Sand Observatory Initiative.” Accessed: Oct. 20, 2024. [Online]. Available: https://unepgrid.ch/en/sand

[5] S. . Andreev *et al.*, *Metallogenic Map of the World Ocean*, 2nd ed. St Petersburg, Russia: Vniiokeangeologia, 2008. [Online]. Available: http://vniio.ru/en/about/science_dept/poleznyeiskopaemie/geominocean_dep/

[6] R. H. T. Garnett and N. C. Bassett, "Placer Deposits," in *One Hundredth Anniversary Volume*, Society of Economic Geologists, 2005. doi: 10.5382/AV100.25.

[7] Kamilli, R.J., B. E. Kimball, and J. F. J. Carlin, "Tin, Chapter S of Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply," Washington D.C., United States, 2018. doi: https://doi.org/10.3133/pp1802S.

[8] International Tin Association, "Global Resources & Reserves: Security of long-term supply," St. Albans, United Kingdom, 2020. [Online]. Available: https://www.internationaltin.org/wp-content/uploads/2020/02/Global-Resources-Reserves-2020-Update.pdf

[9] C. H. Nelson and D. M. Hopkins, "Sedimentary processes and distribution of particulate gold in the northern Bering Sea," 1972. doi: 10.3133/pp689.

[10] R. Garnet, "Mares Australes: Tierra Del Fuego Marine Placer Gold Project Chile," Santiago, Chile, 2013.

[11] G. I. C. Schneider, "Marine diamond mining in the Benguela Current Large Marine Ecosystem: The case of Namibia," *Environ. Dev.*, vol. 36, p. 100579, Dec. 2020, doi: 10.1016/j.envdev.2020.100579.

[12] P. Gales, "Offshore Diamond Mining in SW Africa," Deep Sea Mining Articles. Accessed: Oct. 29, 2024. [Online]. Available: https://deepseamining.ac/article/55#gsc.tab=0

[13] International Seabed Authority, "Secretary General Annual Report," Kingston, Jamaica, 2024. [Online]. Available: https://www.isa.org.jm/secretary-general-annual-report-2024

[14] The Metals Company, "NORI and Allseas Lift Over 3,000 Tonnes of Polymetallic Nodules to Surface from Planet's Largest Deposit of Battery Metals, as Leading Scientists and Marine Experts Continue Gathering Environmental Data," News Releases. Accessed: Nov. 25, 2022. [Online]. Available: https://investors.metals.co/news-releases/news-release-details/nori-and-allseas-lift-over-3000-tonnes-polymetallic-nodules

[15] International Seabed Authority, "Cobalt Rich Crusts," Kingston, Jamaica, 2008. [Online]. Available: https://www.isa.org.jm/wp-content/uploads/2022/06/eng9.pdf.

[15B] International Seabed Authority, Environmental Impact Assessments Kingston, Jamaica, 2025. [Online]. https://www.isa.org.jm/protection-of-the-marine-environment/environmental-impact-assessments/

[16] RSC, "Cook Islands Polymetallic Nodule Deposit," Dunedin, New Zealand, 2023. [Online]. Available: https://www.sbma.gov.ck/s/CIMinRscRevt_final_b.pdf.

[17] International Seabed Authority, "Minerals: Cobalt-rich Ferromanganese Crusts." Accessed: Oct. 20, 2024. [Online]. Available: https://www.isa.org.jm/exploration-contracts/cobalt-rich-ferromanganese-crusts/.

[18] Norwegian Offshore Directorate, "Manganese crusts." Accessed: Oct. 20, 2024. [Online]. Available: https://www.sodir.no/en/facts/seabed-minerals/manganese-crusts/.

[19] Japan Oil Gas and Metals National Corporation, "JOGMEC Conducts World's First Successful Excavation of Cobalt-Rich Seabed in the Deep Ocean; Excavation Test Seeks to Identify Best Practices to Access Essential Green Technology Ingredients While Minimizing Environmental Impact," News Releases. Accessed: Jul. 23, 2023. [Online]. Available: https://www.jogmec.go.jp/english/news/release/news_01_000033.html.

[20] C. Xie *et al.*, "A Compact Design of Underwater Mining Vehicle for the Cobalt-Rich Crust with General Support Vessel Part A: Prototype and Tests," *J. Mar. Sci. Eng.*, vol. 10, no. 2, p. 135, Jan. 2022, doi: 10.3390/jmse10020135.

[21] Z. Ren *et al.*, "Analysis and Research on Mobile Drilling Rig for Deep Seabed Shallow Strata," *Mar. Technol. Soc. J.*, vol. 55, no. 2, pp. 81–93, Mar. 2021, doi: 10.4031/MTSJ.55.2.7.

[22] S. M. Jasinsk, "Phosphate Rock - Mineral Commodity Summaries," Washington D.C., United States, 2022. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-phosphate.pdf

[23] D. Cordell and T. Neset, "Phosphorous Security: Future Pathways to Reduce Food System Vulnerability to a New Global Threat," Development Future Conference Presentation. Accessed: Oct. 20, 2024. [Online]. Available: https://www.slideshare.net/DevFutures/dana-cordell-phosphorus-scarcity#1.

[24] FAO, "World fertilizer trends and outlook to 2022," Rome, Italy, 2019. [Online]. Available: https://openknowledge.fao.org/server/api/core/bitstreams/42d5a668-f44c-4976-8540-8efdb0f4d17b/content.

[25] H. Kudrass, R. Wood, and R. Falconer, “Submarine Phosphorites: The Deposits of the Chatham Rise, New Zealand, off Namibia and Baja California, Mexico—Origin, Exploration, Mining, and Environmental Issues,” in *Deep-Sea Mining*, Cham: Springer International Publishing, 2017, pp. 165–187. doi: 10.1007/978-3-319-52557-0_5.

[26] Golder Associates (NZ) Limited, “Chatham Rock Phosphate Limited Proposed Mining Operation, Chatham Rise Marine Consent Application and Environmental Impact Assessment Non-technical Summary,” 2014. [Online]. Available: https://static1.squarespace.com/static/51d24098e4b0d519d0c065f5/t/5782ea98be6594c387f68478/1468197553465/1178207517_Rev2_CRP_Non-tech%2BSummary_May%2B2014%2BFINAL.pdf.

[27] Environmental Protection Authority, “Decision on Marine Consent Application: Chatham Rock Phosphate Limited To mine phosphorite nodules on the Chatham Rise,” Wellington, New Zealand, 2015. [Online]. Available: https://www.epa.govt.nz/assets/Uploads/Documents/Marine-Activities-EEZ/Activities/990a6509eb/CRP-Decision-EEZ000006.pdf.

[28] Odyssey Marine Exploration, “Odyssey Marine Exploration Provides Update on Mexican Phosphate Project,” Press Releases. Accessed: Oct. 20, 2024. [Online]. Available: https://ir.odysseymarine.com/news/news-details/2018/Odyssey-Marine-Exploration-Provides-Update-on-Mexican-Phosphate-Project-2018-10-19/default.aspx.

[29] Namibian Marine Phosphate, “Media Statement October 2016,” 2016. [Online]. Available: https://www.namphos.com/videos/media-releases/item/download/36_66b7d48aa13f367a9e624fcc96e0beec.

[30] Chatham Rock Phosphate, “Chatham Congratulates NZ Coalition Government on Fast Track Permitting Initiative,” Press Releases. Accessed: Oct. 20, 2024. [Online]. Available: https://www.rockphosphate.co.nz/news/2024/10/8/chatham-congratulates-nz-coalition-government-on-fast-track-permitting-initiative.

Lixinski L. Integrating Culture, Heritage, and Identity in Deep Seabed Mining Regulation. *AJIL Unbound*. 2024;118:78-82. doi:10.1017/aju.2024.7

M Rabone, T Horton, D O B Jones, E Simon-Lledó, A G Glover, A review of the International Seabed Authority database DeepData from a biological perspective: challenges and opportunities in the UN Ocean Decade, *Database*, Volume 2023, 2023, baad013, https://doi.org/10.1093/database/baad013

[31] Odyssey Marine Exploration, “Odyssey Marine Exploration Reports Win in NAFTA Arbitration Case,” Press Releases2. Accessed: Oct. 20, 2024. [Online]. Available:

https://ir.odysseymarine.com/news/news-details/2024/Odyssey-Marine-Exploration-Reports-Win-in-NAFTA-Arbitration-Case/default.aspx.

[32] Namibian Marine Phosphate, "ML 170 Environmental Permitting and Regulated Process Update," 2022. [Online]. Available: https://www.namphos.com/videos/media-releases/item/download/504_0a0b69ac9139c0f769e0c9167c227027.

[33] W. C. P. Shanks *et al.*, "Volcanogenic massive sulfide occurrence model," 2012. doi: 10.3133/sir20105070C.

[34] M. D. Hannington, "Volcanogenic Massive Sulfide Deposits," in *Treatise on Geochemistry*, Elsevier, 2014, pp. 463–488. doi: 10.1016/B978-0-08-095975-7.01120-7.

[35] C. L. Van Dover *et al.*, "Research is needed to inform environmental management of hydrothermally inactive and extinct polymetallic sulfide (PMS) deposits," *Mar. Policy*, vol. 121, p. 104183, Nov. 2020, doi: 10.1016/j.marpol.2020.104183.

[36] Bauer Group, "'Vertical Approach' in deep-sea mining: BAUER Maschinen GmbH and the Harren & Partner Group establish joint venture," Press Releases. Accessed: Oct. 22, 2024. [Online]. Available: https://www.bauer.de/en/media/1160/download?inline.

[37] E. C. Alberts, "Not merely 'exploration': PNG deep-sea mining riles critics & surprises officials," Monga Bay Oceania. Accessed: Oct. 29, 2024. [Online]. Available: https://news.mongabay.com/2024/09/not-merely-exploration-png-deep-sea-mining-riles-critics-surprises-officials/.

[38] T. Washburn *et al.*, "Impacts of the first deep-sea seafloor massive sulfide mining excavation tests on benthic communities," *Mar. Ecol. Prog. Ser.*, vol. 712, pp. 1–19, Jun. 2023, doi: 10.3354/meps14287.

[39] T. E. Laurila, M. D. Hannington, M. Leybourne, S. Petersen, C. W. Devey, and D. Garbe-Schönberg, "New insights into the mineralogy of the Atlantis II Deep metalliferous sediments, Red Sea," *Geochemistry, Geophys. Geosystems*, vol. 16, no. 12, pp. 4449–4478, Dec. 2015, doi: 10.1002/2015GC006010.

[40] C. Bertram, A. Krätschell, K. O'Brien, W. Brückmann, A. Proelss, and K. Rehdanz, "Metalliferous sediments in the Atlantis II Deep—Assessing the geological and economic resource potential and legal constraints," *Resour. Policy*, vol. 36, no. 4, pp. 315–329, Dec. 2011, doi: 10.1016/j.resourpol.2011.09.001.

[41] S.-J. Pak, I. Seo, K.-Y. Lee, and K. Hyeong, “Rare Earth Elements and Other Critical Metals in Deep Seabed Mineral Deposits: Composition and Implications for Resource Potential,” *Minerals*, vol. 9, no. 1, p. 3, Dec. 2018, doi: 10.3390/min9010003.

[42] K. Azami, N. Hirano, S. Machida, K. Yasukawa, and Y. Kato, “Rare earth elements and yttrium (REY) variability with water depth in hydrogenetic ferromanganese crusts,” *Chem. Geol.*, vol. 493, pp. 224–233, Aug. 2018, doi: 10.1016/j.chemgeo.2018.05.045.

[43] Y. Kato *et al.*, “Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements,” *Nat. Geosci.*, vol. 4, no. 8, pp. 535–539, Aug. 2011, doi: 10.1038/ngeo1185.

[44] JAMSTEC, “Great Challenge for Deep-Sea Resources.” JAMSTEC, Yokosuka Japan, 2023. [Online]. Available: https://www.youtube.com/watch?v=NGL5TaU4X2Y

References: Section 7.3

[1] Debmarine Namibia, “Final 2024 Updated Environmental Impact Assessment (EIA) and Environmental Management Plan (EMP) Report to Support the Application for Renewal of Environmental Clearance Certificate (ECC) for Marine Diamond Exploration, Recovery and Production Operations,” Windhoek, Namibia, 2024. [Online]. Available: https://eia.meft.gov.na/screening/4310_final_updated_dbmn_2024_eia_and_emp_report_for_atlantic_1_ml_47_june_2024.pdf.

[2] Golder Associates (NZ) Limited, “Chatham Rock Phosphate Limited Proposed Mining Operation, Chatham Rise Marine Consent Application and Environmental Impact Assessment Non-technical Summary,” 2014. [Online]. Available: https://static1.squarespace.com/static/51d24098e4b0d519d0c065f5/t/5782ea98be6594c387f68478/1468197553465/1178207517_Rev2_CRP_Non-tech%2BSummary_May%2B2014%2BFINAL.pdf.

[3] Coffey Natural Systems, “Environmental Impact Statement Nautilus Minerals Niugini Solwara 1 Project - Summary,” Brisbane, Australia, 2008. [Online]. Available: https://www.sbma.gov.ck/s/1-EIS-Executive-Summary_English.pdf.

[4] BGR, “Environmental Impact Assessment for the testing of a pre-protoype manganese nodule collector vehicle in the Eastern German license area (Clarion-Clipperton Zone) in the framework of the European JPI-O MiningImpact 2 research project,” Hannover, Germany, 2018. [Online]. Available: https://www.isa.org.jm/files/files/documents/EIA_BGR_0.pdf.

[5] Global Sea Mineral Resources, “Environmental Impact Statement,” DEME Group,

Zwijndrecht, Belgium, 2018. [Online]. Available: https://www2.deme-group.com/sites/default/files/isa_eia_2018_gsrnod2019.pdf.

[6] R. Sharma et al., "Environmental Impact Statement," 2020. [Online]. Available: https://moes.gov.in/writereaddata/files/India_PMN_EIS_Jan_2020.pdf.

[7] M. R. Clark, H. Rouse, G. Lamarche, J. Ellis, and C. Hickey, "Preparation of Environmental Impact Assessments: General guidelines for offshore mining and drilling with particular reference to New Zealand," Wellington, New Zealand, 2017. [Online]. Available: https://niwa.co.nz/sites/niwa.co.nz/files/EMOM_EIA_guidelines_Revision_Jan2017.pdf.

[8] M. R. Clark, J. M. Durden, and S. Christiansen, "Environmental Impact Assessments for deep-sea mining: Can we improve their future effectiveness?," Mar. Policy, vol. 114, Apr. 2020, doi: 10.1016/j.marpol.2018.11.026.

[9] L. Maxim, J. H. Spangenberg, and M. O'Connor, "An analysis of risks for biodiversity under the DPSIR framework," Ecol. Econ., vol. 69, no. 1, pp. 12–23, Nov. 2009, doi: 10.1016/j.ecolecon.2009.03.017.

[10] M. Elliott et al., "'And DPSIR begat DAPSI(W)R(M)!' - A unifying framework for marine environmental management," Mar. Pollut. Bull., vol. 118, no. 1–2, pp. 27–40, May 2017, doi: 10.1016/j.marpolbul.2017.03.049.

[11] UN Environment Programme, "Ecosystem-Based Approaches," Topics. Accessed: Aug. 02, 2024. [Online]. Available: https://www.unep.org/topics/ocean-seas-and-coasts/ecosystem-based-approaches.

[12] International Seabed Authority, "The Mining Code." Accessed: Oct. 22, 2024. [Online]. Available: https://www.isa.org.jm/the-mining-code/.

[13] SPREP, Strategic Environmental Assessment (SEA) Guidelines for Pacific Islands Countries and Territories. Secretariat of the Pacific Regional Environment Programme, 2020. [Online]. Available: https://www.sprep.org/sites/default/files/documents/publications/SEA-Guidelines.pdf.

[14] "Regional environmental management plans." Accessed: Oct. 22, 2024. [Online]. Available: https://www.isa.org.jm/protection-of-the-marine-environment/regional-environmental-management-plans/.

[15] International Finance Corporation, Good Practice Handbook for Cumulative Impact Assessment and Management: Guidance for the Private Sector in Emerging Markets.

Washington D.C., United States: International Finance Corporation, 2013.

[16] International Seabed Authority, “Secretary General Annual Report,” Kingston, Jamaica, 2024. [Online]. Available: https://www.isa.org.jm/secretary-general-annual-report-2024.

[17] OceanICU, “Measuring and modelling the ocean carbon sink,” Grant Project Description. Accessed: Oct. 22, 2024. [Online]. Available: https://cordis.europa.eu/project/id/101083922.

[18] European Marine Energy Centre, “Technology Readiness Levels.” Accessed: Oct. 22, 2024. [Online]. Available: https://www.emec.org.uk/services/provision-of-wave-and-tidal-testing/pathway-to-emec/technology-readiness-levels/.

[19] P. McCarthy, “Feasibility studies for mining projects,” AusIMM Bulletin, Melbourne, Australia, p. 1, 2015. [Online]. Available: https://www.ausimm.com/bulletin/bulletin-articles/feasibility-studies-for-mining-projects/.

[20] T. McNulty, “Developing Innovative Technology,” Min. Eng., vol. 50, pp. 50–55, 1998, [Online]. Available: https://api.semanticscholar.org/CorpusID:221629558.

[21] I. Lipton, M. Nimmo, and J. Parianos, “TOML Clarion Clipperton Zone Project, Pacific Ocean,” AMC Consultants Pty Ltd, Brisbane, Australia, 2016. [Online]. Available: www.sedar.com.

[22] United Nations Ocean Economics and Technology Branch, *Analysis of Exploration and Mining Technology for Manganese Nodules*. London, United Kingdom: Graham and Trotman, 1984. doi: 10.1007/778-94-009-5622-3.

[23] Office of Resources and Environmental Monitoring, “Proposed Technologies for Mining Deep-Seabed Polymetallic Nodules,” Kingston, Jamaica, 1999. [Online]. Available: https://www.isa.org.jm/wp-content/uploads/2022/06/proptechnology.pdf.

[24] International Seabed Authority, “Polymetallic Nodule Mining Technology: Current Trends and Challenges Ahead,” Kingston, Jamaica, 2008. [Online]. Available: www.isa.org.jm/wp-content/uploads/2022/06/chennai-19sept-final.pdf.

[25] Golder, “Preliminary economic assessment, NORI Clarion-Clipperton Zone Area D Project, Pacific Ocean,” Brisbane, Australia, 2015.

[26] AMC Consultants, “Technical Report: Preliminary Economic Assessment of the NORI Area D Project Clarion Clipperton Zone,” Brisbane, Australia, 2019.

[27] The Metals Company, “Timeline.” Accessed: Oct. 22, 2024. [Online]. Available: https://metals.co/timeline/.

[28] The Metals Company, “TMC and PAMCO Sign Binding MOU to Complete Feasibility Study to Process Polymetallic Nodules into Battery Metal Feedstocks,” Press Releases. Accessed: Oct. 22, 2024. [Online]. Available: https://www.globenewswire.com/news-release/2023/11/13/2778905/0/en/TMC-and-PAMCO-Sign-Binding-MOU-to-Complete-Feasibility-Study-to-Process-Polymetallic-Nodules-into-Battery-Metal-Feedstocks.html.

[29] NOV, “Deep-sea Mineral Extraction,” Products and Services. Accessed: Oct. 22, 2024. [Online]. Available: https://www.nov.com/products-and-services/capabilities/deep-sea-mineral-extraction.

[30] S. A. Rizea *et al.*, “Making Deep Sea Mining Cleaner and Greener,” *Offshore Technology Conference*. p. D021S021R003, May 01, 2023. doi: 10.4043/32535-MS.

[31] Beijing Pioneer Hi-Tech. Development Corporation Ltd., “Environmental Impact Statement: Joint Test of Deep-sea Miner and Buffer Station in Beijing Pioneer Polymetallic Nodule Contract Area, Western Pacific,” Beijing, China, 2024. [Online]. Available: https://static1.squarespace.com/static/5cca30fab2cf793ec6d94096/t/664bf2ddc192e40f63aebe48/1716253429581/Part+1+Joint+Test+of+Deep-sea+Miner+and+Buffer+Station+in+Beijing+Pioneer+Polymetallic+Nodule+Contract+Area%2C+Western+Pacific.pdf.

[32] E. Silva *et al.*, “TRIDENT - Technology based impact assessment tool for sustainable, transparent Deep Sea Mining Exploration and exploitation: a project overview,” in *Oceans 2023 - {Limerick}*, New York: IEEE, 2023. doi: 10.1109/OCEANSLimerick52467.2023.10244429.

[33] JPI Oceans, “MiningImpact 2 ‘Environmental impacts and risks of deep-sea mining,’” Brussels, Beligium, 2023. [Online]. Available: https://www.jpi-oceans.eu/sites/jpi-oceans.eu/files/MI2_FinalReport_Publishable_web_2023.pdf.

[34] OE Staff, “TMC, Allseas to Develop Commercial Seabed Nodule Collection System. Plan to Buy Another Drillship,” *Offshore Engineer*, Easton, United States, Mar. 2022. [Online]. Available: https://www.oedigital.com/news/495134-tmc-allseas-to-develop-commercial-seabed-nodule-collection-system-plan-to-buy-another-drillship.

[35] Impossible Metals, “Robotic Collection System.” Accessed: Oct. 22, 2024. [Online]. Available: https://impossiblemetals.com/technology/robotic-collection-system/.

[36] Ocean Mining Intel, “Tech Spotlight: Loke Collection Tool for Manganese Nodules,” *Ocean Mining Intel TEchnology News*, Stuart, United States, Apr. 2023. [Online].

Available: https://oceanminingintel.com/news/technology/tech-spotlight-loke-collection-tool-for-manganese-nodules.

[37] P. Gales, “STARS; the Missing Link in DSM Supply Chain,” Deep Sea Mining. Accessed: Oct. 22, 2024. [Online]. Available: https://deepseamining.ac/article/44#gsc.tab=0.

[38] Bauer Group, “‘Vertical Approach’ in deep-sea mining: BAUER Maschinen GmbH and the Harren & Partner Group establish joint venture,” Press Releases. Accessed: Oct. 22, 2024. [Online]. Available: https://www.bauer.de/en/media/1160/download?inline.

[39] Japan Oil Gas and Metals National Corporation, “JOGMEC Conducts World’s First Successful Excavation of Cobalt-Rich Seabed in the Deep Ocean; Excavation Test Seeks to Identify Best Practices to Access Essential Green Technology Ingredients While Minimizing Environmental Impact,” News Releases. Accessed: Jul. 23, 2023. [Online]. Available: https://www.jogmec.go.jp/english/news/release/news_01_000033.html.

[40] C. Xie *et al.*, “A Compact Design of Underwater Mining Vehicle for the Cobalt-Rich Crust with General Support Vessel Part A: Prototype and Tests,” *J. Mar. Sci. Eng.*, vol. 10, no. 2, p. 135, Jan. 2022, doi: 10.3390/jmse10020135.

[41] JAMSTEC, “Great Challenge for Deep-Sea Resources.” JAMSTEC, Yokosuka Japan, 2023. [Online]. Available: https://www.youtube.com/watch?v=NGL5TaU4X2Y.

[42] K. Richardson, “A perspective of marine mining within De Beers,” *J. South. African Inst. Min. Metall.*, vol. 107, p. 10, 2007, [Online]. Available: https://www.saimm.co.za/Journal/v107n06p393.pdf.

[43] J. Anderson and M. Oosthuizen, “How could Indonesia’s election influence its resource nationalism strategy?,” Project Blue Opinion Piece. Accessed: Oct. 22, 2024. [Online]. Available: https://projectblue.com/blue/opinion-pieces/764/how-could-indonesia’s-election-influence-its-resource-nationalism-strategy.

Bibliography: Section 7.3

[1] P. Weaver, J. Aguzzi, R. Boschen-Rose, A. Colaco, H. de Stigter, S. Gollner, M. Haeckel, C. Hauton, R. Helmons, D. Jones, H. Lily, N. Mestre, C. Mohn and L. Thomsen, "Assessing plume impacts caused by polymetalic nodule mining vehicles," Marine Policy, p. 105011, 2022.

[2] S. Ellefmo, N. Aberle, V. Hagspiel, M. Ingulstad and K. Aasly, "Marine minerals' role in

future holistic miineral resource management," Geological Society, London, Special Publications, vol. 526, pp. 319-342, 2022.

[3] S. Haalboom, H. de Stigter, C. Mohn, T. Vandorpe, M. Smit, L. de Jonge and G.-J. Reichart, "Monitoring of a sediment plume produced by a deep-sea mining test in shallow water, Malaga Bight, Alboran Sea (sourthwestern Mediterranean Sea)," Marine Geology, vol. 456, p. 106971, 2023.

[4] S. Haalboom, T. Schoening, P. Urban, I.-Z. Gazis, H. de Stigter, B. Gillard, M. Baeye, M. Hollstein, K. Purkiani, G.-J. Reichart, L. Thomsen, M. Haeckel, A. Vink and J. Greinert, "Monitoring of Anthropogenic Sediment Plumes in the Clarion-Clipperton Zone, NE Equatorial Pacific Ocean," Frontiers in marine Science , p. 882155, 2022.

[5] B. Gillard, K. Purkiani, D. Chatzievangelou, A. Vink, M. Iversen and L. Thomsen, "Physical and hydrodynamic properties of deep sea mining-generated, abysal sediment plumes in the Clarion Clipperton Fracture Zone (eastern central Pacific)," Elementa: Science of the Anthropocene, vol. 7, no. 1, p. 5, 2019.

[6] S. Gollner, M. Haeckel, F. Janssen, N. Lefailble, M. Molari, S. Papadopoulou, G.-J. Reichart, J. Trabucho Alexandre , A. Vink and A. Vanresuesl, "Restoration experiments in polymetallic nodule areas," Integrated Environmental Assessment Management, vol. 18, pp. 682-696, 2022.

[7] S. Gollner, S. Kaiser, L. Menzel, D. Jones, A. Brown, N. Mestre, D. van Oevelen, L. Meno, A. Colaco, M. Canals, D. Cuvelier, J. Durden, A. Gebruk, G. Egho, M. Haeckel, Y. Marcon, L. Mevenkamp, T. Morato , C. Pham, A. Purser, A. Sanchez-Vidal, A. Vanreusel, A. Vink and P. Martinez Arbizu, "Resilience of benthic deep-sea fauna to mining activities," Marine Environmental Research, vol. 129, pp. 76-101, 2017.

[8] M. Haeckel, F. Janssen and P. Martinez Arbizu, "Assessing the impacts of polymetallic nodule mining on the deep-sea environment after an industrial collector test in the German and Belgian contract areas in the CCZ, Cruise No. SO295," Begutachtungspanel Forschungsschiffe, Bonn, Germany, 2023.

[9] L. Haffert, M. Haeckel, H. de Stigter and F. Janssen, "Assessing the temporal scale of deep-sea mining impacts on sediment biogeochemistry," Biogeoscinces, vol. 17, pp. 2767-2789, 2020.

[10] B. Hitchin, S. Smith, K. Kroger, D. Jones, A. Jaeckel, N. Mestre, J. Ardron, E. Escobar, J. van der Grient and T. Amaro, "Thresholds in deep-seabed mining: a primer for their development," Marine Policy, vol. 149, p. 105505, 2023.

[11] N. Lefaible, L. Macheriotou, E. Pape, M. Molari, M. Haeckel, D. Zeppilli and A. Vanreusel, "Industrial mining for polymetallic nodules in the Clarion Clipperton Zone

indicates complex and variable disturbances of meiofaunal communities," Frontiers in Marine Science, vol. 11, 2024.

[12] C. Munoz-Royo, R. Ouillon, S. El Mousadik, M. Alford and T. Peacock, "An *in-situ* study of abyssal turbidity current sediment plumes generated by a deep seabed polymetallic nodule mining preprototype collector vehicle," Science Advances, vol. 8, no. 38, 2022.

[13] J. Spearman, J. Taylor, N. Crossouard and A. Cooper, "Measurement and modelling of deep seas ediment plumes and implications for deep sea mining," Scientific Reports, vol. 10, pp. 1-13, 2020.

[14] J. Volz, W. Geibert, D. Kohler, M. van der Loeff and S. Kasten, "Alpha radiation from polymetallic nodules and potential health risks from deep-sea mining," Scientific reports , vol. 13, p. 7985, 2023.

[15] T. Peacock and R. Ouillon, "The fluid mechanics of deep-sea mining," Annual Review of Fluid Mechanics, vol. 55, no. 1, pp. 403-430, 2023.

[16] S. Alhaddad, D. Mehta and R. Helmons, "Mining of deep-seabed nodules using a coanda-effect-based collector," Results in Engineering, vol. 17, p. 100852, 2023.

[17] R. Helmons, S. Alhaddad, C. Chassagne, M. Elerian, G. Keetels, A. Kirichek and L. Thomsen, "Turbidity at the Source: Aiming for Minimized Sediment Dispersion During Deep-sea Mining," in Deep-Sea Mining and the Water Column, Springer Nature Switzerland, 2024, pp. 209-242.

[18] Z. Yue, G. Zhao, L. Xiao and M. Liu, "Comparative study on collection performance of three nodule collection methods in seawater and sediment-seawater mixture," Applied Ocean Research, vol. 110, p. 102606, 2021.

[19] M. Diaz, H. de Stigter, A. Palanques, M. Arjona-Camas, P. Puig, R. Helmons, L. Thomsen and L. de Jonge, "Monitoring flocculation in a sediment plume produced by a deep-sea mining test in shallow water: preliminary results," in Particles in Europe, Heraklion, Greece, 2023.

[20] D. Jones, S. Kaiser, A. Sweetman, C. Smith, L. Menot, A. Vink, D. Trueblood, J. Greinert, D. Billet, P. Arbizu, T. Radziejewska, R. Singh, B. Ingole, T. Stratmann, E. Simon-Lledo, J. Durden and M. Clark, "Biological responses to disturbance from simulated deep-sea polymetallic nodule mining," PLoS ONE, vol. 12, no. 2, p. e0171750, 2017.

References Section 7.5

[1] ISBA/29/A/8. Consideration, with a view to adoption, of the extended high-level action plan of the International Seabed Authority for the period 2019–2025. Twenty-ninth session, Kingston, 29 July–2 August 2024. [Online]. Available: https://www.isa.org.jm/wp-content/uploads/2024/06/ISBA_29_A_8.pdf and https://www.isa.org.jm/wp-content/uploads/2024/06/ISBA-29-A-8_Annex.pdf.

Section 5A
Chapter 8: Desalination and salt production (liquid salt)

SECTION 8.1 – INTRODUCTION

8.1.1 Growing need for desalination: ~~Out of~~ Of the Earth's 1.4 billion cubic kilometers of water ~~on planet Earth~~, only 2.5 percent is freshwater and 0.3 percent ~~easily~~ readily accessible to human~~skind~~ (World Bank, 2013). ~~Due to rising~~Increasing population, urbanization, climate change and economic developments have resulted in over ~~, more than~~ 2 billion people ~~are~~ experiencing high water stress (UN Water, 2018). ~~Based on the e~~Estimates ~~available~~ for 171 countries indicate that~~,~~ 31 countries experience water stress between 25-70 percent, 22 countries ~~above~~ exceed 70 percent and 11 countries ~~above~~ surpass 100 percent ~~water stress~~ (UN Water, 2018). By 2050, 40 percent of the world's population is projected to live under severe water stress (Salinas-Rodriguez and others, 2021). Oceans cover 140 million square miles (approximately 363 million square kilometers) of the earth's surface and nearly 2.4 billion people live within 100 km of the coast (UN, 2017). To address water scarcity, saline water desalination offers promising solutions. More than 150 countries are using desalination to supply potable water to over 300 million people (World Bank, 2019a). It is well-established that unconventional water sources like desalination will play a key role towards meeting UN's SDG 6 targets for sustainable water management in the coming years (UNEP, 2021).

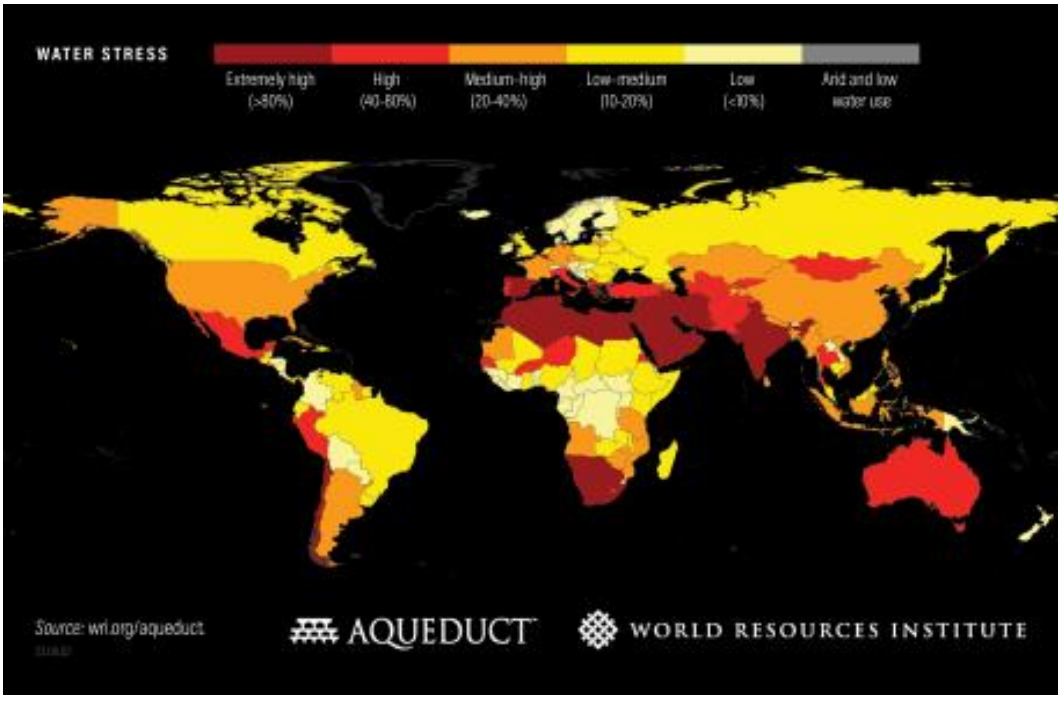


Figure 5A.8.1: Map of Water Stress in 2050 *(World Resources Institute, 2023)*

8.1.2 Desalination systems overview: Desalinated water is used or can be used in various economic sectors such as industry, agriculture, food processing, healthcare, and recreation (Al-Jabri and others, 2019). Among these, the municipal sector uses 62.3 percent, while industries use 30.2 percent of desalinated water production (Cai and others, 2023). In 2019, the desalination market was highest in Middle East and North Africa region (45.32 percent) followed by East Asia and Pacific (17.52 percent), North America (11.34 percent), Western Europe (8.75 percent), Southern Asia (2.94 percent), Eastern Europe and Central Asia (2.26 percent) and sub-Saharan Africa (1.78 percent). In 2020, approximately 97.2 million cubic meters per day of freshwater was produced globally from 20,971 projects, supported by 16,896 installed desalination plants (Do Thi and others, 2021).

On the technological front, most commonly used commercial desalination methods include reverse osmosis, multi-stage flash, and multi-effect distillation, and electrodialysis (Almasoudi and Bassam, 2024). In 2000, thermal technologies and reverse osmosis (RO) accounted for 93 percent of total water volume produced by the desalination process. Since then, both the number and capacity of RO plants have risen exponentially, while thermal technologies have experienced marginal increases (Jones and others, 2019). Membrane desalination technology (involving RO) accounts for about 85 percent of total worldwide desalination plants and generates approximately 69 percent of global desalination capacity. Whereas, thermal desalination, involving multi-stage flash and multi-effect distillation, provides about 18 percent and seven percent of global desalination capacity, respectively. It accounts for 2.1 and 5.6 percent of total desalination plants, respectively (Elsaid and others, 2020a; Curto and others, 2021). In terms of intake sources, desalination plant productions involve 61 percent seawater, 21 percent brackish water, eight percent rivers, six percent wastewater, four percent pure water and one percent brine (Jones and others, 2019).

8.1.3 Salt production and desalination brine systems: Salt is a strategic commodity and fundamental part of society that satisfies human and industrial needs. Traditionally, sea salt has been produced via natural evaporation of seawater in large and shallow basins. Worldwide, salt extraction is around 40 percent via solar evaporation of seawater, 35 percent from inland brine and 25 percent from mining of rock salt and brine solutions, although global productions are fluctuating (Tridge, 2021). In 2023, global salt production was estimated to be around 270 million metric tons with China, United States of America and India being the largest producers of salt (USGS, 2024). Conveying desalination discharges to conventional salt production ponds offers an integrated approach to recover valuable salt from brine (Cipollina and others, 2012; Wenten and others, 2017). Seawater desalination plants produce more than 150 million cubic meters of brine per day globally, 80 percent of which is discharged within ten km of coasts (Eyl-Mazzega and Cassignol, 2022). Brine production in Saudi Arabia, UAE, Kuwait, and Qatar accounts for 55 percent of the total global share (Jones and others, 2019). Reject brine from desalination plants contain high total dissolved solids contents typically ranging between 55 and 70 mg/L (Panagopoulos, 2021a). Findings suggest that integration of brine management with salt

recovery processes can offer opportunities for salt production and recovery, however, further investigations are needed to establish these strategies.

8.1.4 Integration strategies for desalination, salt production and raw materials extraction: Methods commonly used for brine disposal include sea discharge, land disposal, evaporation, membrane distillation, forward osmosis, deep electrodialysis, capacitive deionization, well injection, and sewage disposal (Mavukkandy and others, 2019). Disposal method selection depends upon brine quantity, quality, discharge location, availability of dump sites, operational and transportation costs. Around 5-33 percent of total desalination cost is spent on brine disposal processes (Backer and others, 2022). Minerals recovery and waste-to-value products offer more cost-effective solutions for handling brine. Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) systems for brine treatment enhance freshwater recovery and minimize wastewater effluent. The global MLD and ZLD market was worth US$0.71 billion in 2018, and is expected to rise to US$1.76 billion by 2026, showing a 12.1 percent compound annual growth rate (CAGR) during the projected period (Panagopoulos, 2021a). Most modern seawater desalination plants use reverse osmosis membranes with a recovery of 30–50% water depending on seawater salt concentration and processes involved. Significant salt concentration increase makes recovery of sodium chloride more economical than conventional production methods (Sharkh and others, 2022). Beside sea salt extraction, brines, and bitterns (ultra-concentrated brine left after the sea salt precipitation) have been assessed as an important source of critical raw materials such as boron, magnesium, rubidium, and many other trace elements for which extraction technologies have been recently developed and tested at the pilot scale (Randazzo and others, 2024). Overall, data suggests that sea salt production and mineral recovery from brine can serve as a promising integration strategy for desalination plants and can be established with additional studies.

SECTION 8.2 – PRESSURES AND IMPACTS

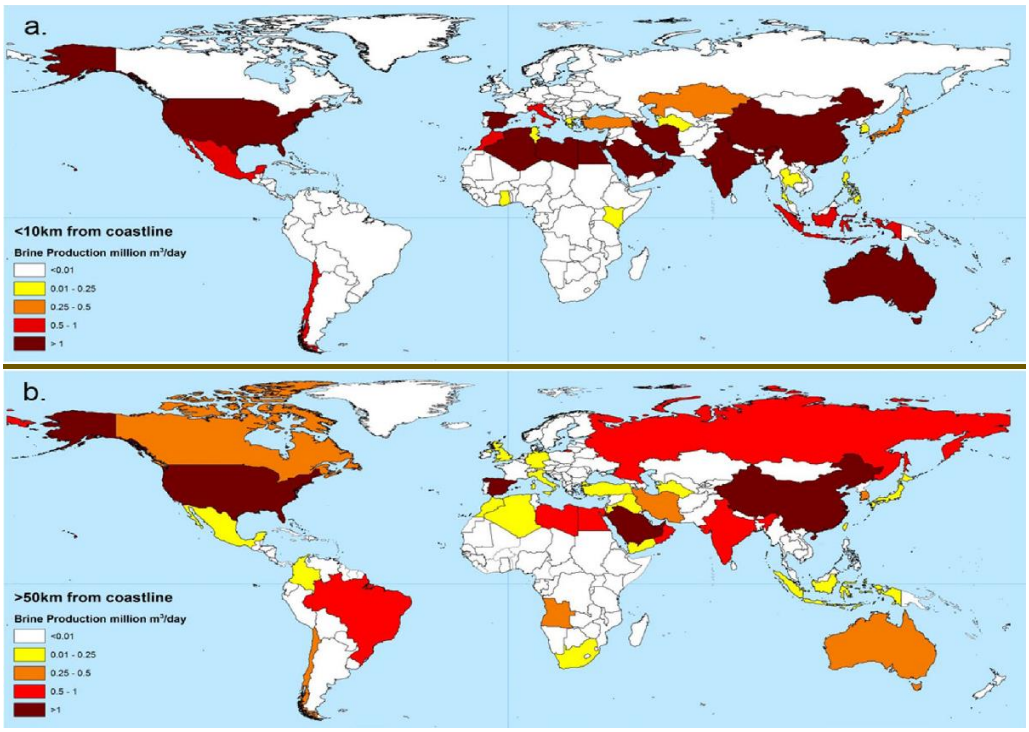
While desalination systems offer reliable water supply and socio-economic welfare, they also lead to potential negative impacts on the environment. The following picture depicts desalination impacts and potential mitigation measures:

Figure 5A.8.2: Desalination Environmental Impacts and Mitigation Avenues (Shokri and Sanavi, 2023)

8.2.1 Environmental impacts of brine discharges: Concentrated brine discharge to sea is the main waste product of desalination plants. Brine discharges from desalination plants lead to higher salinity, elevated temperatures, and release of source water conditioning chemicals. The desalination wastewater salinity ranges 55 to 70 parts per thousand (ppt) compared to regular ocean salinity of 35 to 45 ppt worldwide (Voutchkov and others, 2019). Brine produced via reverse osmosis process has about twice the salinity of seawater, while thermal desalination processes produce brines of around 1.5 times seawater salinity. Brine plumes of waste dissipate rapidly, and salinity stress is often limited to organisms located directly in the vicinity of the outflow (Omerspahic and others, 2022; Panagopoulos and others, 2019). Spatial distribution of brine plume (including perimeter, flow direction, and buoyancy) varies according to discharge volume, rate, and dispersion technology (Petersen and others, 2018). An increase in salt concentration raises water density, turbidity, and fosters stratification of receiving water (Miri and Abdelwahab, 2005). Various chemicals used and produced during the desalination process end up in brine discharges. These compounds include chlorine, anti-scalants, coagulants, flocculants, strong acids, or bases, oxidizing agents, reducing agents, antifouling agents, foaming inhibitors, and heavy metals that are released into the water (Petersen and others, 2018; Do Thi and others, 2021; Omerspahic and others, 2022). These compounds have the potential to alter the pH of the water, increase the amount of nutrients, and produce more algae (Do Thi and others, 2021). Overall, it is well-established that brine discharge for desalination plants pose serious environmental concerns.

8.2.2 Impacts on marine life and source environment: Environmental impacts of desalination plants on marine life and source environment depend upon factors like nature of feed water, desalination technology used, and waste brine management (Missimer and Maliva, 2018). On the water intake side of the plants, marine life is affected via three main processes: entrapment, impingement, and entrainment. Entrapment involves trapping marine species in systems with long offshore pipelines and screens at the onshore end. During impingement, aquatic organisms get sucked against the intake screens and cannot escape. Entrainment happens where smaller species pass through the intake screens and subsequently get killed during the desalination processes (Nielsen and others, 2024). Conventional open-ocean intake systems prominently experiences impingement and entrainment of marine organisms. Submerged pipelines or open intakes of desalination plants remove fish eggs and small marine organisms (like plankton and larvae) from seawater (Missimer and Maliva, 2018; Petersen and others, 2018). Entrainment also affects membrane biofouling associated with the intake of seawater and toxins in the seawater from harmful algal blooms (Anderson and others, 2017). It is well-established that desalination plant water intake structures widely impact nearby marine life.

For locations with closed or shallow circulations, sluggish currents and abundant marine life, the impact of the brine plume can be significant on the local marine ecosystem (Panagopoulos and Haralambous, 2020). The temperature rise due to brine discharges causes lowering of dissolved oxygen content in receiving waters, increased metabolism rate of its faunal inhabitants and elicit physiological and behavioral responses in organisms (Miri and Abdelwahab, 2005). Concentrate disposal can locally harm benthic communities if poorly diluted discharge is allowed to flow across the marine bottom (Missimer and others, 2018). Brine discharges may cause depletion of benthic community abundance and diversity (Sola and others, 2020). Brine effluent impacts coastal species (such as bacteria, zooplankton, seagrass, fish larvae, and corals). Studies have suggested alteration of activity and diversity of bacteria and microalgae, reduction in meiofauna abundance, impacts on the physiology of seagrass meadows near outfall site (Petersen and others, 2018). These processes can lead to the disruption of marine habitats and ecosystems by altering the connections between ecosystem elements. In this context, the development of Marine Protected Areas (MPAs) in coastal waters requires careful planning around the location of desalination facilities so that connectivity between MPAs is not lost due to the impacts of brine or thermal plumes (Heck and others, 2017). WOA III Section 3 Chapter “A Global Overview of Ocean Governance chapter” can be referred for additional information on MPAs. Overall, studies indicate that brine discharges have wide-ranging impacts on marine life and require continued investigations to establish specific trends, which are recognized but still incomplete.



~~**Figure 5A.8.3: Amount of brine generated by each country at a distance of a < 10 km and b > 50 km from the coastline.** Reproduced from Jones and others (2019)~~

8.2.3 Air pollution impact of desalination plants: Energy requirements for the desalination process depend upon the technology used, system details and salinity of water being used as source (Lienhard and others, 2016). Desalination is an energy intensive process that still relies heavily on fossil fuels. Intensive application of energy is mainly associated with fossil fuel burning, electricity generation, plant lighting, freshwater, and brine transportation (Ameen and others, 2017). Large-scale reverse osmosis plants produce water at a rate of between 2.5–4 kWh/m^3 compared to approximately 0.3 kWh/m^3 for the treatment of conventional sources of potable water (Paraschiv and others, 2023; Zarzo and Prats, 2018). Desalination plants utilize five percent of the total energy consumed by the water sector and that value is expected to rise to 20 percent by 2040 (IEA, 2016). Only one percent of total desalinated water uses renewable sources. The expected growth of desalination, if not coupled with renewable energy (RE), will cause a projected 180 percent increase in carbon emissions by 2040 (Caretta and others, 2022). In addition to direct use of renewables, indirect use for desalination will also be important. When electricity production from intermittent and variable renewables exceeds demand, sector coupling can offer mutual benefit to use surplus power for desalination at low cost without having to shut down generation to stabilize the grid.

The air pollution initiated by desalination plants is significant due to greenhouse gases (GHGs) emissions, primarily carbon dioxide (CO_2), acid rain gases, and other air contaminants produced during the production of electricity or steam from fossil fuels

heavily influence the quality of air and accelerates global warming remarkably (Shokri and Sanavi Fard, 2023). While energy consumption varies according to the energy mix, the type of plant and its size, it can nevertheless be estimated that at least 120 million tons of CO_2/year are generated by desalination sectors each year (Eyl-Mazzega and Cassignol, 2022). By 2040, installed desalination capacity worldwide is estimated to contribute 218 million tons of CO_2 annually (Shahzad and others, 2017). Lowering the carbon footprint of desalination technologies becomes essential to reduce global warming and climate change impacts. This can be done by adopting measures towards sustainability including improving the existing desalination systems and plants and relying on more sustainable energy sources. Mitigative strategies like careful selection of land, intake and outfall design, brine mining, brine treatment, application of green desalination technologies, water/energy recovery, environmental impact assessment and CO_2 sequestration, can help to reduce undesirable environmental footprints (Shokri and Sanavi, 2023). Use of renewable energy and mitigation strategies to minimize air pollution and climate change impacts are well-established.

8.2.4 Socio-economic and socio-political impacts: Desalination in the 21st century is inextricably tied to the changing paradigms of water management. Globalization of desalination is driven by techno-political factors, water management decentralization, growing role of infrastructure as a source of revenue for financial actors entering the field of water management, and pressure to facilitate economic growth in particular economic sectors (Williams, 2022). The acceptance and proliferation of desalination systems are impacted by various environmental, economic, and sociopolitical factors that are quite often intermingled and difficult to isolate (Ibrahim and others, 2021). This is especially true in regions heavily affected by climate change, where water crises and increased geopolitical risks arise. Strengthening cooperation between countries of the regions is needed to address these issues (Al-Saidi and others, 2023). Desalination is generally available to regions that can either afford the upfront costs and operational expenditure or have an attractive financial risk profile for investors. This can lead to uneven development, where profitable areas are supplied with high-quality water and unprofitable areas are left un-serviced. There is a growing body of research showing that desalination, depending on how it is deployed, can exacerbate social inequalities (Fragkou 2018; O'Neill, 2024; Velásquez and Wachtendorf, 2023). The strength, weakness, opportunities, and threats (SWOT) analysis of the desalination sector identifies water security, health benefits and political stability as key strengths while employment and female empowerment as potential opportunities (Ibrahim and others, 2021). WOA III Section 5B Chapter 5 "Equity" can be referred for additional details on these aspects. Further studies are needed to understand the global extent of social and economic impacts of desalination systems, as current findings remain inconclusive.

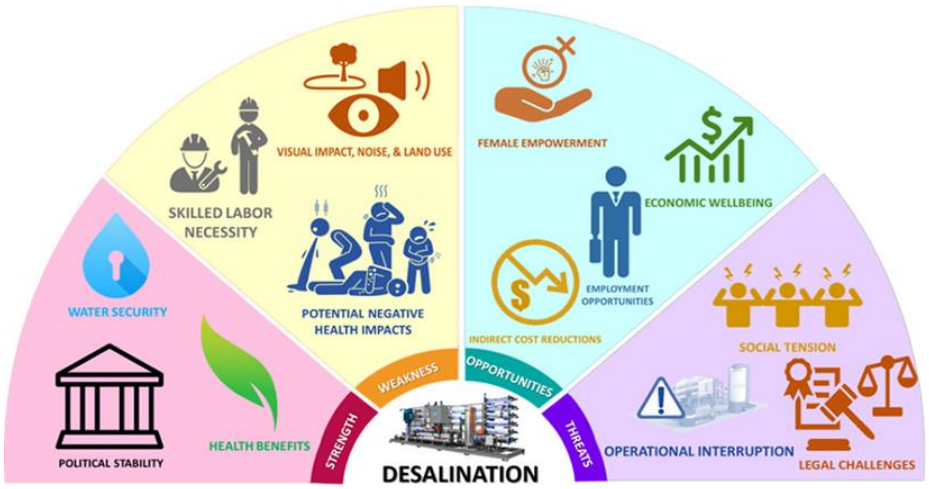


Figure 5A.8.4: Socio-Political factors impacting Desalination Sector (Ibrahim and others, 2021**)**

SECTION 8.3 – SUSTAINABILITY PATHWAYS

8.3.1 Sustainability – Technology: To achieve technological sustainability, efforts focus on reducing costs, energy consumption and minimizing environmental impacts. Advances such as energy-efficient pumps, energy recovery devices, and high flux membrane materials have significantly reduced the energy consumption of RO systems over the years (Ahmed and others, 2021). The incorporation of carbon-based, metal-oxide based, and cellulose-nanocrystals based nanoparticles in desalination membranes enhances performance, positively impacting sustainability (Saleem and Syed, 2020). Alternative system configurations, like closed-circuit RO, osmotically mediated RO, and multipass low-rejection RO, potentially allow reduced specific energy consumption (SEC) and increased water recovery (Lin, 2019). Energy recovery devices such as pressure exchanger, Pelton wheel, Francis Turbines, and hydraulic turbo-charger have already been widely adopted in RO systems to harvest hydraulic energy from brine (Das and others, 2024; Takabatake and others, 2021). Alternative technologies such as forward osmosis (FO), capacitive deionization (CDI), membrane distillation (MD), electrodialysis (ED) and electrodialysis reversal (EDR), are aiming for cost minimization, improved plant operations, reduction in fossil fuel consumption, use of renewable energy sources and cutting down GHG emissions (Elsaid and others, 2020b; Mavukkandy and others, 2019).

Apart from energy and GHG-related sustainability concerns, brine disposal remains a major challenge, particularly for inland desalination plants (Mavukkandy and others, 2019). Sustainable brine management strategies focus on reducing wastewater effluent volumes and recovering valuable materials such as water, minerals, salts, and metals. To achieve this, brine discharge treatment technologies can be combined and integrated with Minimal and Zero Liquid Discharge (MLD/ZLD) systems. The ZLD approach aims to recover 100 percent of freshwater while eliminating liquid waste and producing solid salt

(Panagopoulos, 2022). Another potential strategy is the recovery of osmotic energy from high-salinity brine, although its cost-effectiveness has yet to be demonstrated at commercial scale (Lin, 2019; Wang and others, 2019). To mitigate environmental impacts of high discharge temperatures on oceans, various approaches are employed, including heat recovery exchangers, and low-temperature thermal desalination technologies (Curto and others, 2021; Natarajan and others, 2022). Additionally, water extraction from brine supports the sixth United Nations Sustainable Development Goal targets. As desalination technologies continue to evolve, advancements in recovery and reuse of water and other key materials from brine discharges are highly likely.

8.3.2 Sustainability – environment: Environmentally safe and sustainable management of desalination systems is essential for long-term sustainability. Key mitigation strategies include site-specific environmental impact assessments, long-term monitoring programs tailored to desalination sites, and the application of the best available technologies for managing brine effluent (Gude, 2018). The integration of renewable energy sources—such as solar, wind, and geothermal—provides viable solutions for powering desalination plants, optimizing processes, and reducing both energy costs and specific energy consumption (Abdelkareem and others, 2018; Panagopoulos, 2021b; Saavedra and others, 2021). Figure 5A.8.5 illustrates the current status of various renewable energy technologies:

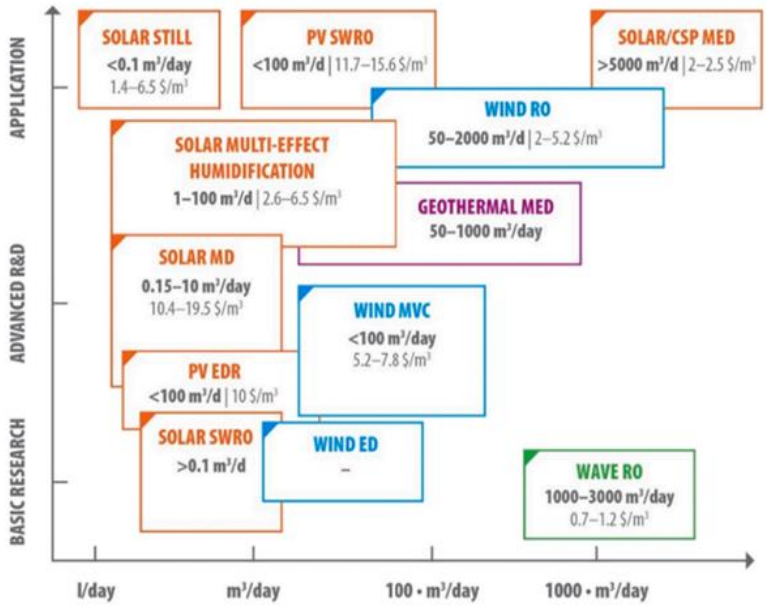


Figure 5A.8.5: Commercialization status of various desalination technologies (Bundschuh and others, 2021)

Solar energy use with battery storage on a large scale is a promising option. Solar photovoltaic powered RO offers an effective alternative (Bundschuh and others, 2021). With plenty of sunlight, Arab countries are the biggest users of solar-powered desalination plants, followed by the United States of America, Australia, China, Central European

countries, Mediterranean countries, and Japan (Almasoudi and Bassam, 2024). The following schematics show solar energy usage in desalination plants.

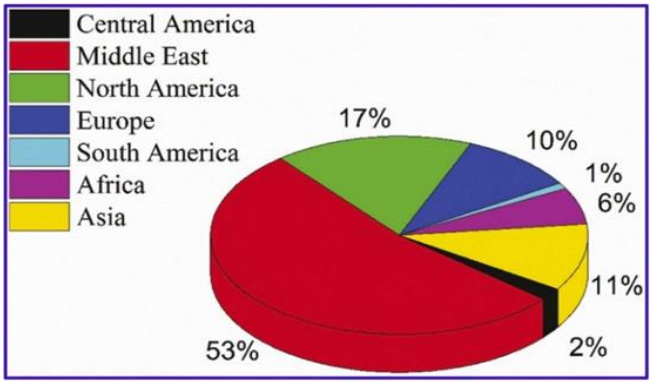


Figure 5A.8.6: Solar powered desalination plants (Almasoudi and Bassam, 2024)

Wind energy has matured into reliable technology with many seawater RO plants implemented in Australia (Voutchkov, 2023). After solar energy, wind power is the second-most frequently used renewable energy source for desalination plants. Constantly rising wind power production accounted for 18 percent (1134 TWh) of world's electricity production from renewable energy sources in 2017 in onshore and offshore applications. Direct wind power use for desalination plants would partially alleviate power grid flexibility and reduce environmental impact up to 75 percent compared to fossil fuels (Greco and others, 2021). Hydraulic pressure stored in deep seawater can also output stable and successive energy flow (Cui and others, 2021). Also, countries like India, China, USA, Pakistan and Iran account for between 56% and 62% of the global desalination demand for irrigation sector. Via irrigation efficiency growth rate improvements, global desalination demand can be reduced by as much as 30% and 60% by 2050 (Caldera and Breyer, 2020). Desalination sector needs additional studies to explore and establish environmental benefits of replacing traditional fossil fuels with alternative renewable energy sources.

8.3.3 Sustainability – Management: Proper management of the desalination sector is necessary to minimize maladaptation and legal issues (Campero and Harris, 2019). Key challenges include the disproportionate burden of tap water pricing on vulnerable households compared to continental water sources (Vicuña and others, 2022) and reduced incentives for adaptation due to the perception of seawater as an infinite resource (Fragkou & Budds, 2020), among others. To achieve sustainable desalination management, plants focus on optimizing resource use, ensuring operational continuity, and implementing risk-mitigation strategies (Al-Saidi and others, 2023). The integration of systems such as Geographic Information Systems (GIS) and Supervisory Control and Data Acquisition (SCADA) plays a crucial role in preventing water shortages. GIS enables visualization, analysis, and asset management of desalination networks, while also assisting with data representation and spatial analysis through advanced tools (Kamal and Mahmoud, 2024). Compliance with environmental regulations requires continuous

monitoring of operational impacts and adherence to legal thresholds (Al-Saidi and others, 2023). Desalination plants implement comprehensive systems to predict, monitor, and mitigate potential ecological impacts throughout all project phases, from planning and design to construction and operation (Voutchkov and others, 2019).

8.3.4 Sustainability - economy and market: To cope with increasing water stress, the desalination industry is growing rapidly and emerging as one of the leading solutions. The majority of this growth has been in seawater, rather than brackish water desalination. Desalination requires complex technology and significant capital expenditure with upfront investment. The capital expenditure (CAPEX) for a desalination plant is estimated between US$0.65 million and US$1.2 million for every 100 m^3/day of desalinated water (Eyl-Mazzega and Cassignol, 2022). Plant operating costs are high, mainly involving energy use, labor, replacements, and chemicals. Out of these, expenses from thermal and electrical energy are expected to be 50% of total cost (Nassrullah and others, 2020). Average desalinated water production cost ranges from \$0.5/m^3 for large plants, to more than \$1.25/m^3 for smaller plants. For mega plants in the Gulf, production cost has reached competitive pricing of below \$0.5/m^3 (Eyl-Mazzega and Cassignol, 2022). Average desalinated water production cost ranges from \$0.5/m^3 for large plants, to more than \$1.25/m^3 for smaller plants. For mega plants in the Gulf, production cost has reached competitive pricing of below \$0.5/m^3 (Eyl-Mazzega and Cassignol, 2022). Since 2010, global installed capacity for water production from desalination plants has increased at an average rate of 7% per annum, corresponding to approx. 4.6 million m^3/day per year (EU, 2024). By 2027, the global desalination market—which was estimated to be worth USD 17.7 billion in 2020—is projected to grow to USD 32.1 billion. From 2020 to 2027, the desalination sector is expected to expand at a robust compound annual growth rate (CAGR) of 9.51 percent worldwide (Do Thi and others, 2021). Figure 5A.8.7 shows the size and spatial distribution of desalination facilities (>1000 m^3/day) (Jones and others, 2019). Given past trends and current water scarcity challenges, it is highly likely that the number of desalination plants and global installed capacity will continue to increase in the future.

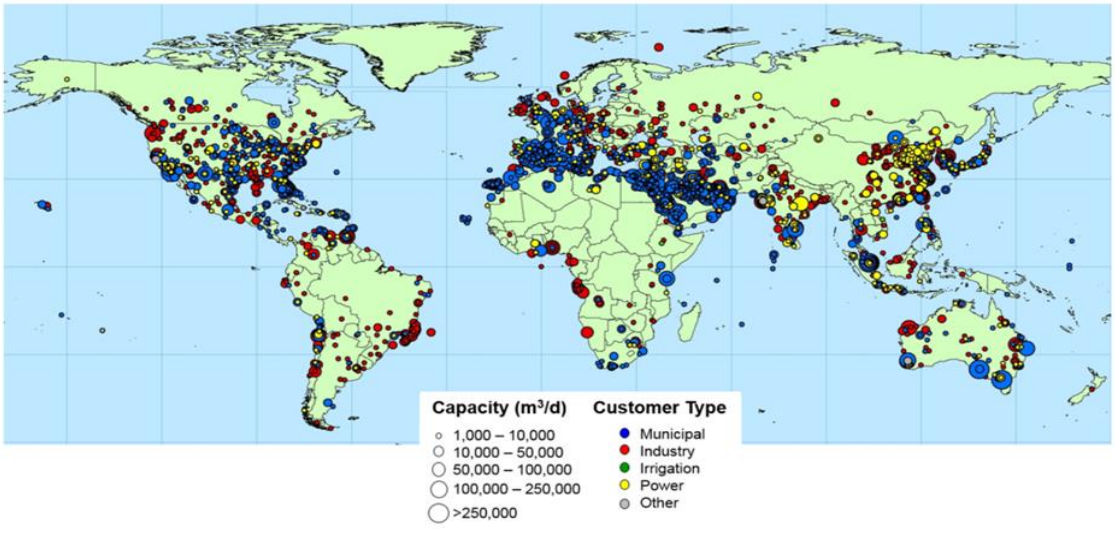


Figure 5A.8.7: Global distribution of operational desalination facilities and capacities (>1000 m3/day) by sectors user of produced water (Jones and others, 2019)

The power industry remains the largest owner of installed capacity for industrial purposes. The Seawater and Engineering-Procurement-Construction (EPC) model is the most frequently used feed water and plant delivery methods, accounting for 57 percent and 71.7 percent of global installed capacity, respectively. Capital cost accounts for the larger share of specific water production cost (Eke and others, 2020). The number and capacity of desalination plants by geographic region, country income level and sectoral use of desalinated water suggest that half of the global desalination capacity is located in the Middle East and North Africa region, with Saudi Arabia, the United Arab Emirates and Kuwait being both the major producers in the region and globally (Jones and others, 2019). Additionally, the Middle East and North African (MENA) states are committing to long-term action plans that involve development of desalination plants. In most countries in these regions, desalination capacity is expected to double by 2030 or 2050 at the latest. Although the desalination sector is dominated by the Middle Eastern Countries, there is also a trend towards geographical dispersal, with markets growing in North Africa, Asia, and the Americas (Eyl-Mazzega and others, 2022). Coupled with this, the importance of desalination to a growing number of industries (e.g., mining in Chile, manufacture of semiconductors in Taiwan Province of China), climate change and other pressures on traditional water resources, desalination is likely to continue to grow as an important frontier of the blue economy (Campero and others, 2023). Europe, Africa, and many other regions are experiencing a sharp rise in desalination capacities that did not support desalination in the past (Eke and others, 2020). Overall, the global footprint of desalination plants will very likely continue to expand.

SECTION 8.4: SOCIAL COMPONENTS

8.4.1 Benefits: Seawater desalination offers numerous environmental, socio-economic and health benefits to humanity (Ihsanullah and others, 2021). Most obvious benefit of desalination is providing drinking and domestic water to millions of people in large cities and especially dry regions (like Gulf Cooperation Council) where reliable water supply is needed to sustain regional economies. (Moossa and others, 2022). Many countries like Bahamas, Maldives, and Malta, meet all their water needs through the desalination process (UNEP, 2021). Apart from drinking and domestic water supplies, desalinated water is used in agriculture, industries, medical facilities, aquaculture, and many other sectors. Water scarcity has led to the use of desalinated water for crop irrigation, especially in arid and semi-arid agricultural countries in the mediterranean and Middle East and North Africa (MENA) regions, such as south-eastern Spain and Israel (Awaad and others, 2020; Martínez-Alvarez and others, 2016). When coupled with water reuse for irrigation, desalination can reduce groundwater extraction, enhance the water cycle, and support adaptation to and mitigation of climate change impacts (Pistocchi and others, 2020). Another important benefit is salt production (liquid salt). Traditionally, evaporative ponds have been used in many countries with high evaporation rates to produce salt. With the

emergence of desalination plants, use of this technology for salt production has been widely reported in the literature (Ahmed and others, 2001; Ahmed and others, 2003). Regarding employment, job trends suggest that the global transition to 100 percent renewable energy across the power, heat, transport, and desalination sectors is a widely recognized and firmly supported approach that will create more stable, local jobs essential for economic growth while reducing unemployment. Direct energy sector jobs across these industries are projected to rise from approximately 57 million in 2020 to nearly 134 million by 2050 (Ram and others, 2022). With its multiple benefits, desalination is increasingly being utilized beyond drinking water, proving its reliability and effectiveness across various applications.

8.4.2 Dis-benefits: Despite its benefits, desalination has some serious drawbacks associated from its siting, functioning to the final use of produced water. Direct seawater intake at desalination plants can absorb planktonic organisms, fish eggs, and larvae, among others, affecting traditional small-scale fishing (Missimer and Maliva, 2018). In the same vein, brine discharge may affect local marine flora and fauna, and discharges can reduce fish populations due to salinity and temperature increase, thus affecting activities that depend on marine resources (Kelaher and Coleman, 2022; Omerspahic and others, 2022). Other impacts of the plants siting are related to land-use conflicts as desalination may compete with recreational coastal activities. Water scarcity has also led to the use of desalinated water for crop irrigation in the Mediterranean and MENA regions (Awaad and others, 2020; Martínez-Alvarez and others, 2016). Although desalinated water is an abundant and climate-independent source, use of desalinated seawater in agriculture is associated with a series of drawbacks such as high boron concentrations, the lack of plant nutrients (compared to continental water sources), accumulation of sodium in soil structure and its high cost. These downsides of desalination technology makes it viable mostly for high value crops (Kaner and others, 2017; Martínez-Alvarez and others, 2016). Finally, the use of desalinated water for human consumption may not guarantee water security or eliminate scarcity on smaller scales, such as that of the household (McEvoy, 2014; Fragkou and McEvoy, 2016), while its integration into urban supply networks may increase the cost of tap water (Ricart and others, 2021), modify its organoleptic characteristics (Shomar and Hawari, 2017), and receive lower consumer approval (Hurlimann and Dolnicar, 2016). What is more, studies on the health impacts of long-term desalinated water consumption indicate a decrease in magnesium levels (Ben Zaken and others, 2020; Koren and others, 2017), a below-average iodine intake (Ovadia and others, 2016) and a wide variability in concentrations of inorganic chemicals that are below or above the WHO recommended limits for drinking water (Rizk, 2009). Due to multiple disadvantages, extensive studies are needed to properly establish correlations between desalinated water, human health impacts and effects on agricultural practices.

8.4.3 Equity: Various benefits and dis-benefits associated with desalination are unevenly distributed, creating winners and losers. These highly context-specific benefits or burdens of desalination reflect on and reinforce existing socio-economic inequalities. In a society where water system is characterized by entrenched inequality and structural problems, the

introduction of desalination is likely to exacerbate these issues, whereas in a context characterized by a greater degree of equity, the benefits and dis-benefits of desalination are likely to be more evenly spread (Fragkou, 2018; McEvoy, 2014). There is a growing body of research that analyzes the implications of desalination for equity and environmental justice (O'Neil and Williams, 2024). The high cost of desalination facilities compared to conventional water source options almost always contributes to rising water prices for consumers, unless subsidized by states or charities, which can create a burden on poorer households. Furthermore, it has been demonstrated that in contexts where water supply systems are fragmented, or where there is no universal networked access to water, the introduction of desalination can further drive fragmentation, often supplying more affluent areas with high quality water and leaving less profitable areas under-serviced (Fragkou, 2018; Velásquez and Wachtendorf, 2023). As desalination technologies are increasingly rolled out in the Global South, there is growing concern that in certain contexts they may have the unintended consequence of increasing water inequalities (Millington and Suraya, 2021; Williams and others, 2023). The extent of inequalities by desalination plants are site specific and widely spread across the sector and unresolved.

8.4.4 Gender: World Bank utility survey from 64 utilities in 28 economies around the world suggests that women are underrepresented in the water sector. Despite a growing understanding of the importance of incorporating women in water management and industry, women represent hardly 18 percent of water utilities employees and occupy around 23 percent of engineering and managerial positions in the water sector. This reflects the low presence of women in science, technology, engineering, and mathematics (STEM) professions, which is a global trade that is gradually changing (World Bank, 2019b). There are some specific examples of overturning this situation in the desalination sector, such as training programs in the field of reverse osmosis exclusively for women in Saudi Arabia (SWM, 2022). In line with this trend, women also tend to have less knowledge on coastal processes and marine ecosystems, which prevents them from taking informed decisions or participating in coastal decision-making processes related to desalination (Heck and others, 2018a). Existing data establishes that the desalination workforce is disproportionately distributed amongst genders with an underrepresentation of women.

8.4.5 Public Perception and Acceptance: Public awareness and acceptance is an important aspect with infrastructure projects built to serve the public good. Regarding desalination, social preference and general public perception have been greatly influenced by coastal environmental effects and high energy consumption. Despite the benefits of new desalination projects, they often face strong opposition from a significant portion of society (Ibrahim and others, 2021). Opposition or acceptance to desalination projects also depend on biological, ecological, and environmental impacts, not-in-my-back-yard (NIMBY) attitude, influence of sociodemographic variables (like gender, age, education, and race on public acceptance) (Haddad and others, 2018), concerns about marine impacts, lack of institutional trust (Heck and others, 2018b) amongst many others. As the use of seawater desalination continues to grow and large-scale plants become more common, public opposition to desalination projects has also grown. While multiple surveys and

studies have shown that the general public is supportive of seawater desalination, many environmental organizations and other public advocacy groups have become outspoken critics of desalination projects (Liu and others, 2022; Haddad and others, 2018; Dolnicar and others, 2011). Desalination projects have been adapting to these concerns by developing greener, more sustainable approaches and establishing public-private partnerships for project development and governance. However, public perception and support for desalination systems remain uncertain and not yet well established.

SECTION 8.5 GOVERNANCE:

8.5.1 Standards and Frameworks: Clear rules, standards and frameworks achieve an open and transparent decision-making process for the permission and regulation of desalination projects (UNEP, 2008). These standards typically involve guidelines for monitoring of design, construction, water quality, water excellence parameters, pollution, emissions, impacts on marine life, and related aspects. In 1984, the World Health Organization first published "Guidelines for Drinking Water Quality (GDWQ)" for safe drinking water supplies that cover a broad spectrum of contaminants and aimed at typical drinking water sources and technologies. This document has gone through several updates and editions since then (1993, 2008, 2017) (WHO, 2008; WHO, 2009). In 2003, UNEP/MAP published ''Sea Water Desalination in the Mediterranean, Assessment and Guidelines'' to offer a common management approach for desalination projects and has been largely used by the Contracting Parties for monitoring desalination projects (UNEP/MAP, 2003). United Nations Environmental Programme (UNEP) report "Resource and Guidance Manual for Environmental Impact Assessments" was published in 2008, in association with WHO, offering guidance to regulators, project designers and decision makers to anticipate and address all relevant concerns associated with desalination projects and achieve maximum beneficial use of water (UNEP, 2008). To cover health and environmental aspects of desalination developments and supplement GDWQ, WHO further prepared the document on "Desalination for Safe Water Supply" in 2011 (WHO, 2011).

8.5.2 Legality and transboundary conflicts: Technical approval, financing, and legal due diligence are essential for the successful completion of desalination projects. The formalization of projects and the relationships among involved stakeholders are established through various contracts, including partnership agreements, framework agreements, agreements between lenders and guarantors, financing contracts, construction and operations contracts, water purchase and sale contracts, as well as lease and land use contracts (Montano and others, 2021). Federal and state level regulatory standards and permits are important for proper execution and handling of sensitive environmental aspects (Alonso and Noemi, 2018; Younos and Juneseok, 2019). Regarding transboundary relations, the role of desalination is rising in national strategies. Desalination provides countries with greater flexibility in negotiations; however, it can also reduce incentives for cooperation. These dynamics are most common in basins where at least one country is highly developed. However, desalination is also playing a role in transboundary basins such as the Nile and Mekong (Katz, 2021). Some studies suggested

that desalination can lead to greater cooperation between neighboring states, either by reducing dependence on transboundary resources, such as rivers or aquifers, or by opening up new opportunities for cooperation, such as energy-for-water agreements (Aviram and others, 2014; Bromberg and others, 2020). Others, by contrast, have suggested that these technologies may exacerbate uneven power relations and tensions between states (Katz, 2021).

8.5.3 Stakeholders Engagement: To ensure transparency and address any community concerns, stakeholders' engagement is necessary during the planning, decision-making and implementation process (UNEP, 2008). From the 1980s, global acceptance of integrated water resource management (IWRM) has led to decentralization of water management. IWRM also increased prospects for greater accountability, environmental sustainability, transparency, equity, and stakeholder participation in water management processes (Patel, 2023). International and regional guidelines from organizations like UNEP, Organization for Economic Co-operation, and Development (OECD), International Dispensary Association foundation, the European Union, and the United States Environmental Protection Agency provide frameworks to standardize these practices and stakeholder involvement in water governance. For example, OECD's requirements for stakeholder engagement in water governance focus on recognizing different actors with a stake, their varied responsibilities, encouraging stakeholders' capacity development, assessing, and evaluating engagement processes, promoting conducive institutions, paying attention to underrepresented groups as well as an identifying appropriate stakeholder engagement initiative (Wehn and others, 2019). Among IWRM's principles, stakeholder participation in desalination projects is considered a democratic right in many places because it is claimed to increase accountability, legitimacy, and trust in governance (Patel, 2023). Stakeholder engagement is a valuable tool for developing a common understanding of context needed for making sustainable water management decisions (Megdal and others, 2017).

Significant emphasis is placed on the role of the private sector in delivering desalination projects through public-private partnerships. This focus is evident both within the industry and among governments and utilities in countries where desalination is widely deployed. One major impact of desalination's expansion has been the acceleration of trends toward the privatization of water supply—or at least an increasing influence of private sector actors in water resource management (Loftus & March, 2016; Williams, 2018). Economically, these financial actors provide essential capital for infrastructure projects but may also lead to higher tariffs, disproportionately affecting low-income households. In this context, public-private partnerships (PPPs) have gained popularity as a means to integrate private sector actors into the provision of government services. Global trends indicate a growing reliance on PPPs in the desalination industry, particularly in countries such as Israel, Australia, and the United States. Research also suggests that the public sector depends on private partners for the design, construction, and operation of desalination plants, regardless of the level of public financing (Greer and others, 2021).

While PPPs play a crucial role in fostering balanced growth within the desalination sector, their long-term effectiveness remains an area of ongoing evaluation.

8.5.4 Cultural Considerations and Indigenous Peoples' Rights: An estimated 476 million Iindigenous Ppeople live in over 90 countries around the world. Globally, they represent 18.7 percent of the extremely poor and around 33 percent of those living in extreme poverty in rural areas (UNHR, 2022a). Indigenous Ppeoples' social, cultural, and economic conditions distinguish them from non-Iindigenous sections of society (Cap-Net UNDP, 2018). Traditionally, water quality in Indigenous Peoples' territories has been preserved due to their sustainable practices and the inaccessibility of many of these areas. However, the growing impacts of extractivism on natural resources and climate change have increasingly threatened access to safe drinking water, posing challenges under international human rights standards. Water pollution, lack of consultation on policies and projects affecting water and sanitation rights, have undermined their access to clean water (UNHR, 2022a). Lack of access to safe drinking water also disproportionately affects Iindigenous women and girls (UNHR, 2022b). In this context, the establishment of desalination plants in regions inhabited by Indigenous Ppeoples can pose challenges to cultural considerations and traditional practices. This is why it is crucial to consider that water and culture are strongly interlinked when implementing a desalination project. Indigenous Peoples' knowledge related to water management and governance should be understood. The inclusion of cultural context is necessary in finding sustainable solutions in water governance (Angelakis and others, 2021; Heinrichs and Rojas, 2022). Relationship between the desalination sector and its impact on global Iindigenous Peoplessocieties is not yet properly established and hence needs to be investigated further.

REFERENCES:

- Abdelkareem, Mohammad Ali, and others. Recent progress in the use of renewable energy sources to power water desalination plants. Desalination, 435, pp. 97-113, 2018.

- Al-Jabri, Salem, and others. Comparative Analysis of Economic and Institutional Aspects of Desalination for Agriculture in the Sultanate of Oman and Spain. Desalination and Water Treatment, 156, pp. 1-6, 2019.

- Ahmed, Mushtaque and others. Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates. Desalination 133, no. 2, pp. 135-147, 2001.

- Ahmed, Mushtaque and others. Feasibility of salt production from inland RO desalination plant reject brine: a case study. Desalination 158, no. 1-3, pp. 109-117, 2003.

- Ahmed, Farah Ejaz, and others. Emerging desalination technologies: Current status, challenges and future trends. Desalination, 517, pp. 115183, 2021.

- Almasoudi, Saleh M., and J. Bassam. Desalination technologies and their environmental impacts: A review. Sustainable Chemistry One World, pp. 100002, 2024.

- Alonso, J. Jaime Sadhwani, and Noemi Melián-Martel. Environmental regulations—inland and coastal desalination case studies. Sustainable Desalination Handbook, Butterworth-Heinemann, pp. 403-435. 2018.

- Al-Saidi, Mohammad, and others. Governing desalination, managing the brine: A review and systematization of regulatory and socio-technical issues. Water Resources and Industry, pp. 100225, 2023.

- Ameen, Fahad, and others. The carbon footprint and environmental impact assessment of desalination. International journal of environmental studies, 75, no. 1, pp. 45-58, 2017.

- Anderson, Donald, and others. Harmful Algal Blooms (HABs) and desalination: A guide to impacts, monitoring and management, Paris, France, Intergovernmental

Oceanographic Commission of UNESCO, IOC Manuals and Guides No.78, 539 pp., 2017.

- Angelakis, and others. Desalination: From ancient to present and future. Water, 13, no. 16, pp. 2222, 2021.

- Aviram, Ram, and others. Desalination as a game-changer in transboundary hydro-politics. Water Policy, 16, no. 4, pp. 609-624, 2014.

- Awaad, Hassan A., and others. Availability and Feasibility of Water Desalination as a Non-Conventional Resource for Agricultural Irrigation in the MENA Region: A Review. Sustainability 12, no. 18: pp. 7592, 2020.

- Backer, Sumina Namboorimadathil, and others. Brine solution: current status, future management and technology development, Sustainability 14, no. 11: 6752, 2022.

- Ben Zaken, Sara, and others. Water desalination, serum magnesium and dementia: a population-based study. Journal of Water and Health, 18, no. 5, pp. 722-727, 2020.

- Bromberg, Gidon, and others. A Green Blue Deal for the Middle East. EcoPeace, 2020.

- Bundschuh, Jochen, and others. State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. Desalination 508, pp. 115035, 2021.

- Cai, Meiquan, and others. Impact of pipeline materials on water quality stability of desalinated seawater in the pipeline network. Desalination 556: 116558, 2023.

- Caldera, Upeksha, and Christian Breyer. "Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems." *Energy* 200, 117507, 2020.

- Campero, Cecilia, and Leila M. Harris. The legal geographies of water claims: seawater desalination in mining regions in Chile. Water, 11, no. 5, pp. 886, 2019.

- Campero, Cecilia, and others. Technologies of dispossession in the blue economy: Socio-environmental impacts of seawater desalination in the Antofagasta Region of Chile. The Geographical Journal, 189, no. 2, pp. 231-245, 2023.

- Cap-Net UNDP. Training Manual: Indigenous Peoples & Integrated Water Resources Management. https://www.waterlex.org/wp-content/uploads/2021/04/Indigenous-IWRM-Jan2019-low-web.pdf, 2018.

- Caretta, Martina A., and others. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551-712, 2022.

- Cipollina Andrea, and others. Integrated production of fresh water, sea salt and magnesium from sea water, Desalination and Water Treatment, 49, pp 390-403, 2012.

- Cui, Yifan, and others. A Hydrostatic Pressure-Driven Desalination System for Large-Scale Deep Sea Space Station. International Journal of Chemical Engineering, 2021, no. 1, pp. 8898472, 2021.

- Curto, Domenico, and others. A review of the water desalination technologies. Applied Sciences, 11, no. 2, pp. 670, 2021.

- Das, Abhimanyu, and others. Pressure exchanger batch reverse osmosis with zero downtime operation. Desalination, 574, pp. 117121, 2024.

- Do Thi, Huyen Trang, and others. Comparison of desalination technologies using renewable energy sources with life cycle, PESTLE, and multi-criteria decision analyses. Water 13, no. 21, pp. 3023, 2021.

- Dolnicar, Sara, and others. What affects public acceptance of recycled and desalinated water? Water research, 45, no. 2, pp. 933-943, 2011.

- Eke, Joyner, and others. The global status of desalination: An assessment of current desalination technologies, plants and capacity. Desalination, 495, pp. 114633, 2020.

- Elsaid, Khaled, others. Environmental impact of desalination technologies: A review. Science of the total environment, 748, pp. 141528, 2020a.

- Elsaid, Khaled, and others. Environmental impact of emerging desalination technologies: A preliminary evaluation. Journal of Environmental Chemical Engineering, 8, no. 5, pp. 104099, 2020b.

- European Union (EU), Desalination, https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/desalination_en#3, 2024.

- Eyl-Mazzega, Marc-Antoine and Élise Cassignol. The geopolitics of seawater desalination. Études de l'Ifri. Paris: Institut Français des Relations Internationales, 2022.

- Fragkou, Maria Christina, and Jamie McEvoy. Trust matters: Why augmenting water supplies via desalination may not overcome perceptual water scarcity. Desalination, 397, pp. 1-8, 2016.

- Fragkou, Maria Christina. Disclosing water inequalities at the household level under desalination water provision: The case of Antofagasta, Chile. In *Tapping the oceans*, Edward Elgar Publishing, pp. 76-97, 2018.

- Fragkou, Maria Christina, and Jessica Budds. Desalination and the disarticulation of water resources: Stabilising the neoliberal model in Chile. Transactions of the Institute of British Geographers, 45, no. 2, pp. 448-463, 2020.

- Greco, Francesca, and others. Integration of wind energy and desalination systems: a review study. Processes 9, no. 12, pp. 2181, 2021.

- Greer, Robert A., and others. Public–private partnerships in the water sector: the case of desalination. Water Resources Management, 35, pp. 3497-3511, 2021.

- Gude, Gnaneswar. Sustainable desalination handbook: plant selection, design and implementation. Butterworth-Heinemann, 2018.

- Haddad, Brent, and others. Social issues and public acceptance of seawater desalination plants. Sustainable desalination handbook, pp. 505-525. Butterworth-Heinemann, 2018.

- Heck, Nadine, and others. Management priorities for seawater desalination plants in a marine protected area: A multi-criteria analysis. Marine Policy, 86, pp. 64-71, 2017.

- Heck, Nadine, and others. Predictors of coastal stakeholders' knowledge about seawater desalination impacts on marine ecosystems. Science of the Total Environment, 639, pp. 785-792, 2018a.

- Heck, Nadine, and others. Management preferences and attitudes regarding environmental impacts from seawater desalination: Insights from a small coastal community. Ocean & Coastal Management, 163, pp. 22-29, 2018b.

- Heinrichs, Danielle H., and Rodrigo Rojas. Cultural values in water management and governance: where do we stand? Water, 14, no. 5, pp. 803, 2022.

- Hurlimann, Anna, and Sara Dolnicar. Public acceptance and perceptions of alternative water sources: A comparative study in nine locations. International Journal of Water Resources Development, 32(4), pp. 650–673, 2016.

- Ibrahim, Yazan, and others. The sociopolitical factors impacting the adoption and proliferation of desalination: A critical review. Desalination 498, 114798, 2021.

- Ihsanullah, Ihsanullah, and others. Desalination and environment: A critical analysis of impacts, mitigation strategies, and greener desalination technologies. Science of the Total Environment, 780, pp. 146585, 2021

- International Energy Agency (IEA), Water Energy Nexus, Excerpt from the World Energy Outlook 2016, https://www.iea.org/reports/water-energy-nexus, 2016

- Jones, Edward, and others. The state of desalination and brine production: A global outlook. Science of the Total Environment, 657, pp. 1343-1356, 2019.

- Kamal, Noha, and Mahmoud S. Ali. Improving the operational efficiency of water desalination systems through the integration of GIS-SCADA. Urban Water Journal, 21, no. 1, pp. 131-142, 2024.

- Kaner, Avigail, and others. Feasibility of desalination as an alternative to irrigation with water high in salts. Desalination, 416, pp. 122-128, 2017.

- Katz, David. Desalination and hydrodiplomacy: Refreshening transboundary water negotiations or adding salt to the wounds? Environmental Science & Policy, 116, pp. 171-180, 2021.

- Kelaher, Brendan and Coleman, Melinda. Spatial extent of desalination discharge impacts to habitat-forming species on temperate reefs. Marine pollution bulletin, 175, pp. 113368, 2022.

- Koren, Gideon, and others. Seawater desalination and serum magnesium concentrations in Israel. Journal of Water and Health, 15, no. 2, pp. 296-299, 2017.

- Lienhard, John, and others. Low Carbon Desalination: Status and Research, Development, and Demonstration Needs, Report of a workshop conducted at the

Massachusetts Institute of Technology in association with the Global Clean Water Desalination Alliance. MIT Abdul Latif Jameel World Water and Food Security Lab, Cambridge, Massachusetts, 2016.

- Lin, Shihong. Energy efficiency of desalination: fundamental insights from intuitive interpretation. Environmental science & technology, 54, no. 1, pp. 76-84. 2019.

- Liu, Ta-Kang, and others. Exploring the social acceptability for the desalination plant project: Perceptions from the stakeholders. Desalination, 532, pp. 115757, 2022.

- Loftus, Alex, and Hug March. Financializing desalination: Rethinking the returns of big infrastructure. International Journal of Urban and Regional Research, 40, no. 1, pp. 46-61, 2016.

- Martínez-Alvarez, V., and others. Seawater desalination for crop irrigation — A review of current experiences and revealed key issues. Desalination, Volume 381, Pages 58-70, 2016.

- Mavukkandy, Musthafa, and others. Brine management in desalination industry: From waste to resources generation. Desalination, 472, pp. 114187, 2019.

- McEvoy, Jamie. Desalination and Water Security: The Promise and Perils of a Technological Fix to the Water Crisis in Baja California Sur, Mexico. Water Alternatives 7(3), pp. 518-541, 2014.

- Megdal, Sharon B., and others. Water governance, stakeholder engagement, and sustainable water resources management. Water, 9, no. 3, pp. 190, 2017.

- Millington, Nate, and Suraya Scheba. Day zero and the infrastructures of climate change: Water governance, inequality, and infrastructural politics in Cape Town's water crisis. International Journal of Urban and Regional Research, 45, no. 1, pp. 116-132, 2021.

- Miri, Rachid, and Abdelwahab Chouikhi. Ecotoxicological marine impacts from seawater desalination plants. Desalination, 182, no. 1-3, pp. 403-410, 2005.

- Missimer, Thomas, and Robert Maliva. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination 434, pp. 198-215, 2018.

- Montano, Borja, and others. The financial and legal feasibility of a desalination project. Desalination, 517, pp. 115238, 2021.

- Moossa, Buzaina, and others. Desalination in the GCC countries-a review. Journal of Cleaner Production, 357, pp. 131717, 2022.

- Nassrullah, Haya, and others. Energy for desalination: A state-of-the-art review. Desalination, 491, pp. 114569, 2020.

- Natarajan, Sendhil Kumar, and others. A review on low-temperature thermal desalination approach. Environmental Science and Pollution Research, 29, no. 22, pp. 32443-32466, 2022.

- Nielsen, Kristin, and others. Potential environmental impacts of coastal desalination intake structures: Urgent data gaps and policy needs. Environmental Science & Technology Letters, 11, no. 5, pp. 384-393, 2024.

- Omerspahic, Mustafa and others. Characteristics of desalination brine and its impacts on marine chemistry and health, with emphasis on the Persian/Arabian gulf: a review. Frontiers in Marine Science, 9, pp. 845113, 2022.

- O'Neill, Brian F., and Joe Williams. Progress in understanding the social dimensions of desalination and future research directions. Global Environmental Change, 87, pp. 102877, 2024.

- Ovadia, Yaniv S., and others. Can desalinated seawater contribute to iodine-deficiency disorders? An observation and hypothesis. Public Health Nutrition, 19, no. 15, pp. 2808-2817, 2016.

- Panagopoulos, Argyris, and others. Desalination brine disposal methods and treatment technologies-A review. Science of the Total Environment, 693, pp. 133545, 2019.

- Panagopoulos, Argyris. Beneficiation of saline effluents from seawater desalination plants: fostering the zero liquid discharge (ZLD) approach-a techno-economic evaluation. Journal of Environmental Chemical Engineering, 9, no. 4, pp. 105338, 2021a.

- Panagopoulos, Argyris. Water-energy nexus: desalination technologies and renewable energy sources. Environmental Science and Pollution Research, 28, no. 17, pp. 21009-21022, 2021b.

- Panagopoulos, Argyris, and Katherine-Joanne Haralambous. Environmental impacts of desalination and brine treatment-Challenges and mitigation measures. Marine Pollution Bulletin, 161, pp. 111773, 2020.

- Panagopoulos, Argyris. Brine management (saline water & wastewater effluents): Sustainable utilization and resource recovery strategy through Minimal and Zero Liquid Discharge (MLD & ZLD) desalination systems. Chemical Engineering and Processing-Process Intensification, 176, pp. 108944, 2022.

- Paraschiv, Spiru, and others. An overview of energy intensity of drinking water production and wastewater treatment. Energy Reports, 9, Proceedings of 2022 7th International Conference on Renewable Energy and Conservation, pp. 118-123, 2023.

- Patel, Ekta J. Debating Desalination: Stakeholder Participation and Decision-Making in Southern California. Water Alternatives, 16, no. 2, pp. 509-540, 2023.

- Petersen, Karen, and others. Impacts of seawater desalination on coastal environments. In Sustainable desalination handbook, Butterworth-Heinemann, pp. 437-463. 2018.

- Pistocchi, Alberti, and others. Can seawater desalination be a win-win fix to our water cycle? Water Research, 182, pp. 115906, 2020.
  U
- Ram, Manish, and others. Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. Energy, 238, pp. 121690, 2022.

- Randazzo, Serena and others. Unlocking hidden mineral resources: Characterization and potential of bitterns as alternative sources of critical raw materials. Journal of Cleaner Production, 436, pp 140412, 2024.

- Ricart, Sandra, and others. Extending natural limits to address water scarcity? The role of non-conventional water fluxes in climate change adaptation capacity: A review. Sustainability, 13, no. 5, pp. 2473, 2021.

- Rizk, Zeinelabidin S. Inorganic chemicals in domestic water of the United Arab Emirates. Environmental geochemistry and health, 31, pp. 27-45, 2009.

- Saavedra, Aldo, and others. Comparative analysis of conventional and emerging technologies for seawater desalination: Northern Chile as a case study. Membranes, 11, no. 3, pp. 180, 2021.

- Saleem, Haleema, and Syed Javaid Zaidi. Nanoparticles in reverse osmosis membranes for desalination: A state of the art review. Desalination, 475, pp. 114171, 2020.

- Salinas-Rodríguez, Sergio and others. Introduction to desalination, Seawater Reverse Osmosis Desalination: Assessment and pretreatment of fouling and scaling, IWA Publications, 2021.

- Shahzad, Muhammad Wakil, and others. Energy-water-environment nexus underpinning future desalination sustainability. Desalination, 413, pp. 52-64, 2017.

- Sharkh, Basel Abu and others. Seawater desalination concentrate—a new frontier for sustainable mining of valuable minerals. *Clean Water* 5, no. 1, pp. 9, 2022.

- Shokri, A., and M. Sanavi Fard. A comprehensive overview of environmental footprints of water desalination and alleviation strategies. International Journal of Environmental Science and Technology, 20, no. 2, pp. 2347-2374, 2023.

- Shomar, Basem, and Jalal Hawari. Desalinated drinking water in the GCC countries–The need to address consumer perceptions. Environmental research, 158, pp. 203-211, 2017.

- Smart Water Magazine (SWM). https://smartwatermagazine.com/news/engie/first-reverse-osmosis-desalination-training-and-hiring-program-launched-saudi-women, 2022.

- Sola, Iván, and others. Sustainable desalination: Long-term monitoring of brine discharge in the marine environment. Marine Pollution Bulletin, 161, pp. 111813, 2020.

- Takabatake, Hiroo and others. Advanced technologies for stabilization and high performance of seawater RO membrane desalination plants. Membranes11, no. 2, pp. 138, 2021.

- Tridge, Industry Report: Salt, Industry_Report_-_Salt_final.pdf (tridge.com), 2021

- UNEP/MAP. Sea water desalination in the Mediteranean: Assessment and guidelines. MAP Technical Reports Series. Nairobi: UNEP/MAP. 2003.

- United Nations Human Rights (UNHR). Water & Sanitation: Indigenous peoples face growing challenges to access safe water.

https://www.ohchr.org/en/stories/2022/10/indigenous-peoples-face-growing-challenges-access-safe-water, 2022.

- United Nations Human Rights (UNHR). Indigenous Peoples' Deep-Seated Care for Water and Water Bodies is a Genuine Expression of Sustainability and an Eco-System Approach such as the World is Now Trying to Implement, Special Rapporteur Tells Human Rights Council. https://www.ohchr.org/en/press-releases/2022/09/indigenous-peoples-deep-seated-care-water-and-water-bodies-genuine, 2022b.

- United Nations (UN), The Ocean Conference, Factsheet: People and Oceans, https://sustainabledevelopment.un.org/content/documents/Ocean_Factsheet_People.pdf, 2017

- United Nations Environment Programme (UNEP). Desalination Resource and Guidance Manual for Environmental Impact Assessments. United Nations Environment Programme, Regional Office for West Asia, Manama, and World Health Organization, Regional Office for the Eastern Mediterranean, Cairo, 2008.

- UNEP, Five Things to Know About Desalination, https://www.unep.org/news-and-stories/story/five-things-know-about-desalination, 2021

- United Nations Water (UN Water), Sustainable Development Goal 6 Synthesis Report on Water and Sanitation, 2018

- United States Geological Survey (USGS), National Minerals Information Center, Mineral Commodities Summary 2024, 2024

- Velásquez, Carolina, and Tricia Wachtendorf. Desalination and the Reproduction of Water Injustices in the San Andrés Island Water Crisis. Water Alternatives, 16, no. 2, pp. 632–658, 2023.

- Vicuña, S., and others. Desalination: Opportunities and challenges to address water insecurity in Chile. Scientific Ministerial Advisory Committee on Climate Change; Ministry of Science, Technology, Knowledge and Innovation. Government of Chile (in spanish), 2022.

- Voutchkov, Nikolay, and others. Sustainable Management of Desalination Plant Concentrate-Desalination Industry Position Paper–Energy and Environment Committee

of the International Desalination Association (IDA). The International Desalination Association World Congress on Desalination and Water Reuse, pp. 1-32, 2019.

- Voutchkov, Nikolay. Striving for desalination's gold sustainability standard. Feature article 2023, The Source, International Water Association, 2023.

- Wang, Qun, and others. Investigation of the reduced specific energy consumption of the RO-PRO hybrid system based on temperature-enhanced pressure retarded osmosis. Journal of Membrane Science, 581, pp. 439-452, 2019.

- Wehn, Uta, and others. Stakeholder engagement in water governance as social learning: lessons from practice. OECD Principles on Water Governance, pp. 34-59. Routledge, 2019.

- Wenten, Gede and others. Integrated processes for desalination and salt production: A mini-review. AIP Conference Proceedings, AIP Publishing, vol. 1818, no. 1, 2017.

- WHO. Desalination for safe water supply, guidance for the health and environmental aspects applicable to desalination, World Health Organization Geneva, Eastern Mediterranean Regional Office Cairo, 2008.

- WHO. WHO Guidelines for Drinking-water Quality: Policies and Procedures used in updating the WHO Guidelines for Drinking-water Quality, Public Health and the Environment World Health Organization Geneva, 2009.

- WHO. Safe Drinking-water from Desalination, WHO/HSE/WSH/11.03, 2011.

- Williams, Joe. Assembling the water factory: Seawater desalination and the techno-politics of water privatisation in the San Diego–Tijuana metropolitan region. Geoforum, 93, pp. 32-39, 2018.

- Williams, Joe. Desalination in the 21st century: a critical review of trends and debates. Water Alternatives, 15, no. 2, pp. 193-217, 2022.

- Williams, Joe, and others. Unconventional waters: A critical understanding of desalination and wastewater reuse. Water Alternatives, 16(2), pp. 429-443, 2023.

- World Bank, 7 Things You May Not Know About Water, World Bank Blogs, https://blogs.worldbank.org/en/opendata/7-things-you-may-not-know-about-water#:~:text=2)%2097.5%25%20of%20the%20world's,rest%20is%20frozen%20or%20underground, 2013

- World Bank. The role of desalination in an increasingly water-scarce world. World Bank, Washington, DC, 2019a.

- World Bank. Women in Water Utilities: Breaking Barriers. World Bank, Washington, DC. http://hdl.handle.net/10986/32319, 2019b.

- Younos, Tamim, and Juneseok Lee. Desalination: opportunities and challenges. Water Environ. Technol, pp. 22-27, 2019.

- Zarzo, Domingo, and Daniel Prats. Desalination and energy consumption. What can we expect in the near future? Desalination 427, pp. 1-9, 2018.

Section 5A

Chapter 9: Coastal Development

Coordinating Author: Dahai Liu (China)

Contributing Authors: Piyali Chowdhury (UK), Yuting Hou (China), Anya Dunham (Canada), Jenna Lamphere (USA), Olanlo Kadjogbe Abra (Togo), Mina Ogbanga (Nigeria), Alex Faerman (Israel), Z. George Xue (USA), Wenxiu Xing (China), Ant Türkmen (Türkiye), Vanessa Stelzenmüller (Germany), Jahson Berhane Alemu (Trinidad and Tobago), Aline Sbizera Martinez (Brazil), Curt Daron Storlazzi (USA), Louis Celliers (South Africa), Pascal Thoya (Kenya), Matthew Eliot(Australia)

1. Keynotes

~~As a concentrated area of global urbanization, the coastal zone is subject to multiple pressures from human activities, land-sea interaction, and natural disasters.~~ As a focal point of global urbanization, the coastal zone faces multiple pressures from human activities, land-sea interactions, and natural disasters. Over the past five years, population, communities, and infrastructure in coastal zones have consistently grown, alongside gradual economic recovery. ~~the population, communities and infrastructures in the coastal zone have shown a continuously growing trend, accompanied by a gradual economic recovery.~~ ~~Coastal pollution has shown more varied issues under the influence of climate change and COVID-19 and has put forward new requirements for corresponding monitoring and control networks.~~Coastal pollution has become more complex due to climate change and the COVID-19 pandemic, necessitating enhanced monitoring and control measures. Public participation has been diversified but still faces difficulties in awareness raising, policy strengthening, equity, and comprehensiveness.

For the coastal zone, integrated management will continue to be needed to achieve a balance between economic ~~growth~~performance and ecological environment. Climate change will be a key factor to ~~be~~ consider~~ed~~ in every aspect of coastal zone development. To build inclusive, safe, and disaster-resilient communities while reducing negative environmental impacts and achieving a sustainable coastal economy, greater emphasis must be placed on green-gray infrastructure, nature/ecosystem-based approaches, institutional integration, and sociocultural aspects. Additionally, urgent breakthroughs are needed in areas such as data collection, technology synthesis, integrated land-sea management, transboundary cooperation and policies, and technical innovations related to Natural and Nature-Based Features (NNBF) and Nature-based Solutions (NbS).

2. Introduction

The coastal zone is broadly defined as the transition region where the land meets the ocean, encompassing both the shoreline and the adjacent marine environment and

terrestrial environment influenced by the presence of the sea. More specifically, the near-coastal zone is defined as land within 100 km of the coast and at an elevation of up to 100 m (Small and Nicholls, 2003). The low-elevation coastal zone (LECZ), which is often used as a proxy for land potentially at risk for future coastal hazards, refers to that with an elevation of up to 10 m (~~Small and Nicholls, 2003;~~ McGranahan and others, 2007).

The coastal zone supports a myriad of productive and valued ecosystems that are interdependent. These areas are essential for human settlements and cultural values, ~~as~~ including ~~well as~~ for fisheries, tourism, recreation, and trade, with associated susceptibility~~making them susceptible~~ to pressures from various activities. ~~Coastal zones are particularly vulnerable to natural hazards such as cyclones, tsunamis, and the impacts of sea-level rise~~Coastal zones are also susceptible to natural hazards like tropical storms, tsunamis, and sea-level rise, where the latter could significantly amplify the impact of the former. As climate change accelerates, the intensity of these hazards is expected to increase, making the management of these areas more critical and complex. Under multiple threats, integrated approaches must be adopted to balance ecological health, economic ~~growth~~performance, and social well-being.

Over the past years, topics such as the impacts of human activities, land-sea interactions, climate change adaptation, and science-management-policy translation mechanisms are receiving increasing attention. This chapter will analyze the current status of urbanization, economy, and pollution of coastal zones at a global level and summarize the development of relevant nature- and ecosystem-based solutions and approaches, as well as public participation, to provide management insights for ~~the~~ future development.

3. Pressures and Impacts

Status and trends in populations and infrastructure

The coastal zone contains some of the world's most densely populated and fastest growing urban areas, as well as many smaller communities. Globally, approximately~~about~~ 2.15 billion people live in the near-coastal zone and 898 million live within the LECZ (Reimann and others, 2023). This represents a significant increase~~is up~~ from 1990 when an estimated~~about~~ 1.2 billion people lived in the near-coastal zone (Small and Nicholls, 2023). ~~The global c~~Coastal populations ~~is~~are espeically concentrated in East, South-East, and South Asia, as demonstrated in Figure 1 (Center for International Earth Science Information Network, 2024). Although estimates vary, those living in the near-coastal zone and LECZ could increase to 2.9 billion and 1.2 billion, respectively, by 2100 (Reimann and others, 2023). In some coastal areas, growth of coastal population within the next decade is anticipated by more than 60% (Geiß and others, 2024).

Coastal infrastructure includes coastal and foreshore defense structures, residential and commercial developments, transport and tourism/recreational facilities, and energy and food production-related structures (Firth and others, 2016). A quantitative assessment of

the global extent of such structures was not yet available at the time WOAII was published. Recently, Bugnot and others (2021) estimated the combined physical footprint of marine (covered in Section4 Chapter6) and coastal (described here) built structures to be at least 32,000 km^2 worldwide as of 2018, expected to increase to 39,400 km^2 by 2028 (Figure 2). The area of seascape modified around structures was 1.0-3.4×10^6 km^2 in 2018. The EEZ with the greatest amount of ~~ocean~~ marine ~~construction~~ built structures was China ~~(40% of global ocean construction, 13,000 km^2 occupying >1% of its EEZ, mainly driven by aquaculture farms including ones offshore and on mudflats, or tidal flats)~~, followed by ~~South Korea~~the Republic of Korea and the Philippines. Most of the physical footprint of wind and tidal farms was located on the coast of the United Kingdom, with the remaining spread along the coasts of North America, India, Germany and in the Asian North Pacific. Tunnels and bridges were mainly located in the Northern Hemisphere, and breakwaters for coastal defense claimed the greatest amount of area in Italy; 34% of marinas were in the United States and Canada. However, the physical footprint of breakwaters for regions with substantial coastal modification (for example, China) was not available (Bugnot and others, 2021). The availability and quality of data on the extent of infrastructure vary depending on structure type and geographic location. Data for regional industries such as recreational marinas and aquaculture are particularly incomplete (Bugnot and others, 2021). It is especially challenging to quantify structures that are static through much of their life span but are occasionally moved to other locations, such as floating docks, homes, lodges, and aquaculture facilities (Iacarella and others, 2019).

The projected increase of human population living in the LECZ (Kulp and Strauss, 2019) will continue to prompt many of the world's coastal cities to extend their boundaries seaward by filling in coastal wetlands and shallow seas. Sengupta and others (2023) quantified coastal reclamation by 135 major coastal cities around the world, finding that 78% (106/135) of these cities reclaimed a total of 253,000 ha of additional land from 2000 to 2020. Reclamation is a global-scale phenomenon in the 21st century, especially prominent in East Asia, the Middle East, and Southeast Asia, followed by Western Europe and West Africa. The most common (>70 cities) land uses on reclaimed spaces are port extensions (Sengupta and others, 2023), a trend that may continue due to sustained increases in container shipping volume around the world (World Shipping Council, 2024). Of the top 50 countries expected to experience the fastest population growth from 2020 to 2100, 86% are African among which 72% are coastal (United Nations, 2017). Many of these countries are characterized by some of the largest remaining stretches of ‘unaltered' coastlines (Firth and others, 2016) in contrast with, for example, the United States, where >50% of natural shorelines have been replaced by seawalls, breakwaters and other hard structures (Gittman and others, 2016).

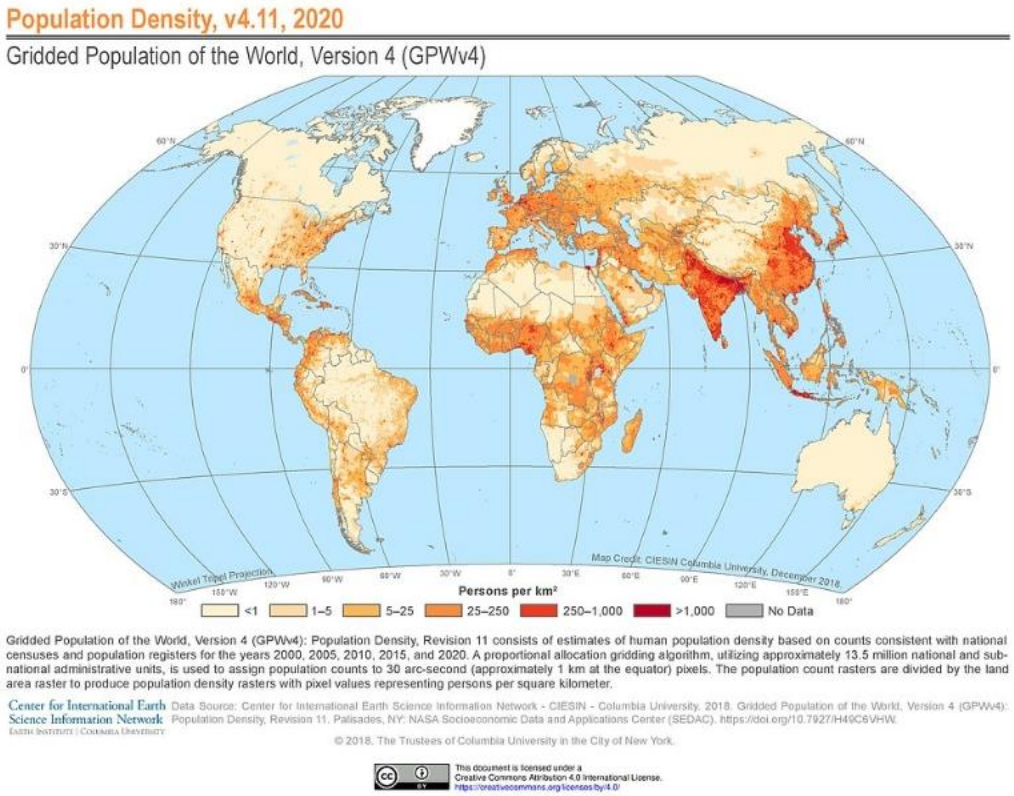


FIGURE 1 Estimates of human population density based on national censuses and population registers (Center for International Earth Science Information Network, 2024).

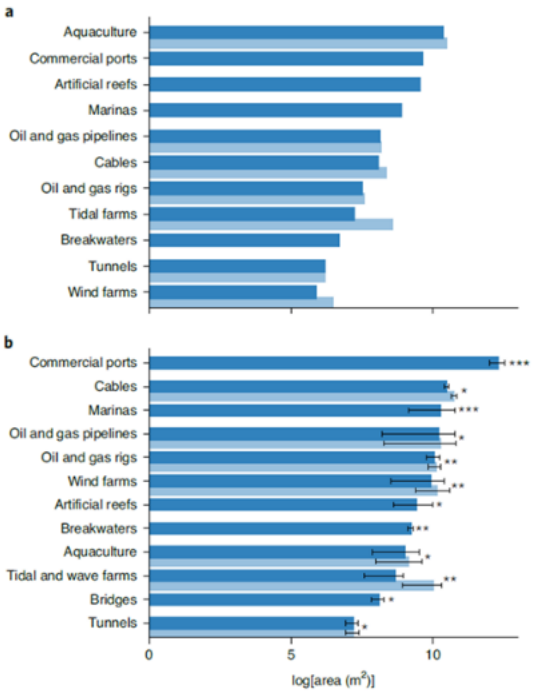


FIGURE 2 (reproduced from Bugnot and others, 2021, with permission). Global extent of marine and coastal construction: (a) area of physical footprint in 2018 (dark blue bars) and predicted for 2028 (light blue bars); (b) modification of

surrounding seascapes, by different types of built structures. Future projections were available only for aquaculture, submarine cables, wave, tidal and wind farms and oil and gas pipelines and rigs; no wave farms were operational up to 2018, hence only future projections are presented. Asterisks denote the scale of seascape modifications: *adjacent (<100 m), **local (>100 m to <10 km) and ***regional (>10 to hundreds of km). Note that marine structures (oil and gas pipelines and rigs and cables) are covered in Section 4 Chapter 6.

Increasing climate risks for urbanization

Growth in coastal urban areas and communities increases the coastal hazard exposure for populations~~risk to populations from coastal hazards~~ (Magnan and others, 2022), infrastructure like ports (Izaguirre and others, 2021) and roadways (Koks and others, 2019), economic assets (Kummu and others, 2016), and cultural heritage (Reimann and others, 2018). As noted in Chapter 8 of the WOAII, the vulnerability of coastal urban areas and communities to the impacts of climate change is also increasingly concerning (United Nations, 2021). However, quantification of climate risks is difficult due to a variety of uncertainties, including future socio-economic policy scenarios, anticipated physical processes, and ~~known and unknown~~ model limitations (Rising and others, 2022). Therefore, risk is often reported in terms of expected levels of impact and central confidence bounds, as opposed to probabilities.

According to the Intergovernmental Panel on Climate Change (IPCC), there is high confidence that projected climate risks will increase with greater exposure to ocean-driven hazards (Glavovic and others, 2022). The IPCC (2022) reports with medium confidence that if global mean sea level rises by 0.15 meters relative to 2020 levels, the population exposed to a 100-year coastal flood is projected to increase by 20%. There is high confidence that coastal flood risk will rapidly increase by 2-3 orders of magnitude by 2100 and medium confidence that this will result in the exposure of $7-14 trillion of coastal infrastructure assets (Glavovic and others, 2022). While there is significant regional variation, risks are especially acute for urban areas and communities located in the Arctic (Tanguy and others, 2024), on low-lying or subsiding small islands (Storlazzi and others, 2018), and along estuarine and deltaic coasts (Nienhaus and others, 2023). Under all climate and socio-economic scenarios, the IPCC (2022) reports with very high confidence that such high-risk areas and communities will experience severe disruption by 2100, with some experiencing it as early as 2050.

Risks to coastal urban areas and communities depend~~s~~ not only on hazard exposure but also vulnerability, which describes both social conditions (i.e., susceptibility) and capacity to respond (i.e., resilience~~resiliency~~) (Steven and others, 2020). While vulnerability varies by country, in a recent cross-country comparison, developed countries were found to be significantly less susceptible and better equipped to deal with climate risks than developing countries (Saeed and others, 2023). Developing countries are often more susceptible due to poor natural and built environments, poverty, and weak socio-economic status (Hamidi and others, 2020). Developing countries also tend to have less capacity to

combat climatic events, as compared to developed countries that have greater stocks of capital that can be mobilized to combat climate risks (Millner and Dietz, 2015). While no country can escape climate risk, exposure, susceptibility, and resilience~~resiliency~~ interact in a dynamic process~~es~~ that result in an uneven distribution of vulnerability that is not strictly environmental but also social and economic (Thomas and others, 2018).

Economic ~~growth~~performance

The coastal economy refers to all economic and industrial activities that take place in or around coastal areas. The activities represent a significant proportion of the global GDP due to their economic diversity. It is also a major driver of employment in many coastal regions, especially in developing countries where it provides crucial opportunities for local communities. The COVID-19 pandemic had a significant impact on the global coastal economy, with disruptions in trade, tourism, and supply chains. Coastal areas experienced economic contraction at the start of the pandemic, but recovery has varied by region and sector. Coastal tourism saw a dramatic decline in 2020, with a decrease in international arrivals of over 70% compared to 2019, according to the World Tourism Organization (UNWTO).

In 2021, economic recovery was uneven. Coastal areas in developed countries, such as the United States and Europe, generally experienced a faster recovery thanks to economic stimulus plans and effective vaccination campaigns. Conversely, coastal areas in developing countries had slower recoveries due to structural challenges and a heavier reliance on tourism. According to data from the World Bank and the International Monetary Fund (IMF), the global coastal economy has shown an average growth of 3-4% per year since 2022, with significant variations depending on the region and sector. Since 2021, trade volumes have rebounded, with robust growth in imports and exports. Data from the World Trade Organization (WTO) show an average growth in global trade volumes of 5-6% per year since 2022.

Coastal pollution

Coastal pollution is a pervasive and growing problem worldwide, threatening the health of marine ecosystems, human well-being, and the economy. The coastal zone is vulnerable to pollution due to its proximity to human activities such as industrialization, agriculture, and urbanization. Pollution in coastal areas includes plastic debris (Bessa and others, 2018; de Deus and others, 2024), nutrients (Grizzetti and others, 2021; Islam and Tanaka, 2004), metals (Qian and others, 2015; Li and others, 2022), and persistent organic compounds (Nunes and others, 2011), amongst others. Different geographical regions have faced different challenges over the past few years, such as the rapid industrialization and inadequate waste management in Asia-Pacific, the dense shipping lanes, oil rigs, and

agricultural runoff in the Mediterranean, and the limited waste management infrastructure in Africa (UNEP, 2019; EU, 2020).

There are also many new perspectives that deserve attention. ~~The g~~Global issues of marine pollution are interlinked with climate change and understanding these connections is key to managing these combined risks (Lincoln and others, 2022; Ford and others, 2022). For instance, extreme weather events contribute to debris of various shapes and weights known to exacerbate the overall damage to the coastal environment through collision and damming loads (Park and others, 2021; Chowdhury and others, 2024). Haarr and others (2022) argue that the geographical distribution of empirical data on marine litter stranded on coastal zones corresponds relatively poorly with the estimated geographical differences in annual mismanaged plastic waste (Lebreton and Andrady, 2019). Western Asia, Europe (excluding Eastern Europe), the Caribbean, North America, and Oceanic countries contribute relatively little mismanaged plastic waste, but have been comparatively well studied. Conversely, Africa, Asia (excluding Western Asia), and Central America were poorly studied, although they have high rates of mismanaged plastic waste. This suggests a mismatch between poorly managed~~mismanaged~~ plastic waste and research initiatives documenting the problem. Plastics are the most abundant waste category in coastal environments (Iñiguez and others, ~~-~~ 2016) and it should be noted that the global COVID-19 outbreak is estimated to have contributed an extra 3.4 billion single-use facemasks/face shields daily (Benson and others, 2021). An assessment of the direct economic costs of marine litter for a coastal region demonstrated that marine litter created costs and inconvenience~~s~~ for stakeholders engaged in marine activities, ~~creating~~ leading to significant financial burdens for small communities (Rodríguez and others, 2020).

4. Sustainability Pathways

Climate change adaptation

Natural coastal habitats can provide an effective first line of defense against climate change related issues (Reguero and others, 2018; Sun and Carson, 2020). However, these natural protection services may be compromised as coastal habitats are degraded or lost due to sea-level rise, water level fluctuations, and encroaching coastal development (Arkema and others, 2013; Quataert and others, 2015; Crosby and others, 2016; Narayan and others, 2017). The proliferation of marine-built structures provides a suite of benefits but can also have unintended and sometimes hidden costs. The artificialization of the global coastline and the threats posed by the warming climate are driving humanity to develop novel solutions that halt biodiversity and habitat loss and enhance the marine built environment. Under these circumstances, enhancing environmental quality in heavily urbanized areas, adapting urban areas, and the conservation, restoration, or construction of coastal natural and nature-based features (NNBF) can provide a potential pathway to

accomplish the multiple goals of managing coastal hazards, restoring native biodiversity, and sustaining ecosystem functions and services (Mayer-Pinto and others, 2017; Morris and others, 2018, 2019; Airoldi and others, 2021; Bridges and others, 2021, 2024; Firth and others, 2024). Hence, integrating NNBF and ecoengineering into Nature-based Solutions (NbS) is ~~crucial~~beneficial for addressing challenges posed by climate change, benefiting both people and nature.

Natural ecosystems in urban areas, such as estuarine margins and coastal beachfronts, can be restored to enhance ecological health and resilience. Such actions can be achieved through soft or hybrid ecoengineering approaches (Dafforn and others, 2015a; Morris and others, 2018, 2019; Firth and others, 2024). Ecological or "green" coastal and marine ecoengineering involves the use of natural materials and processes to enhance coastal resilience and restore ecosystems, such as planting mangroves or marsh grasses. Hybrid "green-gray" ecoengineering combines ecological approaches with traditional gray engineering techniques, such as integrating oyster reefs with seawalls or building concrete base structures and outplanting corals on top of them to provide both ecological and structural benefits. Currently, these initiatives are mostly concentrated along coastlines in temperate regions (Bridges and others, 2021). While integrated green-gray infrastructure is gaining significant attention from a policy standpoint, there is still limited research from engineering, scientific, or economic perspectives regarding its integration and implementation (Kuwae and Crooks, 2021; O'Shaughnessy and others, 2020; Chavez and others, 2021; Viehman and others, 2023).

This ~~lack of information on such green-gray infrastructure~~ underscores the urgent need to expand and accelerate such practices in other regions of the world,~~. This is~~ particularly ~~concerning for~~in developing nations, which often have more people living in vulnerable areas and where coastal urbanization is occurring more rapidly (Firth and others, 2016; Merkens and others, 2016; Reimann and others, 2023). Hard, gray coastal and marine ecoengineering offers a viable solution in urbanized areas modified by artificial structures, relying on local knowledge to achieve these goals (Strain and others, 2018). It can adapt traditional engineered structures like seawalls and breakwaters with more complex designs to enhance local biodiversity and ecosystem services (e.g., Adams and others, 2021; Morris and others, 2018; Vozzo and others, 2021). This method could also be applicable to future interventions where green approaches are not feasible (Morris and others, 2018, 2019), distinguishing itself from traditional engineering by prioritizing environmental sustainability. It is important to recognize that the above methods may not be universally applicable or inherently sustainable (Parkinson and Ogurcak 2018). Implementing gray, green or hybrid ecoengineering requires careful planning and further research, with caution to prevent 'greenwashing' or 'bluewashing' (Dafforn and others, 2015a, b; Firth and others, 2020, 2024). Adaptive monitoring programs with appropriate

quantitative measures are also needed to evaluate and enhance the efficiency of interventions to protect coastal cities (Bredes and others, 2024).

Despite the growing body of knowledge on NbS, gaps remain (Lacambra and others, 2024; Seddon and others, 2020). For instance, measures to quantify the effectiveness of NNBF at mitigating coastal hazards and adapting to climate impacts are still lacking (Viehman and others, 2023). Due to the site-specific nature, decision-makers often lack information on assessing their suitability in different environments. Research on NNBF suitability and monitoring is yet to be institutionalized into policy, regulations, and decision-making. The development of risk-based valuations of the ecosystem services attributed to NNBF has been limited by the lack of high-resolution data on bathymetry, topography, ecosystems, and economic asset, and the difficulty in modeling complex hydrodynamic and ecological processes (Reguero and others, 2021). A better understanding of the hydrodynamics, morphodynamics, and ecology across a variety of spatial and temporal scales, as well as across a range of types of NNBF, is critical for clearly defining the benefits of NNBF and advancing NbS solutions.

The gaps in understanding also proliferate due to a lack of studies on the broader effectiveness and the context-dependence of coastal NbS, including the scale of implementation, ecological characteristics, and socio-economic conditions. Specifically, there is a need for more empirical evidence on the long-term effectiveness and cost-benefit analysis of NbS compared to traditional gray infrastructure. Chausson and others (2020) found that performance indicators, including cost, were broadly assessed for ~10% of coastal NbS projects, including coral reefs, mangroves, seagrasses, and saltmarsh restoration, although new studies are incorporating more long-term costs in both the gray and green components of NbS (Storlazzi and others, 2025). This uncertainty also extends to gray infrastructure; however, a key difference between NbS and gray infrastructure is that NbS adaptation services are hypothesized to increase over time, while gray infrastructure adaptation services may decline (Avery and others, 2023; Feagin and others, 2021).

Monitoring and control network

Coastal areas face ongoing threats from various pollutants and challenges from natural processes, such as coastal erosion, sea level rise, and the degradation of cliffs and beaches (see relevant ~~Section~~sections). Effective monitoring and control networks are crucial to mitigate these impacts and preserve coastal environments.

An example is presented for ~~H~~harmful algal blooms (red tides) and hypoxia (a.k.a. “Dead Zone”), which can usually be monitored using in-situ measurement, remote sensing, and numerical modeling methods (e.g., Liu and others, 2022; Ou and Xue, 2024). Detecting and forecasting their movement using available remote sensing and high-fidelity modeling

technology is essential since traditional ship-based field sampling and analysis are very limited in both space and temporal frequency. Many countries have established red tide or algal bloom monitoring systems relying on satellite imagery, on-site observations, models, and buoy data (Lee and others, 2013; Guan and others, 2022). For example, NOAA's NCCOS developed the Algal Bloom Monitoring System to routinely deliver near real-time products for use in locating, monitoring and quantifying algal blooms in coastal and lake regions of the US (NOAA, 2023). The monitoring of pollutants like sewage discharge, marine debris, and microplastics in the ocean through remote sensing can be effectively accomplished by using sensitivity analysis, optical simulation, and satellite image spectral analysis. To improve the accuracy and reliability of marine pollutants monitoring and forecasting, it is important to integrate remote sensing, numerical and AI/ML(Artificial Intelligence and Machine Learning) modeling (e.g., Ou and others, 2022) with other monitoring tools like ship sensors, buoy sensors, aircraft sensors, and biosensor networks.

In terms of coastal erosion, technologies such as satellite imagery, drones, and Geographic Information Systems (GIS) are essential for tracking changes in the coastline. Near real-time~~Real-time~~ data collection allows for the early identification of erosion hotspots and timely intervention. Effective mitigation strategies can be designed based on the comprehensive understanding of erosion patterns and their causes. For sea level rise, tide gauges, satellite altimetry, and climate models are critical tools for measuring and projecting changes. These provide accurate data, enabling managers to assess risks and plan adaptive measures. Early warning systems and predictive models can help prepare communities and infrastructure for future sea level scenarios. Restoration of cliffs and beaches is essential for maintaining natural coastal defenses against erosion and flooding, which often includes beach nourishment, revetments and sea walls. It is worth mentioning that all shoreline monitoring and controlling require a comprehensive coastal erosion modeling study to assess potential impacts and design appropriate mitigation measures.

The forecast modeling process typically includes the following steps.~~:~~ First is gathering historical and current data on waves, tides, sediment transport, and shoreline changes with technologies like instrument moorings, satellite imagery, aerial photography, and field surveys. ~~The s~~Second is utilizing ~~advanced~~ computational models such as Delft3D, MIKE21, ROMS, and SWAN (and the coupling of these models, e.g., COAWST, Warner and others, 2010) to simulate coastal processes and predict future changes under various scenarios. These models can assess the impact of new infrastructure on flooding and/or erosion patterns and identify vulnerable areas. Third is evaluating different development and mitigation scenarios to understand their potential impacts on coastal flooding and/or erosion. This includes the construction of breakwaters, jetties, and other structures, as well as natural solutions like beach nourishment and vegetation planting~~,~~ (it should be noted that for eroded shores, vegetation planting requires structures that protect the

panted trees from wave action to be effective). Then follows risk assessment, which ~~will identify~~ identifies areas at high risk of erosion and ~~recommending~~ recommended mitigation strategies. This involves a combination of engineering solutions and ecosystem-based approaches. The last step is implementing continuous monitoring programs to track the effectiveness of mitigation measures and adapt them as necessary based on observed changes and new data.

Integrated land and sea management

The ecosystem-based approach (EBA) – a strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way (CBD, 2000) – and similar concepts such as ecosystem-based management (EBM) and ecosystem approach (EA) (Kirkfeldt, 2019), require integrated land and sea management, due to ~~Based on~~ the connectivity of terrestrial ecosystems, including watersheds and estuaries, with near-shore marine ecosystems~~., integrated land and sea management is also an important direction for nature/ecosystem-based management.~~ . The concept is reflected in the classic pathway of Integrated Coastal Zone Management (ICZM), which has been a policy option for more than 50 years and has been implemented in more than 100 states and regions, to promote integrated environmental protection and economic growth in the coastal zone (Ye and others, 2015; Singh and others, 2021). At present, ~~The concept of integrated land and sea management~~it is also ~~is~~ increasingly emphasized ~~often reflected in emphasizing the need~~in both land planning and ~~for~~ Marine Spatial Planning (also referred to as Maritime Spatial Planning; MSP) to focus on the interaction of various elements at the land-sea interface, such as socio-cultural, coastal erosion, and climate change (Maragno and others, 2020; Stancheva and others, 2021; Pikne and others, 2022). ~~It is also reflected in the classic pathway of Integrated Coastal Zone Management (ICZM), which has been a policy option for more than 50 years and has been implemented in more than 100 states and regions, to promote integrated environmental protection and economic growth in the coastal zone (Ye and others, 2015; Singh and others, 2021). Land-based source and watershed management for multiple pollutants entering the sea is also an important manifestation of the concept, including point and non-point source pollution control, estuarine and bay management, and integrated basin-nearshore water zoning (de Andres and Munoz, 2022; Huang and others, 2023).~~

From the perspective of planning practices, land and sea used to be studied and planned separately as two relatively independent parts, ignoring their synergistic effects. Currently, coordinated planning has become a direct means of resolving use conflicts and realizing synergistic development in many states and regions. For example, over the past five years, China has carried out reforms in spatial planning ~~centered~~ with~~on~~ the concept of land-sea coordination, which emphasizes the seamless planning of land and sea, paying attention to the coherence of different ecosystems, promoting the marine, coastal, and land industry

as a system, and driving the inland development through marine economy. In the current Coastal Zone Plan, which is an important component of Territorial Spatial Planning~~In the current Territorial Spatial Planning and Coastal Zone Plan, ,~~ the idea of land-sea coordination is fully emphasized through the integration of sectoral responsibilities, department cooperation, shoreline categorization and control, and the idea of multiple plans in one (Liu and Xing., 2019; Wang and others, 2024). Another example is the UK Marine Policy Statement (2011), which makes it clear that marine planning must interact with existing terrestrial planning, especially in physically overlapping areas. Land-use plans and marine plans share many common goals. Relevant policies suggest that the coordination of marine and terrestrial planning could be achieved through maintaining the coherence of different documents, enhancing the cooperation and communication between land and sea planning authorities, sharing data in the decision-making process, and following the methods and principles of ICZM. The consideration of land-sea interactions has also been clearly stated in various documents related to EU MSP, but specific pathways still need to be explored with more research and practices. These initiatives could support global efforts for sustainability, as the United Nations Environment Programme (2023) highlights the need to connect land and sea planning to better manage coastal and marine resources.

Trans-boundary management practices

Trans-boundary management requires coordinated and cooperative governance of marine resources and ecosystems that span the borders of multiple states or regions, which also often involves coastal zone areas. MSP is the most prominent governance process that implements national regulations of human activities (Stelzenmüller and others, 2018). In trans-boundary settings such as in Europe (Mackelworth and others, 2024) or in the Yellow Sea (Ma and others, 2023), where socioeconomic interests are confined to national management boundaries, but ecosystem health and resilience depend on ecosystem processes and exposure to human pressures at different scales, national MSP processes also face the challenge of international consultations (Elliott and others, 2023). Thus, transboundary management is confronted with a high level of complexity regarding the coordination of actions but also the enforcement and the monitoring of compliance, a lack of which can undermine the effectiveness of management regulations (Cormier and others, 2018). Next to the regulation of human activities, the implementation of marine conservation areas or marine protected areas (MPAs) can require transboundary coordination for enforcement and management efforts to ensure the protection of those areas of high conservation values and their respective assets. Examples of such transboundary management efforts can be found in the Mediterranean Sea (The Mediterranean Network of MPAs; MedPAN or Pelagos Sanctuary for Mediterranean Marine Mammals); Southeast Asia and the Pacific (Coral Triangle Initiative; CTI-CFF), the Wadden

Sea (Trilateral Wadden Sea Cooperation) or Caribbean Sea (Punta Manabique Wildlife Refuge and Sarstoon-Temash National Park).

To bridge the gap between European Maritime Spatial Planning frameworks and the unique challenges of the Yellow Sea, it is imperative to foster enhanced collaboration between European nations and the states bordering the Yellow Sea. The Yellow Sea Large Marine Ecosystem has a history of regional cooperation, providing a foundation for further collaboration on transboundary management (UNDP, 2021). This collaboration should focus on the sustainable management of shared maritime resources, robust environmental protection measures, and the achievement of sustainable development goals. The European Union's International Ocean Governance agenda emphasises the importance of multilateral cooperation to address global ocean challenges, which can serve as a model for the Yellow Sea region. By engaging in joint initiatives, sharing best practices (Douvere, 2008), knowledge on enabling conditions (Zuercher and others, 2022), and aligning policies, these regions can develop harmonised MSP approaches that effectively manage transboundary marine ecosystems and address common environmental concerns. The importance of marine spatial planning in advancing ecosystem-based sea use management is crucial for addressing the complex interactions between human activities and the marine environment (Yatim and others, 2016). Such efforts would not only enhance the ecological health of the Yellow Sea (Ma and others, 2023) but also promote socio-economic benefits for the coastal communities dependent on these vital marine resources. Regional environmental governance initiatives, such as those focused on the Yellow Sea and Bohai Sea, offer valuable insights into the complexities of land-sea coordination in addressing pollution and promoting sustainable development (Liu and others, 2021).

The European Union underscores the paramount importance of multilateral cooperation in addressing global ocean challenges through its International Ocean Governance agenda. As a proponent of multilateral responses to global issues, the EU endeavours to fortify the international rules-based framework. The EU collaborates on ocean governance with bilateral, regional, and multilateral partners globally, with its primary legal instrument being the United Nations Convention on the Law of the Sea. Through the EU Maritime Security Strategy, the EU addresses challenges impacting the security of the ocean, such as cross-border and organised crime, threats to freedom of navigation, threats to biodiversity, climate security challenges, and environmental degradation. The EU's approach to ocean governance aligns with its broader foreign policy goals, promoting sustainable development, security, and stability beyond its borders (Delmartino, 2009).

Based on past cases of transboundary MSP, experiences for transboundary management can be summarized. First is the enormous role of transboundary and regional

organizations, which can coordinate different administrative bodies, facilitate cooperation and promote research and implementation in the form of various funds. The second is the need to actively play the role of expert consultation, which could bring together universities and research institutes from different regions to promote exchange and implementation. Thirdly, the analysis and integration of different management systems and institutions, the interoperability, unification and disclosure of data and information from various sources and including various users and departments into the decision-making system are the key factors to ensure the success of trans-boundary management. Fourthly, communication, exchange, identification of similarities and differences, negotiation and coordination among different management bodies are necessary in the entire process of all kinds of transboundary management practices.

5. Social components

Enhancing public participation

Coastal zone management is a public policy process for which community and public involvement in environmental decision-making is a critical element of governance (Edwards and others, 1997). Workshops, meetings, interviews, surveys, participatory mapping, social network analysis and virtual space are all methods to engage stakeholders and practice public participation (Ison and others, 2024; Sartorius and others, 2024). Each of these methods uniquely engages the public and gathers input, e.g., workshops and meetings enable direct interaction, whereas interviews and surveys offer more in-depth responses. Participatory mapping empowers communities to visualize their environment, while social media and virtual spaces provide platforms for broader, more dynamic engagement.

While the concept is simple, the reality of encouraging participation is not. The decision on who to include is itself challenging and fundamental to the success of the process to broaden engagement in the governance of the coast (Reed and others, 2018; Celliers and others, 2023). The importance of public participation, social equity and agency is a growing topic of both research and implementation of coastal policies (Norström and others, 2020; Muhl and others, 2023; Morris and others, 2024). The practice of public participation is thus an issue strongly related to the transformation of society to sustainability, increasing social equity, and enabling the inclusion of human-nature connectedness, agency and leadership in the participation processes relating to coastal management (Tallent and Zabala, 2024; West and others, 2024; Engen and others, 2024)

Public participation has long been legally embedded in the formal planning process for major developments through the process of Environmental Impact Assessment (EIA) (Johnson and Dagg, 2003). It is also already part of most coastal management frameworks

(Sowman and Malan, 2018; Harvey and Clarke, 2019). Participatory GIS mapping is used as a direct means of co-producing knowledge with stakeholder and community interests (Burdon and others, 2019). Public Participatory GIS (PPGIS) has been demonstrated to be a valuable tool for policy advice and promoting the inclusion and empowerment of underrepresented populations in the decision-making process. Moreover, PPGIS allows for assessing the perception and acceptability of land and marine use planning from a social perspective (Vieira da Silva and others, 2021). For instance, the New Hampshire Living Shoreline Site Suitability Assessment applied GIS-based methods to identify appropriate sites for nature-based shoreline stabilization, integrating ecological, physical, and social criteria into coastal planning (Balasubramanyam and Howard, 2019). There are also several emerging approaches. Citizen science is an integral part of a burgeoning global initiative aimed at involving the community in scientific research (Elrick-Barr and others, 2023). This approach fosters collaboration between non-professionals and scientists in a reciprocal process (Garcia-Soto and others, 2021). For instance, CoastSnap is a~~n affordable~~ community beach monitoring program that transforms everyday smartphones into tools for measuring coastal responses to cyclones, sea-level rise, human modifications, and other factors (Harley and Kinsela, 2022). It is expected to significantly enhance understanding of changing coastlines and provide the scientific community with robust quantitative data. Co-production of knowledge intends to improve decision quality through deliberation and collaborative management by fostering viable, fair, and inclusive decision options and solutions (Turnhout and others, 2020). For example, co-production of climate services for coastal flooding and the use of story maps offers the possibility to visualize scientific information and climate data in an accessible format and, as web-based tools, reach a large audience (Vollstedt and others, 2021). Another example is UNESCO-IOCs Tsunami Ready Recognition Program (TRRP), a voluntary, performance-based community recognition programme that promotes an understanding of the concept of readiness as an active collaboration among national and local warning and emergency management agencies and government authorities, scientists, community leaders, and the public to build resilient communities through the fulfilment of a set of established indicators (UNESCO, 2025).

COVID-19 posed a significant challenge for many coastal management processes. It has also demonstrated that it is possible to work online with minimal impact on collaboration and engagement. While there are clear environmental benefits to public participation "going digital", it is crucial to recognize potential drawbacks. Public participation may become disengaged from coastal zone issues and management due to a lack of digital literacy, the high costs of emerging technologies (such as virtual reality platform development), and the limited capacity to create and implement digital solutions (McKinley and others, 2021).

Enhancing participation through arts-based methods significantly contributes to coastal sustainability by raising awareness, fostering learning, and promoting engagement and enjoyment among project participants (Matias and others, 2023). Greater focus is required in urban policy and academic research on the implications of creating temporary urban art spaces for immediate inclusive engagement with end users and for sustained community development (e.g., the British Coast; see Zebracki, 2018). Art-science approaches could also offer valuable avenues for communication and inquiry (Paterson and others, 2020). Developing socio-ecological scenarios also involves a participatory process that engages stakeholders (Allan and others, 2022). Scenario development as a tool describes various potential future states and has been utilized to e.g., aid coastal adaptation planning (Gray and others, 2020). The robust and structured stakeholder engagement process fostered strong local ownership of both the scenarios and the overall process (Allan and others, 2022). Social media has emerged as a powerful tool for driving change by influencing conversations and boosting interest and participation (Vince and Hardesty, 2018). These platforms are now well-established as quick and effective means of disseminating information (da Costa and others, 2020). It can play a crucial role in engaging society with reliable information, altering habits, and promoting sustainable behavior (Otero and others, 2021).

Human Rights, Equity, Gender, Indigenous Peoples, traditional owner and local community knowledge related issues

Social equity in coastal zone management is increasingly recognized as crucial for effective and just conservation practices. It involves considering the distribution of benefits and burdens among different stakeholders, ensuring fair access to resources, and promoting inclusive decision-making processes (Bennett and others, 2021). The call for equity in coastal zone management stems from the exclusion of marginalized groups, including Indigenous ~~communities~~Peoples and small-scale fishers, who rely on marine ecosystems for their livelihoods and cultural identity, from the decision-making process and benefits derived from exploitation of marine resources (Cisneros-Montemayor and others, 2019; Bennett, 2022). Despite the growing recognition, social equity is often overlooked in national-level blue economy initiatives that prioritize large, influential stakeholders (Bennett and others, 2021; Jewel Das, 2023; Thoya and others, 2022).

Take small-scale fishers as an example, who are traditional owners of fishing grounds, mostly inherited from their ancestors. Recent blue economy initiatives have encroached upon their traditional spaces, resulting in land grabbing, displacement, and environmental degradation (Bennett and others, 2021; Jewel Das, 2023; Mads Barbesgaard, 2018). As a result, these fishers face diminished access to vital marine resources, threatening both their livelihoods and adversely impacting their human rights and well-being. The reduction

in ecosystem services, such as fish stocks and clean waters, further exacerbates their challenges, leaving them vulnerable to poverty and food insecurity (Bennett and others, 2021). Similarly women who carry a significant role in small-scale fisheries, mariculture, and post-harvest processing, contributing to both household income and food security, are often undervalued and overlooked in decision-making processes (Lentisco and Lee, 2015; de Mattos and others, 2022; Preez, 2018). They face numerous barriers in coastal zone development, including limited access to resources such as land, credit, and technology. Cultural norms and gender-based discrimination further restrict their participation in governance and policy-making (Frangoudes and others, 2019; Preez, 2018).

The inclusion of Indigenous Peoples, local communities, women and girls, children and youth and persons with disabilities in decision-making, particularly by using traditional knowledge, is essential but often overlooked in favor of top-down approaches (Mauro and Hardison, 2000; Peci Lyons and others, 2023). To address these inequalities, a paradigm shift in policies is needed: one that integrates diverse perspectives, traditional knowledge, and participatory approaches into marine policy and management (Bennett and others, 2021; Jewel Das, 2023). Ensuring the participation of local communities not only promotes fair distribution of benefits but also enhances the sustainable use of natural resources and biodiversity conservation, which are closely linked to climate change adaptation efforts (Cisneros-Montemayor and others, 2019). Legal frameworks such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), the Indigenous and Tribal Peoples Convention (ILO 169), and the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries have recognized these rights and provided guidance for the inclusion of Indigenous Peoples and local communities in ocean governance at national and local levels (Mauro and Hardison, 2000; Jentoft and others, 2007), which should be further emphasized in the future.

6. Governance

Coastal zone development faces multiple social, economic and environmental pressures from the continuing growth of populations, communities and infrastructures, especially impacts related to climate change. In the face of these circumstances, the outlook for the coastal zone governance must be integrated and adaptive, whether it is for economic growth, relieving various pressures, near-shore pollution management, or responding to climate change, land-sea integration, and transboundary management issues. For example, the goals of coastal economic growth are multiple and aim to maximize economic benefits while ensuring environmental sustainability and the resilience of coastal communities. An integrated approach will help overcome challenges and maximize benefits for all stakeholders to ensure sustainable management of the coastal zone. When looking at marine pollution from a complex systems perspective, it is not possible to

separately consider land-based impacts and coastal governance. The coastal zone is the sink for many of the products and wastes of human activities, and it requires management in a much larger context (Lu and others, 2018).

Currently, coastal governance structures vary widely among states around the globe. In ~~states~~nations such as the United States, Brazil, India and Japan, responsibility for coastal management is often decentralized to regional or local governments within a framework established at the national level. In states such as Australia and Germany, where the coastal zone is not controlled with significant central government involvement, more streamlined and coherent policies may be implemented over a larger geographical area. The Council of Europe promotes local governance in coastal management, emphasizing that local authorities can best understand and address the specific challenges in cooperation with local stakeholders (Toledo and others, 2024). Many states have established relevant legislative frameworks for coastal governance, but implementation enforcement varies quite a bit (Kay and Alder, 2017). At the global level, recommendations for coastal zone governance tend to be biased towards a characteristic goal, although integrated pathways are constantly emphasized. For example, the IPCC suggests that a mix of infrastructural, nature-based, institutional, and sociocultural innovations is needed to reduce the climate change--compounded risks to coastal urban areas and communities. Overall, despite the consensus on an integrated management pathway for coastal zone development, current research and regional management structures still tend to be fragmented or single-targeted. There is an urgent need for targeted guidelines or initiatives for coastal zone governance at the global level that encompass legislation, institutionalization, hierarchical relationships, balancing of socio-economic-environmental elements, and adaptation to climate change.

7. References

Adams, L. W., and others. Making marinas bivalve friendly for enhanced biodiversity outcomes. Marine Pollution Bulletin, vol. 169, art. 112464, 2021.

Airoldi, L., and others. Emerging solutions to return nature to the urban ocean. Annual Review of Marine Science, vol. 13, pp. 445–477, 2021.

Allan, A., and others. Developing socio-ecological scenarios: A participatory process for engaging stakeholders. Sci Total Environ, vol. 807, art. 150512, 2022.

Arkema, K. K., and others. Coastal habitats shield people and property from sea-level rise and storms. Nature Climate Change, vol. 3, pp. 913–918, 2013.

Balasubramanyam, V., and K. Howard. (2019). New Hampshire Living Shoreline Site Suitability Assessment. Tech. Report. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/r-wd-19-19.pdf

Barbesgaard, M. Blue growth: Savior or ocean grabbing? The Journal of Peasant Studies, vol. 45, No. 1, pp. 130-149, 2018.

Bennett, N. J., and others. Blue growth and blue justice: Ten risks and solutions for the ocean economy. Marine Policy, vol. 125, art. 104387, 2021.

Bennett, N. Mainstreaming equity and justice in the ocean. Frontiers in Marine Science, vol. 9, art. 873572, 2022.

Benson, N.U., D.E. Bassey, and T. Palanisami. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Heliyon, vol. 7, No. 2, 2021.

Bessa. F., and others. Occurrence of microplastics in commercial fish from a natural estuarine environment. Mar Pollut Bull, vol.128, pp.575–584, 2018.

Bredes A.L., and others. A 20-Year Systematic Review of Wave Dissipation by Soft and Hybrid Nature-Based Solutions (Nbs). Available at SSRN: https://ssrn.com/abstract=4866957 or http://dx.doi.org/10.2139/ssrn.4866957.

Bridges, T.S., and others. 2021. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. Vicksburg, MS: U.S. Army Engineer Research and Development Center. Retrieved from https://ewn.erdc.dren.mil/?page_id=4351

Bugnot, A.B., and others. Current and projected global extent of marine built structures. Nature Sustainability, vol. 4, pp. 33–41, 2021.

Burdon, D., and others. Expanding the role of participatory mapping to assess ecosystem service provision in local coastal environments. Ecosystem Services, vol. 39, 2019.

CBD. COP5 Decisions. Fifth Meeting of the Conference of the Parties to the Convention on Biological Diversity. Nairobi, Kenya, 2000. Retrieved from https://www.cbd.int/decision/cop?id=7148

Celliers, L., and others. Stratification of stakeholders for participation in the governance of coastal social-ecological systems. Ambio, vol. 52, pp. 1418-1430, 2023.

Center for International Earth Science Information Network. 2024. "Population Density: Maps." Retrieved July 23, 2024. https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/maps

Chausson, A., and others. Mapping the effectiveness of nature-based solutions for climate change adaptation. Global Change Biology, vol. 26, No. 11, pp. 6134-6155, 2020.

Chavez, V., and others. Coastal green infrastructure to mitigate coastal squeeze. Journal of Infrastructure Preservation and Resilience, vol. 2, art. 7, 2021.

Chowdhury, P., and others. Mixed debris interaction with obstacle array under extreme flood conditions. Journal of Flood Risk Management, art. e12987, 2024.

Ciisneros-Montemayor, A. M., and others. Social equity and benefits as the nexus of a transformative Blue Economy: A sectoral review of implications. Marine Policy, vol. 109, art. 103702, 2019.

Cormier, R., and others. The science-policy interface of risk-based freshwater and marine management systems: from concepts to practical tools. Journal of Environmental Management, vol. 226, pp. 340–346, 2018.

Crosby, S. C., and others. Salt marsh persistence is threatened by predicted sea-level rise. Estuarine, Coastal and Shelf Science, vol. 181, pp. 93–99, 2016.

Da Costa, J. P., and others. The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. Frontiers in Environmental Science, vol. 8, 2020.

Dafforn, K. A., and others. Application of management tools to integrate ecological principles with the design of marine infrastructure. Journal of Environmental Management, vol. 158, pp. 61-73, 2015.

Dafforn, K. A., and others. Marine urbanization: an ecological framework for designing multifunctional artificial structures. Frontiers in Ecology and the Environment, vol. 13, pp. 82-90, 2015.

Das, J. Blue Economy, blue growth, social equity and small-scale fisheries: A global and national level review. Studies in Social Science Research, vol. 4, No. 1, pp. 38, 2023.

~~de Andres, M., and Munoz, J. M. B. The limits of coastal and marine areas in Andalusia (Spain). A socio-ecological approach for ecosystem-based management. Land Use Policy, vol. 120, art. 106250, 2022.~~

de Deus, B.C.T., and others. Coastal plastic pollution: A global perspective. Marine Pollution Bulletin, vol. 203, pp. 116478, 2024.

de Mattos, S. M. G., and others. (2022). Coastal Small-Scale Fisheries in Brazil: Resentment Against Policy Disarray. In Blue Justice (pp. 35-54). Springer.

Deloitte. (2023). Global Port Trends 2030.

Delmartino, F. Environmental Governance: A Multi-level Governance Approach. EU Studies in Japan, pp. 1-18, 2009.

Douvere, F. The importance of marine spatial planning in advancing ecosystem-based sea use management. Marine Policy, vol. 32(5), pp. 762-771, 2008.

Edwards, S. D., and others. Participation in coastal zone management initiatives: A review and analysis of examples from the UK. Ocean & Coastal Management, vol. 36, pp. 143-165, 1997.

Elliott, M., Á. Borja, and R. Cormier. Managing marine resources sustainably – ecological, societal and governance connectivity, coherence and equivalence in complex marine transboundary regions. Ocean & Coastal Management, vol. 245, art 106875.

Elmqvist, T., and others. Benefits of restoring ecosystem services in urban areas. Current Opinion in Environmental Sustainability, vol. 14, pp. 101-108, 2015.

Elrick-Barr, C. E., and others. Understanding coastal social values through citizen science: The example of Coastsnap in Western Australia. Ocean & Coastal Management, vol. 238, art. 106563, 2023.

Engen, S., and others. Co-creating coastal sustainability goals and indicators. Sustainability Science, vol. 19, pp. 1327-1343, 2024.

EU (European Union). (2020). Marine Pollution. Retrieved from (link unavailable)

Feagin, R. A., and others. Infrastructure investment must incorporate Nature's lessons in a rapidly changing world. One Earth, vol. 4, No. 10, pp. 1361-1364, 2021.

Firth, L. B., and others. Ocean sprawl: Challenges and opportunities for biodiversity management in a changing world. In: Hughes, R. N., Hughes, D. J., and Smith, I. P., eds. Oceanography and Marine Biology: An Annual Review, vol. ~~54.~~ 54, pp. 193-269, 2016.

Firth, L. B., and others. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. Journal of Applied Ecology, vol. 57, pp. 1762-1768, 2020.

Firth, L., and others. Coastal greening of grey infrastructure: an update on the state-of-the-art. Proceedings of the Institution of Civil Engineers, vol. 177, No. 2, pp. 35-67, 2024.

Ford, H.V., and others. The fundamental links between climate change and marine plastic pollution. Science of the Total Environment, vol. 806, art. 150392, 2022.

Frangoudes, K., and others. Situated transformations of women and gender relations in small-scale fisheries and communities in a globalized world. Maritime Studies, vol. 18, No. 3, pp. 241–248, 2019.

Garcia-Soto, C., and others. Marine citizen science: Current state in Europe and new technological developments. Frontiers in Marine Science, vol. 8, 2021.

Geiß, C., and others. Anticipating a risky future: long short-term memory (LSTM) models for spatiotemporal extrapolation of population data in areas prone to earthquakes and tsunamis in Lima, Peru. Natural Hazards and Earth System Sciences (NHESS), vol. 24, pp. 1051-1064, 2024.

Gittman, R.K., and others. Ecological consequences of shoreline hardening: a meta-analysis. BioScience, vol. 66, pp. 763–773, 2016.

Glavovic, B.C., and others. "Cross-Chapter Paper 2: Cities and settlements by the sea", in *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H.-O. Portner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Landsdorf, S. Loschke, and V. Moller, eds. New York: Cambridge University Press, 2022.

Grizzetti, B., and others. How EU policies could reduce nutrient pollution in European inland and coastal waters. Global Environmental Change vol. 69, pp. 102281, 2021.

Guan, W., M. Bao, X. Lou, Z. Zhou, and K. Yin. Monitoring, modeling and projection of harmful algal blooms in China. Harmful Algae, vol. 111, art. 102164, 2022.

Haarr, M. L., J. Falk-Andersson, and J. Fabres. Global marine litter research 2015–2020: geographical and methodological trends. Science of The Total Environment, vol. 820, art. 153162, 2022.

Hamidi, A.R., and others. Household vulnerability to floods and cyclones in Khyber Pakhtunkhwa, Pakistan. International Journal of Disaster Risk Reduction, vol. 46, pp, 101496, 2020.

Harley, M. D., and M. A. Kinsela. CoastSnap: A global citizen science program to monitor changing coastlines. Continental Shelf Research, vol. 245, art. 104796, 2022.

Harvey, N., and B. Clarke. 21st Century reform in Australian coastal policy and legislation. Marine Policy, vol. 103, pp. 27-32, 2019.

HM Government, Northern Ireland Executive, Scottish Government, Welsh Assembly Government. 2011. UK Marine Policy Statement.

~~Huang, P., and others. Integrated Zoning and Spatial Heterogeneity of Coastal Watershed-Nearshore Waters. Remote Sensing, vol. 15, art. 3597, 2023.~~

Iacarella, J.C., I.C. Davidson, and A. Dunham. Biotic exchange from movement of 'static' maritime structures. Biological Invasions, vol. 21, pp. 1131–1141, 2019.

Iñiguez., M.E., and others. Marine debris occurrence and treatment: A review. Renewable and Sustainable Energy Reviews, vol.64, pp.394-402. 2016.

International Monetary Fund. (2022,2023). World Economic Outlook. https://www.imf.org/en/Publications/WEO

IPCC. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Technical Report. Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and N.M. Weyer (eds.). In press.

IPCC. (2022). "Fact Sheet: Cities and Settlements by the Sea," Sixth Assessment Report. Retrieved December 15, 2024 (https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_CitiesSettlementsBtS.pdf).

Islam, M. S., and M. Tanaka. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. Marine Pollution Bulletin, vol. 48, No. 7-8, pp. 624–649, 2004.

Ison, S., and others. Participatory research in complex marine conservation settings: A review of recent trends and lessons for the future. Ocean & Coastal Management, vol. 253, No. 3, art. 107053, 2024.

Izaguirre, C., and others. Climate change risks to global port operations. Nature Climate Change, vol. 11, pp. 14–20, 2021.

Jentoft, S. Limits of governability: Institutional implications for fisheries and coastal governance. Marine Policy, vol. 31, pp. 360-370, 2007.

Jentoft, S., and others. (2017). The small-scale fisheries guidelines: Global implementation (Vol. 14). Springer.

Johnson, D. E., and S. Dagg. Achieving public participation in coastal zone environmental impact assessment. Journal of Coastal Conservation, vol. 9, pp. 13-18, 2003.

Kay, R., and Alder, J. (2017). Coastal Planning and Management, Coastal Planning and Management. CRC Press.

Keeler, B. L., and others. Social-ecological and technological factors moderate the value of urban nature. Nature Sustainability, vol. 2, pp. 29-38, 2019.

Kirkfeldt, T. S. An ocean of concepts: Why choosing between ecosystem-based management, ecosystem-based approach and ecosystem approach makes a difference. Marine Policy, vol 106, art. 103541, 2019.

Koks, E.E., and others. A global multi-hazard risk analysis of road and railway infrastructure assets. Nature Communications, vol. 10, art. 2677, 2019.

Kulp, S.A., and B.H. Strauss. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nature Communications, vol. 10, art. 4844, 2019.

Kummu, M., and others. Over the hills and further away from the coast: global geospatial patterns of human and environment over the 20th-21st centuries. Environmental Research Letters, vol. 11, art. 034010, 2016.

Kuwae, T., and S. Crooks. Linking climate change mitigation and adaptation through coastal green–gray infrastructure: a perspective. Coastal Engineering Journal, vol. 63, No. 3, pp. 188–199, 2021.

Lebreton, L., and A. Andrady. Future scenarios of global plastic waste generation and disposal. Palgrave Communications, vol. 5, No. 1, pp. 1–11, 2019.

Lee, C., T. Park, Y. Park, and W. Lim. Monitoring and trends in harmful algal blooms and red tides in Korean coastal waters, with emphasis on Cochlodinium polykrikoides. Harmful Algae, vol. 30, pp. S3–S14, 2013.

Lentisco, A., and Lee, R.U. (2015). A REVIEW OF WOMEN'S ACCESS TO FISH IN SMALL-SCALE FISHERIES.

Lincoln, S., and others. Marine litter and climate change: inextricably connected threats to the world's oceans. Science of The Total Environment, vol. 837, art. 155709, 2022.

Li, C., and others. Heavy metal pollution in coastal wetlands: A systematic review of studies globally over the past three decades. Journal of Hazardous Materials, vol. 424, pp. 127312, 2022.

Liu, C.H., and others. Regional environmental governance of the Yellow Sea and Bohai Sea from the perspective of land and sea coordination: Conference report. Marine Policy, 127, 2021.

Liu, D., and Xing, W. Analysis of China’s coastal zone management reform based on land-sea integration. Marine Economics and Management, vol. 2, No. 1, pp. 39–49, 2019.

Liu, Y., and others. Termination of the 2018 Florida red tide event: A tracer model perspective. Estuarine, Coastal and Shelf Science, vol. 272, pp. 107901, 2022.

Lozano-Rivera, P., and others. Nature-Based Solutions. Coral Reefs, vol. 26, pp. 17-000.

Lu, Y., and others. Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. Environmental Pollution, vol. 239, pp. 670–680, 2018.

Ma, C., and others. A risk-based approach to cumulative effects assessment for large marine ecosystems to support transboundary marine spatial planning: a case study of the Yellow Sea. Journal of Environmental Management, vol. 342, art. 118165, 2023.

Mackelworth, P., and others. Ecologically and biologically significant areas (EBSAs) as an enabling mechanism for transboundary marine spatial planning. Marine Policy, vol. 166, art. 106231, 2024.

Magnan A. K., and others. Over the hills and further away from the coast: global geospatial patterns of human and environment over the 20th-21st centuries. Environmental Research Letters, vol. 11, art. 034010, 2016.

Maragno, D., and others. Land-sea Interaction: Integrating Climate Adaptation Planning and Maritime Spatial Planning in the North Adriatic Basin. Sustainability, vol. 12, art. 5319, 2020.

Matias, A., and others. (2023). The role of art in coastal and marine sustainability. Cambridge Prisms: Coastal Futures 1:1-22.

Mauro, F. & Hardison, P. (2000). TRADITIONAL KNOWLEDGE OF INDIGENOUS AND LOCAL COMMUNITIES: INTERNATIONAL DEBATE AND POLICY INITIATIVES.

Mayer-Pinto, M., and others. Building 'blue': An eco-engineering framework for foreshore developments. Journal of Environmental Management, vol. 189, pp. 109-114, 2017.

McKinley, E., and others. ‘Going digital’ - Lessons for future coastal community engagement and climate change adaptation. Ocean & Coastal Management, vol. 208, art. 105629, 2021.

McGranahan, G., and others. The rising tide. Environment and Urbanization, vol. 19, pp. 17–37, 2007.

Merkens, J.-L., and others. Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. Global and Planetary Change, vol. 145, pp. 57-66, 2016.

Merkens, S., and others. Gridded population projections for the coastal zone under the shared socioeconomic pathways. Global and Planetary Change, vol. 145, pp. 57–66, 2016.

Millner, A. and others. Adaptation to climate change and economic growth in developing countries. Environment and Development Economics, vol. 20, pp. 380-406, 2015.

Morris, A., and others. Advancing equitable partnerships: Frontline community visions for coastal resiliency knowledge co-production, social cohesion, and environmental justice. Geoforum, vol. 154, No. 1, art. 104051, 2024.

Morris, R. L., and others. (2019). Design Options, Implementation Issues and Evaluating Success of Ecologically Engineered Shorelines. In: Hawkins, S. J., and others, eds. Oceanography and Marine Biology: An Annual Review, vol. 57. CRC Press, Boca Raton, pp. 169–228.

Morris, R. L., and others. Fish-smart seawalls: a decision tool for adaptive management of marine infrastructure. Frontiers in Ecology and the Environment, vol. 16, pp. 278-287, 2018.

Morris, R. L., and others. From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence. Global Change Biology, vol. 24, pp. 1827–1842, 2018.

Muhl, E.-K., and others. Transitioning toward "deep" knowledge co-production in coastal and marine systems: Examining the interplay among governance, power, and knowledge. Ecology and Society, vol. 28, No.4, art. 17, 2023.

Narayan, S., and others. The value of coastal wetlands for flood damage reduction in the Northeastern USA. Scientific Reports, vol. 7, art. 9463, 2017.

Nienhuis, J.H., and others. River Deltas and Sea-Level Rise. Annual Review of Earth and Planetary Sciences, vol. 51, pp. 79-104, 2023.

NOAA. Harmful Algal Bloom Monitoring System. https://coastalscience.noaa.gov/science-areas/habs/hab-monitoring-system/

Norström, A. V., and others. Principles for knowledge co-production in sustainability research. Nature Sustainability, vol. 3, pp. 182-190, 2020.

Nunes. M., and others. PCDD/ Fs and dioxin-like PCBs in sediment and biota from the Mondego estuary (Portugal). Chemosphere, vol.83, pp.1345–1352, 2011.

Organisation for Economic Co-operation and Development. (2023). OECD Territorial Reviews: Regional Development Including Coastal Areas. www.oecd.org/territorial-reviews

O'Shaughnessy, K.A., and others. Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users. Urban Ecosystems, vol. 23, pp. 431–443, 2020.

Otero, P., J. Gago, and P. Quintas. Twitter data analysis to assess the interest of citizens on the impact of marine plastic pollution. Marine Pollution Bulletin, vol. 170, art. 112620, 2021.

Ou, Y., and Xue, Z.G. Hydrodynamic and biochemical impacts on the development of hypoxia in the Louisiana–Texas shelf–Part 1: roles of nutrient limitation and plankton community. Biogeosciences, vol. 21(10), pp. 2385-2424, 2024.

Ou, Yanda., and others. Hydrodynamic and biochemical impacts on the development of hypoxia in the Louisiana–Texas shelf–Part 2: statistical modeling and hypoxia prediction. Biogeosciences, vol. 19(15), pp. 3575-3593, 2022.

Park, H., and others. Experimental study of debris transport driven by a tsunami-like wave: application for non-uniform density groups and obstacles. Coastal Engineering, vol. 166, art. 103867, 2021.

Paterson, S. K., and others. Examining the potential of art-science collaborations in the Anthropocene: A case study of Catching a Wave. Frontiers in Marine Science, vol. 7, art. 340, 2020.

Paxton, A. B., and others. What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol. Environmental Evidence, vol. 12, No. 1, p. 11, 2023.

Peci Lyons, S., and others. Enabling indigenous innovations to re-centre social licence to operate in the Blue Economy. Marine Policy, vol. 147, art. 105348, 2023.

Pikner, T., and others. Sociocultural Dimension of Land-sea Interactions in Maritime Spatial Planning: Three Case Studies in the Baltic Sea Region. Sustainability, vol. 14, No. 4, art. 2194, 2022.

Preez, M.D. (2018). Gender and Small-scale Fisheries in Africa.

Qian. Y., and others. Metal pollution in coastal sediments. Curr Pollut Rep, vol.4, pp.203–219, 2015.

Quataert, E., and others. The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. Geophysical Research Letters, vol. 42, pp. 6407-6415, 2015.

Reed, M. S., and others. A theory of participation: What makes stakeholder and public engagement in environmental management work? Restoration Ecology, vol. 26, pp. S7-S17, 2018.

Reguero, B. G., and others. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLoS One, vol. 13, art. e0192132, 2018.

Reguero, B. G., and others. The value of U.S. coral reefs for flood risk reduction. Nature Sustainability, vol. 4, pp. 688–698, 2021.

Reimann, L., A. T. Vafeidis, and L. E. Honsel. Population development as a driver coastal risk: current trends and future pathways. Cambridge Prisms: Coastal Futures, vol. 1, art. e14, 2023.

Reimann, L., and others. Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea level rise. Nature Communications, vol. 9, art. 4161, 2018.

Reimann, L., and others. Population development as a driver of coastal risk: Current trends and future pathways. Cambridge Prisms: Coastal Futures, vol. 1, e14, 2023.

Rodríguez, Y., A. Ressurreição, and C. K. Pham. Socio-economic impacts of marine litter for remote oceanic islands: the case of the Azores. Marine Pollution Bulletin, vol. 160, art. 111631, 2020.

Rising, J., and others. The Missing Risks of Climate Change. Nature, vol. 610, pp. 643-651, 2022.

Saeed, S.; and others. Climate Change Vulnerability, Adaptation, and Feedback Hypothesis: A Comparison of Lower-Middle, Upper-Middle, and High-Income Countries. Sustainability, vol. 15(5), pp. 4245, 2023.

Sartorius, J. V., and others. Participation and co-production in climate adaptation: Scope and limits identified from a meta-method review of research with European coastal communities. WIREs Climate Change, art. e880, 2024.

Sengupta, D., and others. Mapping 21st century global coastal land reclamation. Earth's Future, vol. 11, art. e2022EF002927, 2023.

Singh, G. G., and others. Governing the Land-sea Interface to Achieve Sustainable Coastal Development. Frontiers in Marine Science, vol. 8, art. 709947, 2021.

Small, C., and R.J. Nicholls. A global analysis of human settlement in coastal zones. Journal of Coastal Research, vol. 19, pp. 584–599, 2003.

Sowman, M., and N. Malan. Review of progress with integrated coastal management in South Africa since the advent of democracy. African Journal of Marine Science, vol. 40, pp. 121-136, 2018.

Stancheva, M., and others. Coastal erosion driven land-sea interactions in maritime spatial planning—a case of Bulgaria. Journal of Coastal Conservation, vol. 25, pp. 1–19, 2021.

Steven, A.D.L., and others. (2020). Coastal Development: Resilience, Restoration and Infrastructure Requirements. Washington, DC: World Resources Institute. www.oceanpanel.org/blue-papers/coastal-development-resilience-restoration-and-infrastructure- requirements.

Stelzenmüller, V., and others. A risk-based approach to cumulative effect assessments for marine management. Science of the Total Environment, vol. 612, pp. 1132–1140, 2018.

Strain, E. M. A., and others. Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? Journal of Applied Ecology, vol. 55, pp. 426-441, 2018.

Storlazzi, C.D., and others. Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. Science Advances, vol. 4, pp. 9741, 2018.

Storlazzi, C.D., and others. Hybrid coral reef restoration can be a cost-effective solution to provide protection to vulnerable coastal populations. Science Advances, vol. 11, pp. 4004, 2025.

Sun, F., and R. T. Carson. Coastal wetlands reduce property damage during tropical cyclones. Proceedings of the National Academies of Sciences, vol. 117, No. 11, pp. 5719-5725, 2020.

Tanguy, R., and others. Pan-Arctic Assessment of Coastal Settlements and Infrastructure Vulnerable to Coastal Erosion, Sea-Level Rise, and Permafrost Thaw. Earth’s Future, No. 12, pp. e2024EF005013. 2024.

Tallent, T., and Zabala, A., Social equity and pluralism in Nature-based Solutions: Practitioners' perspectives on implementation. Environmental Science & Policy, vol. 151, 2024.

Thoya, P., and others. Policy gaps in the East African Blue Economy: Perspectives of small-scale fishers on port development in Kenya and Tanzania. Frontiers in Marine Science, vol. 9, 2022.

Toledo, I., and others. Local authorities or national frameworks? A global review on coastal protection policies. Environmental Development, vol. 53, pp. 101119, 2025.

Thomas, K., and others. Explaining differential vulnerability to climate change: A social science review. Wiley Interdisciplinary Reviews: Climate Change, vol. 10(2), pp. e565, 2019.

Turnhout, E., and others. The politics of co-production: Participation, power, and transformation. Current Opinion in Environmental Sustainability, vol. 42, pp. 15-21, 2020.

UNDP. (2021). The YSLME Story: Management and Governance for the Restoration and Protection of the Yellow Sea Large Marine Ecosystem. UNDP/GEF Yellow Sea Large Marine Ecosystem (YSLME) Phase II Project, Incheon, RO Korea. pp 96.

UNEP (United Nations Environment Programme). (2019). Marine Pollution. Retrieved from (link unavailable)

United Nations Department of Economic and Social Affairs (UN DESA). (2024). Tuvalu Coastal Adaptation Project.

United Nations Environment Programme. Coastal and marine resources: Sustainable management and impact analysis. www.unep.org/coastal-marine-resources, 2023.

United Nations Web TV. (2021). Barbados: Sea-level Rise & Coastal Erosion - United Nations Chief sees Climate Impacts ahead of COP26.

United Nations. (2017). Population division, world population prospects. https://population.un.org/wpp/

United Nations. (2021). The Second World Ocean Assessment. https://www.un.org/regularprocess/woa2

UNESCO. (2025). Tsunami Ready. https://tsunami.ioc.unesco.org/en/tsunami-ready

Viehman T.S., and others. Coral restoration for coastal resilience: a framework for multi-scale integration of ecology, hydrodynamics, and engineering. Ecosphere, vol. 14, pp. e4517, 2023.

Vieira da Silva, C., and others. Participatory Geographic Information Systems (PGIS): Alternative approaches to identify potential conflicts and positional accuracy in marine and coastal ecosystem services. Marine Policy, vol. 131, art. 104650, 2021.

Vince, J., and B. D. Hardesty. Governance solutions to the tragedy of the commons that marine plastics have become. Frontiers in Marine Science, vol. 5, art.214, 2018.

Vollstedt, B., and others. Co-production of climate services: A story map for future coastal flooding for the city of Flensburg. Climate Services, vol. 22, art, 100225, 2021.

Vozzo, M. L., and others. Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates. Marine Environmental Research, vol. 165, art. 105243, 2021.

Warner, J.C., and others. Development of a coupled ocean–atmosphere–wave–sediment transport (COAWST) modeling system. Ocean modelling, vol. 35(3), pp. 230-244, 2010.

Wang, S., and others. Benefits and approaches of incorporating land–sea interactions into coastal spatial planning: evidence from Xiamen, China. Frontiers in Marine Science, vol. 11, art. 1137147, 2024.

West, S., and others. Relational approaches to sustainability transformations: Walking together in a world of many worlds. Ecosystems and People, vol. 20, No. 1, art. 2370539, 2024.

Williams, A., and others. The management of coastal erosion. Ocean & Coastal Management, vol. 156, pp. 4-20, 2017.

World Bank. Coastal development: challenges and opportunities. www.worldbank.org/coastal-development, 2023.

World Shipping Council. (2024). Containers lost at sea–2023 update. Accessed on July 9, 2024. Available at: https://static1.squarespace.com/static/5ff6c5336c885a268148bdcc/t/6667a1b5a8b88c3efac6665e/1718067641677/Containers_Lost_at_Sea_2024_FINAL.pdf

World Trade Organization. (2020-2023). *World Trade Statistical Review*. https://www.wto.org/english/res_e/reser_e/statistics_e.htm

World Travel & Tourism Council. (2021). *Economic Impact Report*. https://wttc.org/Research/Economic-Impact

Yatim, M. H. M., and others. INSTITUTIONAL MAPPING TOWARDS DEVELOPING A FRAMEWORK FOR SUSTAINABLE MARINE SPATIAL PLANNING. Remote Sensing, pp. 159-166, 2016.

Ye, G., and others. Is integrated coastal management an effective framework for promoting coastal sustainability in China's coastal cities? Marine Policy, vol. 56, pp. 48–55, 2015.

Zebracki, M. Regenerating a coastal town through art: Dismaland and the (l)imitations of antagonistic art practice in the city. Cities, vol. 77, pp. 21-32, 2018.

Zuercher, R., and others. Enabling conditions for effective marine spatial planning. Marine Policy, 143, 2022.

Section 5A
Chapter 10 Geoengineering

This chapter outlines the current consensus and roadmaps for marine-based geoengineering, including ~~marine-~~marine-based carbon dioxide removal (mCDR), defined as "human activity that captures CO_2 from the atmosphere and stores it for decades to millennia", (Smith and others, 2024), ~~and~~ as well as other geoengineering approaches , defined as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change", (Markusson, and others, 2013), comprising here solar radiation modification (SRM) and structural engineering. The Internation Maritime Organisation defines marine geoengineering as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe"

1. Keynotes

- The scientific consensus remains that proposed novel geoengineering approaches are unproven in practice, and there is significant uncertainty around the possible risks and impacts of deployment on the climate and environment~~requiring significant research to establish their potential to mitigate climate change~~.
- Paris Agreement compliant Intergovernmental Panel on Climate Change (IPCC) scenarios require 7 to 9 $GtCO_2$ removal per year by 2050, in addition to reductions in greenhouse gas emissions. Currently only 2 $GtCO_2$ p.a. of conventional, low durability terrestrial CDR has materialised.
- Monitoring, Reporting and Verification (MRV) protocols are being developed that will be key to demonstrating if mCDR approaches are effective.
- mCDR pilot studies are likely to deliver key knowledge advances in the coming decade.
- Governance frameworks are underdeveloped. Efforts to develop an international governance framework under the London Convention and Protocol are ongoing but progress has been slow.

Key synthesis reports and overviews

High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques GESAMP (2019)
A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration NASEM (2021)
IPCC, 2018: Global Warming of 1.5°C (2022)
Ocean Visions high-level roadmap (2023)
Strategy for NOAA Carbon Dioxide Removal Research (2023)
Guide to Best Practices in Ocean Alkalinity Enhancement Research (2023)
A Code of Conduct for Marine Carbon Dioxide Removal Research (2023)
The State of Carbon Dioxide Removal (2024)

2. Introduction

The Paris Agreement (2015) sets a goal of limiting temperature increases to "well below 2℃", ideally 1.5℃, above pre-industrial levels, which will require rapid, deep and sustained greenhouse gas reductions and ultimately the attainment of net zero CO_2 emissions by mid-century (IPCC, 2018; UNFCCC, 2023). A significant gap remains between international targets and the actions required to limit the extent of warming to 1.5℃ (IPCC ~~2022~~2023). All scenarios and action pathways that achieve the Paris goal require global net negative emissions, whereby the greenhouse gas taken up by land and ocean exceed the amount released to the atmosphere (Schipper and others, 2022). One proposed pathway for achieving this is the implementation of geoengineering approaches to counterbalance residual or harder to abate emissions (Pathak and others, 2022; IPCC, 2022) and their impact on global warming. ~~, although~~ That said, approaches remain unproven in practice, requiring significant research abiding by the precautionary principle (Cooley and others 2023). Further, t~~t~~here is considerable debate around the definition and quantification of residual emissions (Buck and others, 2023).

The range of biological, chemical and physical processes that influence air-sea CO_2 exchange (see section 5B chapter 1) suggest that it may be possible to enhance the rate and capacity for ocean carbon storage via methods such as the implementation of mCDR techniques (NASEM, 2021), figure 5A.10.1. Most mCDR methods seek to enhance the diffusion of atmospheric CO_2 into seawater by increasing the production and/or storage of organic carbon, or by altering the inorganic pool of dissolved carbon. Biological mCDR techniques, including direct nutrient addition or upwelling of nutrient rich waters to encourage primary production and the restoration of coastal vegetated ecosystems (Lovelock and Duarte, 2019), stimulate the conversion of dissolved CO_2 into plant matter via photosynthesis, fixing that carbon in a way that prevents its release back into the atmosphere following degradation. Deposition of terrestrial biomass into the deep ocean for long-term storage is also proposed. Chemical mCDR

approaches enhance the capacity of the ocean to absorb atmospheric CO_2 by either increasing alkalinity, which forces the conversion of dissolved CO_2 into the more stable compounds, or by electrochemically removing the dissolved CO_2 for geological storage (e.g. Eisaman and others, 2023). In both cases the perturbations in seawater chemistry create an air-to-sea gradient that drives the absorption of more atmospheric CO_2 into the ocean (Schulz and others, 2023). Physical mCDR approaches, including the downwelling of carbon-enriched surface waters, have also been suggested.

Ultimately, the successful long-term storage of CO_2 depends on either its incorporation into stable biogeochemical compounds in the ocean, and ultimate burial in deep sediments, (e.g. Boyd and others, 2024), or carbon dioxide capture and geological storage, (CCS), which offers the most certainty for permanent CO_2 removal (IPCC, 2022). The placement of CO_2 saturated fluids on the deep seabed has also been considered, but concerns have been raised about ecological impacts, long-term stability, and legality (IPCC, 2005). Deposition of terrestrial biomass into the deep ocean for long-term storage is another method, with similar uncertainties (Levin and others 2023).

Structural geoengineering techniques, include the adoption of low carbon manufactured building products and design of marine structures to enhance biodiversity, (UNEP 2023, Fennel et al. 2021, Dafforn et al. 2015, Firth et al. 2024). Such approaches may be relevant as coastal development (including for mCDR) progresses (see section 5A chapter 9).

Marine SRM approaches seek to explore increasing~~e~~ the albedo of the ocean's surface, enabling more energy to be reflected away from the Earth's surface. Techniques include seawater sprays stimulating cloud formation, enhancing sea ice, microbubbles and reflective foams (e.g. GESAMP 2019), figure 5A.10.1. Ocean heat displacement and the use of more sustainable or bio-based materials in ocean engineering have also been proposed as mechanisms for supporting decarbonisation via the production of renewable electricity and CO_2 emission reduction during construction (GESAMP, 2019; NRC, 2006).

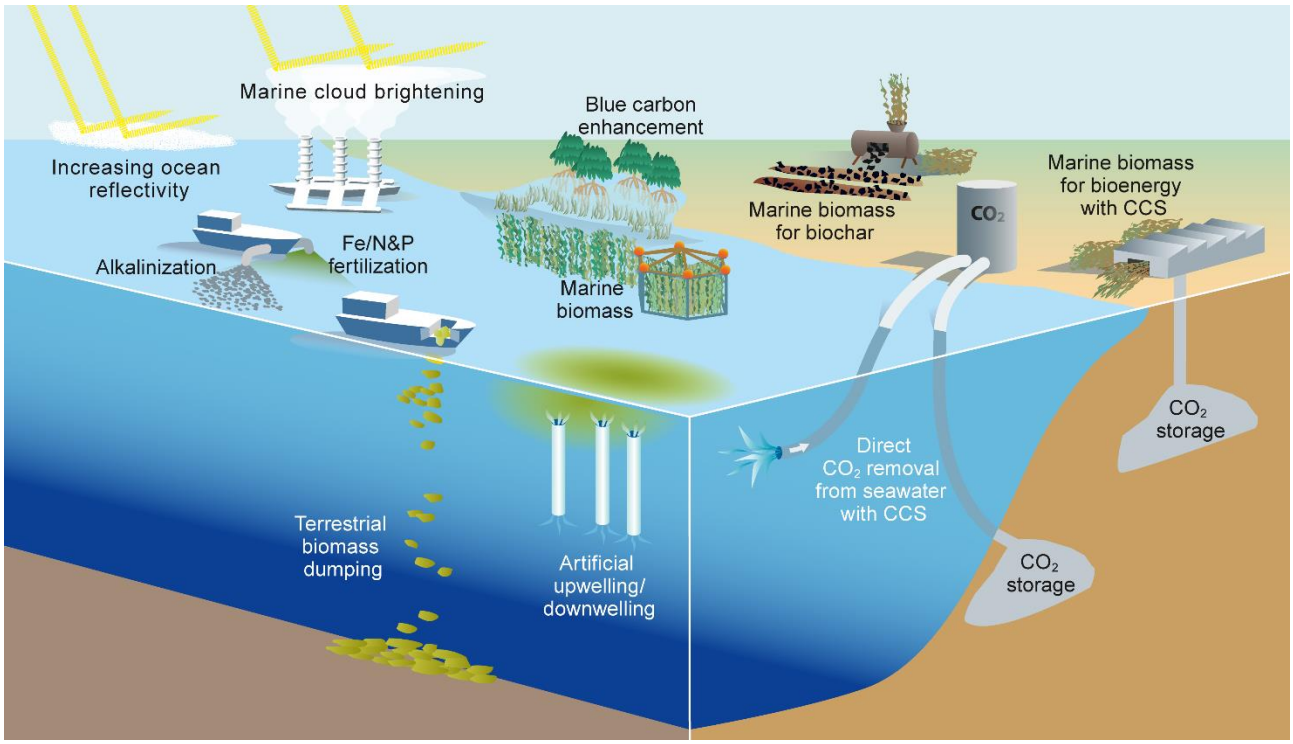


Figure 5A.10.1. Solar radiation modification and mCDR approaches. Artwork: Rita Erven, GEOMAR, CC BY-SA 4.0

Although the fundamental scientific principles of geoengineering approaches are well known, their technological maturity, environmental impact and potential for wide-scale implementation vary significantly, figure 5A.10.2. Several recent synthesis reports outline the challenges and research gaps (see above), and whilst there is debate, the current consensus is that most of the techniques are not yet proven effective, safe or technologically mature enough to scale. Correspondingly, the level of investment in marine based techniques remain considerably lower than terrestrial alternatives such direct capture, bioenergy with CCS (BECCS) and biochar (Smith and others, 2024). Notwithstanding the London Protocol (see below), t~~T~~here are no binding international agreements that comprehensively and specifically address mCDR (Webb and others, 2023). Small scale, controlled pilot studies are starting to address some of the critical knowledge gaps in these approaches. GESAMP (2024) currently identify 39 substantive mCDR initiatives aimed at sequestering carbon in the marine environment. Of these the most numerous are macroalgae farming, ocean alkalinity enhancement, biomass sinking and ocean fertilization (28, 20, 18 and 15% respectively). Crop wastes feature strongly in the biomass disposal category, alongside sargassum, accounting for a further 4 of the macroalgae farming initiatives. The development of Monitoring, Reporting and Verification (MRV) protocols that assess carbon storage whilst accounting for local to global-scale marine processes, is another recognised research priority. Additional uncertainties regarding the potential environmental impacts, societal acceptability and economic viability of marine geoengineering and mCDR approaches will need to be adequately addressed, with effective governance frameworks implemented, prior to deployment at climatically relevant scales.

This chapter outlines the current challenges and priorities for marine geoengineering, including mitigation potential, environmental effects, impacts on communities, economic feasibility, governance and pathways for ensuring sustainable development.

Geoengineering category		Method	Carbon storage pool	Storage time-scale	Readiness	Mitigation potential	Location	Spatial interactions with other ocean users	Potential for natural system feedbacks
Biological mCDR	Ecosystem restoration	via mangrove / saltmarsh / seagrass restoration	biota	short <100 yr	medium TRL 5–6 demonstration	small <3 $GTCO_2$/yr	mostly coastal	likely >66%	likely >66%
		via mangrove / saltmarsh / seagrass restoration							
		via marine aquaculture / shellfish farming							
	Macroalgae growth	with deposition in deep marine	sediments	medium 100–1000 yr		large >9 $GTCO_2$/yr	coastal		
		with deposition in anoxic basins							
		with deposition on land	soils						
	Microalgae growth / fertilisation	via macronutrient addition / upwelling	sediments			moderate 3–9 $GTCO_2$/yr	oceanic	likely as not 33–66%	
		via micro nutrient addition							
		deposition of terrestrial carbon at sea							
Chemical mCDR	Direct ocean capture with CCS	via electrolysis	geological	long >1000 yr	low TRL ≤4 research and development	large >9 $GTCO_2$/yr	coastal	unlikely <33%	unlikely <33%
		via electrodialysis							
	Ocean alkalinity enhancement	via silicate mineral weathering	minerals				oceanic	likely as not 33–66%	likely as not 33–66%
		via ocean liming							
		via dissolution of limestone and other carbonates							
		ocean crust mineralisation	geological						
Physical mCDR		artificial downwelling		short			mostly oceanic	likely >66%	likely >66%
Solar radiation management	Oceanic albedo	via enhanced sea ice formation	N/A	N/A		N/A			
		via microbubbles							
		via reflective foam and other materials							
		via marine cloud brightening							
Structural	Zero carbon	use of low carbon / biomaterials in ocean engineering	construction	short <100 yr					
	Habitat	structures to enhance ecosystems	biota		medium				

Figure 5A.10.2. Status of mCDR and other marine geoengineering approaches, based on Smith and others, (2024) and Cooley and others, (2023). Blank spaces indicate a lack of data.

3. Pressures and Impacts

3.1 Chemical mCDR approaches

Chemical mCDR methods that increase the pH and/or alkalinity of seawater (either via mineral addition or electrochemical methods) are thought to have significant long-term carbon sequestration potential (NASEM, 2022; Kwiatkowski and others, 2023; Oschlies and others, 2023; Palmiéri and Yool, 2024, see also section 5B chapter 3). However, complex multi-scale ocean mixing processes, and the long timescales required for CO_2 diffusion into seawater (Jones and others, 2014), create significant uncertainty for their potential efficacy. Furthermore, any alteration to marine chemistry resulting in increased carbon storage will impose chemical gradients that exceed normal variability. Reducing these gradients by spreading operations over larger areas will have implications for both cost and monitoring and for the social acceptability of mCDR projects (Satterfield and others 2023).

A large body of research describes ecosystem impacts arising from increasing levels of CO_2 leading to ocean acidification (Doney and others, 2020). Conversely, little work to date has looked at the ecological effects of increased alkalinity. Subhas and others (2022) and Ferderer and others (2022) both noted limited impacts on plankton communities during small scale microcosm experiments, but highlight the need for further research (Bach and others, 2024).

Estimates of chemical mCDR potential have been reported in the range of 3-30 GT CO_2 yr^{-1}, (Köhler and others, 2013; Renforth and Henderson, 2017; Feng and others, 2017), but current pilots operate at the scale of tonnes. Operations would need to increase in both number and capacity by orders of magnitude, accompanied by increased environmental impacts and process uncertainties, within a relatively short time scale (Ocean Visions 2023; Boyd and others, 2024).

Apart from sequestration and impact potential, the scalability of chemical mCDR approaches will depend on the deployment location (open ocean vs coastal), deployment strategy (e.g. choice of alkalinity source), delivery mechanism (coastal or ship-based), infrastructure needs (e.g. systems for electrochemical stripping) and feasibility, making a full life-cycle analysis imperative (Eisaman and others, 2023).

3.2 Biological mCDR approaches

The conservation and expansion of macroalgal coastal ecosystems like salt marshes (section 4 chapter 5i), mangroves (section 4 chapter 5h), seagrass meadows (section 4 chapter 5g), and kelp forests (section 4 chapter 4i) protects biodiversity, stabilises coastal habitats and act as carbon sinks, with an estimated storage potential of <0.3 $GtCO_2$ yr^{-1} (UNFCCC Ocean Dialogue 2023; Canadell and others, 2021; Erlania and others 2023; Krause-Jensen and Duarte, 2016; do Amaral Camara Lima and others, 2023; Yau and others, 2023).

Macroalgae aquaculture can potentially contribute to mCDR if it leads to long term carbon storage. Alternatively, such aquaculture can contribute indirectly to reducing climate pressures via food and product provision, improving water quality (Krause and others, 2022; Duarte and others, 2022) and mitigating local ocean acidification and deoxygenation (Guang Gao and

others, 2022; Xi Xiao and others, 2021; Dinghui Zou, 2005). Deposition of the harvested macroalgae may significantly increase carbon sequestration and its climatic benefits (e.g. Wu and others, 2023), though the potential scalability and durability remains uncertain (Berger and others, 2023).Other post-harvest uses of macroalgae, (feed additives to reduce ruminant methane emissions, biofuels and plastic substitutes), have additional climatic benefits (Kinley and others, 2020), while the removal and use of beach wrack for agricultural soil improvement can have a positive impact on carbon sink efficiency if done sustainably (Lanari and others 2024). In all cases, the potential ecological impacts habitats need to be considered (Ross and others, 2023; Chopin and others, 2024; Hyndes and others, 2022). Deposition of shells from shellfish aquaculture has also been proposed as a mCDR technique, though efficiency of the process has been questioned, and full lifecycle assessments are yet to be conducted (e.g. Boyd and others, 2024).

Microalgal mCDR methods aim to increase primary productivity via fertilisation using micronutrients, such as iron fertilization, or macronutrients (e.g. nitrogen, phosphorous) via upwelling of deep nutrient rich waters. Iron fertilization has been shown to promote the local growth of phytoplankton, particularly diatoms, but an increase in the amount of carbon that reaches the deep ocean is not always observed (Boyd and others, 2007; Martin and others, 2013; Jiang and others, 2024). Iron fertilization may also lead to widescale changes in nutrient distribution, reduced interior oxygen concentrations, and decreases in ecosystem biomass in the tropics with implications for fisheries (Tagliabue and others, 2023). Further research is needed to better assess the efficacy, impacts and feasibility of this approach (Buesseler and others, 2024). Fertilisation via the upwelling of nutrient-rich waters has been shown have scalability constraints, with the CDR potential of the approach thought to be limited to 0.1GT CO_2 y^{-1} (Koweek, 2022; Yool and others, 2009).

3.3 Physical mCDR approaches

Artificial downwelling has been proposed as a method to accelerate the sinking of carbon carrying biomass to the deep ocean, driven by pumps or increased salinity gradients, (NASEM, 2022), with only regional tests conducted (Stigebrandt and others, 2015). Primarily proposed as a method by which to counter deep ocean hypoxia, impacts and efficacy in sequestering carbon are unknown. Impacts on local temperature, salinity and plankton communities can be envisaged, and model studies have suggested that downwelling is highly unlikely to be competitive (Zhou and Flynn, 2005).

3.4 Structural geoengineering

Traditionally, coastal and marine developments involve the construction of rigid infrastructures such as seawalls, piers, ports as well as wind farms and oil platforms. These constructions, although needed for a wide range of societal demands, have considerable environmental impacts, including habitat loss. The production of building materials also generates carbon emissions (Fennel et al. 2021). Geoengineering approaches can be applied in this context to promote low-carbon sustainable development practices aimed at mitigating environmental impacts from both existing and new marine infrastructure.

Bio-based materials are emerging as a solution for decarbonization through the responsible management of carbon cycles, with the potential of reducing construction related emissions by

up to 40% by 2060 (UNEP 2023, Fennel et al. 2021). This approach involves using alternative raw materials, cement chemistries and fuels in the production process (Fennel et al. 2021). Other approaches, such as eco-engineering, may also be viable alternatives, by designing structures to promote the colonization of carbon-capturing organisms (Dafforn et al. 2015, Firth et al. 2024). These approaches enhance local biodiversity, contributing to conservation of ecosystem services.

Implementing a large-scale transition to circular and bio-based materials in the built environment involves significant risks. Without careful planning, decarbonisation can lead to unintended ecological impacts, if bio-based materials are not sourced sustainably, (UNEP 2023). Additionally, it can worsen unfair labour practices and result in uneven economic shifts during industry transitions, (Lehne and Preston 2018).

3.5 Solar Radiation Modification in marine environments

Unlike CDR approaches which reduce atmospheric CO_2, the root cause of warming, SRM works by reflecting incoming solar radiation, purporting to cause a cooling effect (MacMartin and others 2018). Whilst theoretically effective, there is potential to generate adverse impacts on climate, weather, ecosystems and air quality with geopolitical implications (Jones and others, 2013; Jones and others, 2018; NASEM, 2021; UNEP 2023; Mengis and others, 2016). From an ocean perspective, changing the heat and light reaching the surface ocean may alter ecosystems by changing hydrodynamics, nutrient supply to the photic zone and photosynthetically available radiation. The effect on carbon cycles is highly uncertain (Cao L, 2018; Zarnetske and others 2021). Consequently, at present SRM is a controversial approach, with no international consensus on research pathways (UNEP 2023), nor successful calls to establish international scientific review and governance processes to ensure an equitable, transparent and rigorous body of knowledge (UNEP, 2023).

3.6 Monitoring, Reporting and Verification

One of the most acute challenges for geoengineering is establishing protocols that deliver sufficient certainty into the efficacy of each method and generate trust in regulators, publics and markets (e.g. Ho and others, 2023; Boyd and others, 2023). The time and spatial scales over which geoengineering interventions may be realised complicates such protocols and the potential lag between mCDR implementation and carbon drawdown presents a challenge for financing.

A joint model-observation approach to MRV for mCDR is recommended (Ocean Visions, 2023), so that predictive models can establish the likelihood of success of a given intervention, whilst being appraised by observations. However models have inherent uncertainties, which cannot be completely resolved by cost-limited observations, suggesting that complete certainty will be elusive (Bach and others, 2023)

From an observational perspective, appropriate sensors and their deployment options are generally well established (e.g. Yin and others 2021; Lichtschlag and others, 2021). However, their capability for measuring key parameters for conducting market- and regulatory-acceptable MRV at and beyond initial deployment locations is yet to be proven. Similarly, the financial and

carbon emission of at-sea monitoring are currently considered to be prohibitive for at-scale implementation and remain a focus of on-going research activities.

Modelling capability is relatively well established, falling into two broad categories.

- High resolution local to regional scale models, that address single or clusters of geoengineering/mCDR operations, assessing dispersal, ecosystem impact, local sequestration efficacy, and advection to deep water (Khangaonkar and others 2024).
- Global ocean or Earth system models that assess the long-term effectiveness of upscaled geoengineering /mCDR approaches, which consider the biotic and abiotic carbon cycles and macro-scale hydrodynamics and operate on decadal to millennial scales. (Oschlies and others, 2023; Bach and others, 2023).

Lack of explicit biodiversity in standard marine models may restrict the ability to accurately simulate biological mCDR. Whilst the marine carbonate system is well understood, care must be taken that the chemical parameterisations still hold for mCDR interventions and are applied in both observational and modelling studies (Dupont and Metian, 2023; Schulz and others, 2023).

MRV for mCDR is a rapidly growing area of research drawing on natural analogues (Subhas and others, 2023) and small-scale field trials (Cyronak and others, 2023). Interactive tools (Chay and others, 2022) also provide high-level frameworks with which to establish confidence levels for various approaches, though the status of current certification practices remains complex, diverse and inconsistent (Arcusa and Sprenkle-Hyppolite, 2022). In contrast protocol development for SRM is in its infancy.

4. Socio-economic considerations

4.1 Societal perceptions

Public attitudes toward mCDR and geoengineering reveal tensions that are better understood as two categories of support, “conditional supporters” and “unconditional opponents” (Jebari and others, 2021). On one hand, there is theoretical support for strategies to reduce carbon dioxide. On the other, opposition emerges when specific projects are proposed, due to unfamiliarity with these technologies, leading to uncertainties about their risks and reversibility (Cox and others, 2022). This tension is further compounded by the divide between “natural” and “engineered” solutions, as public perceptions are heavily influenced by how technologies are framed (Bertram and Merk, 2020).

Conditional supporters favour mCDR technologies, but their acceptance is typically contingent on the perception of co-benefits, controllability, and alignment with conservation efforts (Bertram and Merk, 2020). For example, in countries like the US, Canada, and the UK, where prior knowledge of CDR remains very low, public support can waver depending on the perceived risks and benefits (Cox and others, 2020). This divergence is particularly evident in responses to different approaches: ecosystem-based solutions, such as blue carbon management, tend to receive more public support, while engineered methods like ocean fertilization face significant resistance (Jinnah and others, 2021).

Less controversial approaches which align with traditional conservation methods, like wetland restoration and algal farming, tend to receive conditional support. Acceptability follows from perceived co-benefits,

e.g. food security, and enhanced biodiversity (Were and others 2019). These nature-based solutions, are preferred globally, especially where local livelihoods are intertwined with ecosystems (Bertram and Merk, 2020). However, in regions with limited knowledge of mCDR, even supporters of climate mitigation express concerns about the potential social, economic, or environmental impacts. These concerns grow when interventions appear intrusive or large-scale, particularly with engineered solutions like ocean alkalinity enhancement (Bertram and Merk, 2020). Conversely, in the Global North, concerns are often centred around environmental risk and governance, with public preference leaning toward small, localised projects (Bertram and Merk, 2020; Baum and others, 2024).

These issues are especially acute in the Global South, where large-scale projects intended to offset emissions in the Global North raise ethical issues regarding land-use and sovereignty (Zeng and others, 2021; Hickel and Slamersak, 2022). Concerns about exploitation and inequity in the Global South are further fuelled by fears of wealthier nations reliance on technological fixes rather than reducing their emissions at the source (Jinnah and others, 2021). This amplifies opposition in areas where the risks associated with new technologies are perceived as disproportionately impacting poorer nations (Satterfield and others, 2023). Conversely, unconditional opponents reject mCDR projects outright, regardless of potential benefits or efforts to mitigate negative impacts, like the resistance seen with carbon taxation, (charging a tax on the carbon content of fossil fuels to encourage the reduction of carbon emissions, Campbell and Kay, 2014). This resistance is not confined to one region but is observed globally, reflecting a scepticism towards interventions perceived as disruptive or risky.

Also significantly influencing public acceptance of mCDR is the perceived urgency of climate change (Bellamy 2022). Individuals who view climate change as a critical issue are generally more open to various mCDR approaches. However, this openness does not equate to uncritical acceptance, comfort with specific technologies varies depending on perceived risks and uncertainties. While natural solutions like coastal restoration and direct air capture tend to be more favoured, experimental technologies like ocean fertilization and ocean alkalinity enhancement face greater scepticism, largely due to concerns about environmental impacts and the permanence of carbon storage (Cox and others, 2024; Nawaz and others, 2023). Generally public support for geoengineering techniques such as SRM are lower than those for mCDR, with concerns about controllability, reversibility and a preference for mitigation techniques over temperature management (NASEM 2021).

These disparities reflect how climate vulnerability, inequity, and development priorities shape regional attitudes toward climate intervention technologies.

4.2 Economic potential and sustainability

The economic potential of geoengineering depends on integration into carbon markets, providing financial incentives and fostering new industries. The co-benefits from mCDR could include, enhancing biodiversity and supporting sectors such as tourism and fisheries, contributing to a "blue growth" strategy.

Integrating CDR strategies into carbon markets presents challenges and risks, particularly when there's an over-reliance on market mechanisms. A major concern is greenwashing, -use of low-quality carbon credits to falsely claim emission reductions (Trencher and others, 2024). Another issue is double counting, which undermines carbon market integrity and leads to inflated claims

of mitigation progress. Without prevention of double-claiming, the Voluntary Carbon Market (VCM) may struggle to encourage genuine mitigation efforts. Accurate MRV is essential for maintaining market credibility, as inadequate MRV creates uncertainties about the actual carbon removal achieved. As environmental conditions change, it becomes challenging to assess the true impact of CDR projects, leading to credits that may not accurately reflect real carbon removal. Issues of additionality also arise when projects receive credits for carbon removal that would have happened without market incentives (Betz and others, 2023).

VCM, if challenges and risks are managed, provides a valuable means for financing climate action and sustainable development, especially for projects in vulnerable areas. Smaller-scale projects like the Mikoko Pamoja project in Kenya funded through the VCM offer a promising opportunity for Small Island Developing States (SIDS) (Kairo and others, 2018). This approach can be especially effective when combined with organic certification in areas with existing aquaculture, generating revenue through carbon credits, supporting local livelihoods and community development.

To tackle challenges of accurately measuring carbon sequestration within restoration (Macreadie and others, 2019), regional and international networks like the Blue Forests Project, the Blue Planet fund, and the Blue Carbon Initiative , are developing best practices to effectively utilize international carbon finance (OECD, 2020).

~~From 2020 to 2021 c~~Carbon credit issuances are currently rising exponentially (37M tons CO_2 by July 2025 - CDR.fyi) whilst retirements of carbon credits has plateaued (Sylvera 2024).~~doubled to 353 metric tons of CO_2 equivalent. Retirements of credits also rose by 70% to address growing net-zero commitments from 2,253 companies (Climate Focus, 2021)~~. The economic feasibility of the carbon market hinges on developing MRV capacity and a combination of technical readiness, storage verification, supportive policies, and strategies to mitigate carbon leakage (emissions reductions in one region that lead to increased emissions elsewhere, Schroeder and Stracca, 2023), while maintaining industry competitiveness (IFC, 2023).

The global carbon market is bolstered by policies and mechanisms facilitating emissions reductions and promoting sustainable investment (IFC, 2023). Carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems like the EU Emissions Trading System (ETS), incentivize companies to reduce emissions~~, while regulatory frameworks include Nationally Determined Contributions (NDCs) under the Paris Agreement~~. The idea of integrating removals into the EU ETS is gaining traction, (Meyer-Ohlendorf, 2023). Novel carbon removal methods with strong potential in Europe include marine based BECCS (Fridahl and others, 2023), regulated by the EU CCS Directive.

Supportive policies are applied to encourage market participation. On 10 April 2024, the European Parliament approved the CRCF Regulation, creating the first EU-wide framework for certifying carbon removals, carbon farming, and carbon storage. It sets quality standards, tackles greenwashing, and promotes investment in carbon removal technologies and sustainable farming to support the EU's climate goals.

Recent projections suggest that by 2030, ocean-based industries could significantly outpace global economic growth, potentially doubling their contribution and creating approximately 40 million full-time jobs (OECD, 2020). Various levels of implementation for sustainable ocean-based economy programs, including established Official Development Assistance, involve key mechanisms such as conservation trust funds, blue carbon payments, and private sector concessions. Improving practices that facilitate carbon sequestration by ocean ecosystems offers economic opportunities through emerging blue carbon markets. These activities require a robust framework for successful carbon investing, including precise measurement and verification (World Bank, 2023).

As part of the outcome of the first Global Stocktake, parties to the Paris Agreement, "Commit to accelerate action in this critical decade on the basis of the best available science, reflecting equity and the principle of common but differentiated responsibilities and respective capabilities in the light of different national circumstances and in the context of sustainable development and efforts to eradicate poverty;" UNFCCC decision 1 CMA.5, paragraph 6.

5. Sector relevant governance

Governance of marine geoengineering and CDR spans international, regional and domestic frameworks. Currently, there are no binding international laws specifically governing marine geoengineering or CDR, but various general international agreements and rules of customary international law may apply (see Section 3 Governance). Non-binding instruments, including a 2010 resolution of the parties to the Convention on Biological Diversity (CBD), which applies to geoengineering broadly (Decision X/33 (2010)) and persuasive norms have filled some gaps, (e.g. International Law Commission, Prevention of Transboundary Harm from Hazardous Activities, Oxford Principles on Geoengineering, Reykjavik Protocols).

Marine geoengineering could implicate various provisions of the **United National Convention on Law of the Sea (UNCLOS)**, including those governing marine scientific research (MSR) and protection of the marine environment, particularly as MSR has been interpreted as encompassing marine geoengineering research (Brent and others, 2019; Webb and others, 2023). Under Article 192 and 194(1), UNCLOS includes an obligation to protect the marine environment by taking all measures "necessary to prevent, reduce and control" marine pollution. This has some implications for geoengineering both directly in association with the introduction of substances or energy into the ocean (Ghaleigh and Boyle, 2016; Reynolds, 2018; Webb and others, 2023) and also indirectly through its application to reduce greenhouse gas emissions (GHGs). In a recent Advisory Opinion, the International Tribunal on the Law of the Sea determined that GHG emissions into the atmosphere constitute marine pollution, and thus States have an obligation to reduce emissions under UNCLOS.

The modernising **London Protocol** (LP), an extension to the **London Convention (LC)** (1972), entered into force in ~~2005~~2006, but has not been ratified by all Convention parties and thus the two instruments continue to operate in parallel. While the Convention is generally more permissive of dumping of wastes, the LP takes a more precautionary approach, prohibiting the dumping of all wastes and other matter, except those on the 'reverse list' in Annex 1. In 2006, carbon dioxide was added to Annex 1 of the LP, thereby enabling sub-seabed carbon storage, subject to purity standards and risk assessment procedures, amended in 2009 to allow export of

CO_2 to other countries for storage. The amendment is yet to enter into force but is being provisionally applied. This has implications for some forms of mCDR.

In 2008, the parties to the LC and LP adopted a non-binding resolution on ocean fertilization in 2008, declaring that "ocean fertilization activities other than legitimate scientific research should not be allowed" (Resolution LC-LP.1, 31 Oct. 2010). In 2010, the parties adopted an assessment framework for evaluating proposed scientific research projects, requiring (among other things) ex ante environmental review and ongoing monitoring and management of risks (Resolution LC-LP.2, 14 Oct. 2010). This approach to ocean fertilisation of allowing some scientific research but restricting commercial deployment was codified in a formal amendment to the LP in 2013 (Resolution LP 4(8), 18 Oct. 2013). The amendment is yet to enter into force but is intended to establish a governance framework for certain marine geoengineering and CDR activities listed in a new Annex 4 (Röschel & Neumann 2023). Currently only ocean fertilization is listed.

In 2022 LP parties committed to evaluate four marine geoengineering techniques – ocean alkalinity enhancement, biomass cultivation for carbon removal, marine cloud brightening, and surface albedo enhancement – for potential listing under the 2013 amendment (London Convention, 2022). ~~While that process remains ongoing, in 2023, the parties issued a statement indicating that marine geoengineering activities "other than legitimate scientific research should be deferred" (Statement on Marine Geoengineering (LC 45/LP19)).~~

The 1992 **United Nations Framework Convention on Climate Change** (UNFCCC, 1992) does not refer to geoengineering explicitly. It refers to "removal by sinks", language repeated in the Paris Agreement (UNFCCC, 2015). The UNFCCC defines "sink" as "any process, activity or mechanism which removes a greenhouse gas…from the atmosphere." (UNFCCC, 1992). ~~This is widely understood to encompass CDR techniques, including ocean-based techniques (Reynolds, 2015; Craik & Burns, 2016; Brent and others, 2019).~~ The recognition of the ocean's critical role in climate action under the UNFCCC has evolved significantly over time. The Sharm el-Sheikh Implementation Plan, adopted in 2022, encouraged Parties to integrate ocean-based actions into their national climate goals. In 2023, the outcome of the first global stocktake (Decision 1/CMA.5, para. 180) encouraged further strengthening of ocean-based action and called on Parties to contribute to "accelerating zero- and low-emission technologies, including, …abatement and removal technologies such as carbon capture and utilization and storage, particularly in hard-to-abate sectors …" (UNFCCC decision 1/CMA.5, paragraph 28e). ~~In 2024, the co-facilitators of the ocean and climate change dialogue noted the potential use of CDR in mitigating climate change but observed that mCDR methods vary in several important respects (e.g., technological maturity, mitigation potential, cost, etc.) and recommended that parties consider these differences and potential trade-offs in developing their implementation strategies. .~~

While yet to enter into force, the 2023 Agreement under UNCLOS on the **Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction** (BBNJ Agreement) may have implications for marine geoengineering and CDR activities. For example, Part III outlines a framework for establishing area-based management tools, Part IV outlines

detailed environmental assessment requirements, which could be used to control where and how marine activities are conducted (Webb, 2024).

Also, potentially relevant to marine geoengineering and CDR are international agreements governing shipping, such as the **MARPOL Convention** (prevention of pollution from shipping), global human rights conventions, and regional seas conventions including **OSPAR** and the **Helsinki Convention** (protection of the marine environment of the North-East Atlantic and Baltic respectively)**,** and the **Barcelona Convention and Bucharest Convention** (protection of the Mediterranean Sea and Black Sea respectively against pollution).

5.1 Emerging domestic governance frameworks

Marine geoengineering and CDR activities are often regulated under domestic environmental laws, including laws enacted to implement the LC, LP, and other international agreements, however regulation varies significantly between countries (Silverman-Roati and Webb, 2023). For example, in the United States, the federal Marine Protection, Research, and Sanctuaries Act—i.e., the domestic law implementing the LC—governs many marine activities. Other federal, state, tribal, and local laws may also apply to some projects. The laws generally allow marine geoengineering or CDR, subject to permitting and other requirements (Silverman-Roati and Webb, 2023). At least one other country – Australia – has taken steps to implement the 2013 LP Amendment revising it's Environmental Protection (Sea Dumping) Act 1981, but the revisions will not take effect until the LP Amendment enters into force.

In contrast other countries have implemented regulation that is more restrictive than the 2013 LP amendment. For example, in Germany, the High Seas Dumping Act prohibits any addition of substances to the ocean in connection with marine geoengineering/CDR, with only a limited exception for certain ocean fertilization research (Proelss & Steenkamp, 2023).

Further see section 3 Governance.

6. Sustainability pathways

Although the potential for geoengineering approaches to support climate change mitigation is now well established, the ability of any proposed method to make a meaningful contribution towards global targets is not ~~(IPCC, 2022)~~. Nevertheless, interest and efforts on the research and development of various techniques has accelerated significantly since the publication of the World Ocean Assessment II, delivering a rapidly evolving knowledge base. Generically, motivations and challenges identified are diverse and sometimes opposing, but may be broadly summarise as environmental, social, economic, regulatory and technical, table 5A.10.1.

The co-benefits of macroalgal mCDR approaches are more established, for example in protecting biodiversity, creating gender positive roles and providing food and other resources (Larson and others, 2021; Zhang and others, 2022). Expansion will benefit from a sustainability framework that emphasizes the critical importance of environmental limits and constraints imposed by nature, ecological impacts (Boyd and others, 2023), and incorporates performance indicators, ensures societal acceptance and enables policy-making that considers marine space allocation and reduces regulatory barriers (Cordell and others, 2009; Krause-Jensen and Duarte, 2016; Herrero and others, 2021). Conversely, biological mCDR methods based on the

stimulation of phytoplankton productivity are thought to offer fewer direct co-benefits and have greater potential for disruptive ecosystem feedbacks, via altering the magnitude and geography of marine primary production (Tagliabue and others, 2023).

Concentrating deployments in designated offshore marine areas could provide infrastructural, economic, and environmental benefits through a multi-use approach (Schupp and others, 2019) reducing user conflicts. The benefits of multi-use offshore wind farms with aquaculture include sustainable energy, seafood, and ecosystem services, supporting global sustainable development goals (Marr and others, 2023). Seaweed and mussel farming adapted to local conservation targets can contribute to the goals of marine protected areas (MPAs), all while providing jobs and revenue to local communities (Le Gouvello and others, 2017).

	Motivations	Challenges
Environmental	• Addressing climate change and the Paris Agreement goals • Reducing ocean acidification, GHG levels and emissions • Preserving marine ecosystems, biodiversity and ecosystem services • Sea level change management • Understanding impacts of geoengineering on ecosystems • Nature based solutions	• Life-cycle assessment, including lack of feasibility studies and post implementation impact understanding • Potential for and lack of assessment of significant negative impacts, including technological limitations
Social	• Quality of life for future generations • Sustainable communities • Application of traditional knowledge	• Social licence to operate, awareness and education • Ethical and moral challenges – managing finite resources, who benefits and who pays, trans-national impacts
Economic	• Limiting economic threats of climate change • Lowering cost of geoengineering / CDR and capacity building	• Lack of incentive, financing and funding for capacity building, especially in LDCs and SIDS
Governance	• Development of regulations, legislation and policies • International cooperation and dissemination	• Lack of consistent policy, regulations, monitoring and standards • Interactions between landlocked and coastal states
Technical	• Technology development, innovation and R&D excellence • Technology for exploration and sustainable exploitation of natural resources • Toolbox solutions to aid solutions	• Deep ocean exploration and monitoring

Table 5A.10.1. Motivations and challenges derived from the UN regional workshops

Several small-scale pilot studies assessing potential chemical mCDR approaches are currently in progress (Ocean Visions 2024; GESAMP 2024). Independent scientific oversight of these as well

as the proposed approaches to upscaling will be crucial to maximise learnings in the next few years. Upscaling will require a full life-cycle assessment such that carbon emissions from energy, transport and installation are offset against carbon sequestered. For methods to upscale sufficiently interventions will span local and national jurisdictions to the open ocean, suggesting a requirement for international coordination.

There remains little consensus on testing, development, monitoring or regulation of SRM with the controversial approach not considered as mitigation when the terminology of the Intergovernmental Panel on Climate Change is applied. Nevertheless, funding and research and development is likely to increase in this sector over the coming years.

In summary the key enablers for sustainable progress are:

- Scientifically endorsed, standardised and accessible MRV approaches.
- Responsive international funding mechanisms, coupled with collaboration and transparency for research will be required for geoengineering approaches to demonstrate feasibility (or lack of) and upscale effectively and safely if realistic.
- Global policy that prioritizes addressing knowledge gaps, equity concerns, ~~and~~ risk perceptions and rational governance to strengthen understanding~~-~~ for mCDR and geoengineering research.

7. References

Arcusa, S., and Sprenkle-Hyppolite, S. Snapshot of the Carbon Dioxide Removal certification and standards ecosystem (2021–2022). Climate Policy, vol. *22*(9–10), pp. 1319–1332, 2022. https://doi.org/10.1080/14693062.2022.2094308

Bach, Lennart. T., and others. Technical note: Ocean Alkalinity Enhancement Pelagic Impact Intercomparison Project (OAEPIIP), Biogeosciences, vol. 21, pp. 3665–3676, 2024. https://doi.org/10.5194/bg-21-3665-2024

Bach, Lennart T. and others. Toward a consensus framework to evaluate air–sea CO2 equilibration for marine CO2 removal, Limnology and Oceanography Letters vol. 8, pp. 685–691, 2023. https://doi.org/10.1002/lol2.10330

Baum, C.M., and others. Public perceptions and support of climate intervention technologies across the Global North and Global South. Nature Communications, vol. 15(1), art. 2060, 2024.

Bellamy, R. Mapping public appraisals of carbon dioxide removal. Global Environmental Change, vol. 76, art.102593, 2022.

Berger, Manon and others. Ocean dynamics and biological feedbacks limit the potential of macroalgae carbon dioxide removal. Environmental Research Letters vol. 18 art.0240392023, 2023. https://doi.org/10.1088/1748-9326/acb06e

Bertram, Christine, and Christine Merk. Public perceptions of ocean-based carbon dioxide removal: the nature-engineering divide?. *Frontiers in Climate vol.* 2 art. 594194, 2020. https://doi.org/10.3389/fclim.2020.594194

Boettcher Miranda and Kerryn Brent. The potential of the BBNJ clearing house mechanism to enhance knowledge pluralism in marine carbon dioxide removal assessment, Frontiers in

Climate vol. 6, 2024, https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2024.1497476/full

Boyd Philip. W. and others. Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, vol. 315, pp. 612-617, 2007. https://doi.org/10.1126/science.1131669

Boyd, Philip W., and others. Operational Monitoring of Open-Ocean Carbon Dioxide Removal Deployments. Oceanography vol. 36.1, pp. 2-10, 2023. https://www.jstor.org/stable/27217363

Boyd, Philip W., and others. Potential negative effects of ocean afforestation on offshore ecosystems. Nature Ecology and Evolution vol. 6, pp. 675–683, 2022. https://doi.org/10.1038/s41559-022-01722-1

Boyd Philip W., and others. Limited understanding of basic ocean processes is hindering progress in marine carbon dioxide removal. Environmental Research Letters, vol. 19 (6), art. 061002, 2024. https://doi.org/10.1088/1748-9326/ad502f

Boyle, Alan, and Navraj Singh Ghaleigh. Climate Change and International Law beyond the UNFCCC, in Gray, Kevin R. and others, (eds), The Oxford Handbook of International Climate Change Law, 2016. https://doi.org/10.1093/law/9780199684601.003.0002

Brent Kerryn, and others. Governance of Marine Geoengineering, Centre for International Governance Innovation Special Report, 2019. https://www.cigionline.org/publications/governance-marine-geoengineering/

Buck, Holly J., and others. Why residual emissions matter right now. *Nat. Clim. Chang.* **13**, 351–358 (2023). https://doi.org/10.1038/s41558-022-01592-2

Buesseler KO, and others. Next steps for assessing ocean iron fertilization for marine carbon dioxide removal. Frontiers in Climate vol. 6 art. 1430957, 2024. https://doi.org/10.3389/fclim.2024.1430957

Campbell TH, and Kay AC. Solution aversion: on the relation between ideology and motivated disbelief. Journal of Personality and Social Psychology vol. 107 pp. 809–824, 2014. https://doi.org/10.1037/a0037963

Canadell, J.G., and others: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V., and others (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, 2021 https://doi.org/10.1017/9781009157896.007.

Cao, L. The Effects of Solar Radiation Management on the Carbon Cycle. Current Climate Change Reports vol. 4, pp. 41–50, 2018. https://doi.org/10.1007/s40641-018-0088-z

Chay, F. and others. Verification Confidence Levels for carbon dioxide removal, CarbonPlan, 2022. https://carbonplan.org/research/cdr-verification-explainer

Chopin, Thierry and others. Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass, One Earth, vol. 7, Issue 3, pp. 359 – 364, 2024

Cooley, Sarah R. and others. Sociotechnical considerations about ocean carbon dioxide removal. Annual Review of Marine Science vol. 15.1, pp. 41-66, 2023. https://doi.org/10.1146/annurev-marine-032122-113850

Cordell, Dana and others. The story of phosphorus: Global food security and food for thought, Global Environmental Change, vol. 19, (2), pp.292-305, 2009. https://doi.org/10.1016/j.gloenvcha.2008.10.009.

Cox E, and others. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nature Climate Change vol. 10 pp.744–49, 2020.

Cox, E., and others. But they told us it was safe! Carbon dioxide removal, fracking, and ripple effects in risk perceptions. Risk Analysis, vol. 42(7), pp. 1472-1487, 2022. https://doi.org/10.1111/risa.13717

Cox, E., and others. Public attitudes and emotions toward novel carbon removal methods in alternative sociotechnical scenarios. Environmental Research Letters, vol. 19(8), art. 084026, 2024.

~~Craik Alastair N. and William C. G. Burns. Climate Engineering under the Paris Agreement: A Legal and Policy Primer, Special Report, Centre for International Governance Innovation, 2016. https://ssrn.com/abstract=2872528~~

Cyronak, T., and others. Field experiments in ocean alkalinity enhancement research, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-7-2023

Dafforn K.A. and others. Marine urbanization: an ecological framework for designing multifunctional artificial structures. Frontiers in Ecology and the Environment, vol. 13, pp. 82-90, 2015.

Dinghui Zou. Effects of elevated atmospheric CO2 on growth, photosynthesis and nitrogen metabolism in the economic brown seaweed, Hizikia fusiforme (Sargassaceae, Phaeophyta), Aquaculture, vol. 250, pp. 726-735, 2005. https://doi.org/10.1016/j.aquaculture.2005.05.014.

do Amaral Camara Lima, Mariana, and others. A review of seagrass ecosystem services: providing nature-based solutions for a changing world. Hydrobiologia vol. 850, pp. 2655–2670, 2023. https://doi.org/10.1007/s10750-023-05244-0

Doney, Scott, and others. The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. Annual Review of Environment and Resources, vol. 45 pp. 83-112, 2020. https://doi.org/10.1146/annurev-environ-012320-083019

Duarte, C.M., and others. A seaweed aquaculture imperative to meet global sustainability targets. Nature Sustainability vol. 5, pp. 185–193, 2022. https://doi.org/10.1038/s41893-021-00773-9

Dupont, S. and Metian, M. General considerations for experimental research on ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-4-2023

Eisaman, M. D., and others. Assessing the technical aspects of ocean-alkalinity-enhancement approaches, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-3-2023

Erlania, and others. Patterns and drivers of macroalgal 'blue carbon' transport and deposition in near-shore coastal environments, Science of The Total Environment, vol. 890, art. 164430, 2023. https://doi.org/10.1016/j.scitotenv.2023.164430.

Feng, E., Y., and others. Model-based assessment of the CO2 sequestration potential of coastal ocean alkalinization, Earth's Future, vol. 5, pp. 1252–1266, 2017. https://doi.org/10.1002/2017EF000659

Fennel, K., and others. Modelling considerations for research on ocean alkalinity enhancement (OAE), in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-9-2023

Fennell P.S., and others. Decarbonizing cement production. Joule, vol. 5, pp. 1305-1311, 2021.

Ferderer, A., and others. Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community, Biogeosciences, vol.19, pp. 5375–5399, 2022. https://doi.org/10.5194/bg-19-5375-2022

Firth Louise B., and others. Coastal greening of grey infrastructure: an update on the state-of-the-art. Proceedings of the Institution of Civil Engineers, vol. 177(2) pp. 35-67, 2024. https://doi.org/10.1680/jmaen.2023.003

Fridahl, M., and others. Novel carbon dioxide removals techniques must be integrated into the European Union's climate policies. Communication Earth and Environment vol. 4, art. 459, 2023. https://doi.org/10.1038/s43247-023-01121-9

Friedlingstein, P. and others. Global Carbon Budget 2023, Earth Syst. Sci. Data, 15, 5301–5369, 2023. https://doi.org/10.5194/essd-15-5301-2023

Gagern, Antonius, and others. Ocean-Based Carbon Dioxide Removal: A New Frontier in the Blue Economy. Marine Technology Society Journal, vol. 1, pp. 40-48, 2022. https://doi.org/10.4031/MTSJ.56.1.15

GESAMP. High level review of a wide range of proposed marine geoengineering techniques. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/ UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p, 2019. High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques | GESAMP

GESAMP. Ocean Interventions for Climate Change Mitigation. WG 41:Ocean Interventions for Climate Change Mitigation | GESAMP, 2024.

Guang Gao, and others. The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. Environmental Research. Letters. vol. 17 art. 014018, 2022. https://doi.org/10.1088/1748-9326/ac3fd9

Herrero, Mario and others. Articulating the effect of food systems innovation on the Sustainable Development Goals, The Lancet Planetary Health, vol. 5, (1), pp. e50-e62, 2021. https://doi.org/10.1016/S2542-5196(20)30277-1.

Hickel, J. and Slamersak, A. Existing climate mitigation scenarios perpetuate colonial inequalities. The Lancet Planetary Health, vol. 6(7), pp. e628-e631, 2022.

Ho, D. T., and others. Monitoring, reporting, and verification for ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-12-2023

Hyndes, G.A., and others. The role of inputs of marine wrack and carrion in sandy-beach ecosystems: a global review. Biological Reviews, vol. 97, pp. 2127-2161, 2022. https://doi.org/10.1111/brv.12886

IFC report: Deep Blue: Opportunities for Blue Carbon Finance in Coastal Ecosystems, International Finance Corporation, 2023. https://www.ifc.org/en/insights-reports/2023/blue-carbon-finance-in-coastal-ecosystems

IPCC. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. 2018. https://doi.org/10.1017/9781009157940

IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, P. R. , and others (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, ~~2022~~ 2023 https://doi.org/10.1017/9781009157926

IPCC. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B. and others (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp, 2005.

Jebari J, and others. From moral hazard to risk-response feedback. Climate Risk Management vol. 33 art.100324, 2021.

Jiang, Hai-Bo, and others. Complexities of regulating climate by promoting marine primary production with ocean iron fertilization, Earth-Science Reviews, vol. 249, art. 104675, 2024. https://doi.org/10.1016/j.earscirev.2024.104675 .

Jinnah, S., and others. Splitting climate engineering governance: how problem structure shapes institutional design. Global Policy, vol. 12, pp.8-19, 2021. https://doi.org/10.1111/1758-5899.12900

Jones, A. C., and others. Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering, Earth's Future, vol. 6, pp 230–251, 2018. https://doi.org/10.1002/2017EF000720

Jones, A., and others. The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, vol. 118, pp.9743–9752, 2013.

Jones, D. C., and others. Spatial and seasonal variability of the air-sea equilibration timescale of carbon dioxide, Global Biogeochemical Cycles, vol. 28, pp.1163–1178, 2014. doi:10.1002/2014GB004813

Kairo, James G. and others. Mikoko Pamoja, A Demonstrably Effective Community-Based Blue Carbon Project in Kenya, in Windham-Myers, Lisamarie and others (eds) A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice and Policy, CRC Press, Boca Raton, ISBN9780429435362, 2018. https://doi.org/10.1201/9780429435362

Khangaonkar, Carter and others. Mixing and dilution controls on marine CO_2 removal using alkalinity enhancement. Environmental Research Letters, vol. 19, (10), art. 104039, 2024. https://doi.org/10.1088/1748-9326/ad7521

Kinley, Robert D, and others. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, Journal of Cleaner Production, vol. 259, art. 120836, 2020 https://doi.org/10.1016/j.jclepro.2020.120836.

Köhler, P., and others. Geoengineering impact of open ocean dissolution of olivine on atmospheric CO2, surface ocean pH and marine biology, Environmental Research Letters, vol. 8, art. 014009, 2013. https://doi.org/10.1088/1748-9326/8/1/014009

Konar, Manaswita and Helen Ding. Ocean Panel report: A Sustainable Ocean Economy for 2050: Approximating Its Benefits and Costs, 2020. https://oceanpanel.org/wp-content/uploads/2022/05/Ocean-Panel_Economic-Analysis_FINAL.pdf

Koweek DA. Expected Limits on the Potential for Carbon Dioxide Removal From Artificial Upwelling. Frontiers in Marine. Science. vol. 9 art. 841894, 2022. https://doi.org/10.3389/fmars.2022.841894

Krause G, and others. Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World. Frontiers in Sustainable Food Systems, vol 6 art.875509, 2022. https://doi.org/10.3389/fsufs.2022.875509

Krause-Jensen, D and Duarte, C. Substantial role of macroalgae in marine carbon sequestration. Nature Geosciences vol. 9, pp. 737–742, 2016. https://doi.org/10.1038/ngeo2790

Kwiatkowski, Lester, and others. Contrasting carbon dioxide removal potential and nutrient feedbacks of simulated ocean alkalinity enhancement and macroalgae afforestation. Environmental Research Letters, Vol. 18, art. 124036, 2023. https://doi.org/10.1088/1748-9326/ad08f9

Lanari, Marianna, and others. From sink to source: Dynamic of greenhouse gases emissions from beach wrack accumulations in a temperate coastal bay, Science of The Total Environment, vol. 925, art. 171783, 2024. https://doi.org/10.1016/j.scitotenv.2024.171783.

Larson, Silva, and others. Women's well-being and household benefits from seaweed farming in Indonesia, Aquaculture, vol. 530, art. 735711, 2021. https://doi.org/10.1016/j.aquaculture.2020.735711.

Le Gouvello R., and others. Aquaculture and marine protected areas: Potential opportunities and synergies. Aquatic Conservation: Marine and Freshwater Ecosystems, vol 27(S1), pp 138–150, 2017. https://doi.org/10.1002/aqc.2821

Lehne J, and Preston F. Making Concrete Change: Innovation in Low-carbon Cement and Concrete. Chatham House: The Royal Institute of International Affairs. Energy, Environment and Resources Department. 138 pp., 2018. Making Concrete Change: Innovation in Low-carbon Cement and Concrete | Chatham House – International Affairs Think Tank

Li, Z., and others. Recent acceleration in global ocean heat accumulation by mode and intermediate waters. Nature Communication vol 14, art. 6888, 2023. https://doi.org/10.1038/s41467-023-42468-z

Lichtschlag, Anna and others. Suitability analysis and revised strategies for marine environmental carbon capture and storage (CCS) monitoring, International Journal of Greenhouse Gas Control, vol. 112, art. 103510, 2021. https://doi.org/10.1016/j.ijggc.2021.103510.

London Convention. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972. https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx

London Convention. Marine geoengineering techniques - potential impacts, Marine geoengineering techniques - potential impacts, 2022.

Lovelock C.E. and Duarte C.M. Dimensions of Blue Carbon and emerging perspectives. Biology Letters, vol. 15, art. 20180781, 2019. http://dx.doi.org/10.1098/rsbl.2018.0781

Maar, Marie., and others. Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. Communications Earth and Environment vol. 4, art. 447, 2023. https://doi.org/10.1038/s43247-023-01116-6

MacMartin, Douglas G., and others. Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. Philosophical Transactions of the Royal Society A. vol. 376, art. 20160454, 2018. http://doi.org/10.1098/rsta.2016.0454

Macreadie, P.I., and others. The future of Blue Carbon science. Nature Communications vol. 10, art. 3998, 2019. https://doi.org/10.1038/s41467-019-11693-w

Markusson, N., and others, 'In case of emergency press here': framing geoengineering as a response to dangerous climate change†. Wiley Interdisciplinary Reviews 5: Climate Change 281-290. 2013. https://doi.org/10.1002/wcc.263

Martin, P., and others. Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX, Global Biogeochemical Cycles, vol. 27, pp. 871–881, 2013. https://doi.org/10.1002/gbc.20077.

Mengis, N., and others. Assessing climate impacts and risks of ocean albedo modification in the Arctic, Journal of Geophysical Research, Oceans, vol. 121, pp. 3044–3057, 2016. https://doi.org/10.1002/2015JC011433

Meyer-Ohlendorf, Nils. Making Carbon Removals a Real Climate Solution. How to integrate carbon removals into EU Climate Policies. Berlin: Ecologic Institute, 2023. https://www.ecologic.eu/19290

NASEM: National Academies of Sciences, Engineering, and Medicine NASEM. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. 2022. https://doi.org/10.17226/26278.

NASEM: National Academies of Sciences, Engineering, and Medicine. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. 2021. https://doi.org/10.17226/25762.

Nawaz, Sara and others. Public evaluations of four approaches to ocean-based carbon dioxide removal, Climate Policy, vol. 23:3, pp. 379-394, 2023. https://doi.org/10.1080/14693062.2023.2179589

NRC, National Research Council. Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation. Washington, DC: The National Academies Press. 2006. https://doi.org/10.17226/11558

Ocean Visions. A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030, 2023 https://oceanvisions.org/wp-content/uploads/2023/10/A-Comprehensive-Program-to-Prove-or-Disprove-Marine-Carbon-Dioxide-Removal-Technologies-by-2030_FINAL.pdf

Ocean Visions. mCDR Field Trial Database, Ocean Visions | mCDR Field Trial Database, 2024

OECD, Sustainable Ocean for All: Harnessing the Benefits of Sustainable Ocean Economies for Developing Countries, The Development Dimension, OECD Publishing, Paris, 2020. https://doi.org/10.1787/bede6513-en.

Oschlies, A., and others. Climate targets, carbon dioxide removal, and the potential role of ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-1-2023

Palmiéri, J., and Yool, A. Global-scale evaluation of coastal ocean alkalinity enhancement in a fully coupled Earth system model. Earth's Future, vol. 12, art. e2023EF004018, 2024. https://doi.org/10.1029/2023EF004018

Paris Agreement's trading mechanism (A6.4-SB009-A02), Recommendation: Activities involving removals under the Article 6.4 mechanism, 2023. https://unfccc.int/sites/default/files/resource/a64-sb009-a02.pdf).

Pathak, M. and others.: Technical Summary. In: Shukla, P.R. and others, (eds.) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,. Cambridge University Press, Cambridge, UK and New York, NY, USA ,2022. https://doi.org/10.1017/9781009157926.002

Proelss, Alexander and Robert Steenkamp, Germany in Ocean Carbon Dioxide Removal for Climate Mitigation, Edward Elgar Publishing, Cheltenham, UK and Northhampton, MA, USA, 2023.

Renforth, Phil. and Henderson, Gideon. Assessing ocean alkalinity for carbon sequestration, Reviews of Geophysics, vol. 55, pp. 636–674, 2017. https://doi.org/10.1002/2016RG000533

Reynolds, Jesse., and Gernot Wagner. Governance of highly decentralized nonstate actors: the case of solar geoengineering. Belfer Center for Science and International Affairs Discussion Paper, Harvard Kennedy School, Harvard, 2018. Governance of Highly Decentralized Nonstate Actors: the Case of Solar Geoengineering | The Belfer Center for Science and International Affairs

~~Reynolds, Jesse. International Law, in Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide removal, 57 (Gerrard Michael B. & Tracy Hester eds), Cambridge University Press, 2018~~

Röschel, Lina and Babara Neumann. Ocean-based negative emissions technologies: a governance framework review. Frontiers in Marine Science, vol. 10, 2023, https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2023.995130/full

Ross, Finnley W.R. and others. Potential role of seaweeds in climate change mitigation, Science of The Total Environment, vol. 885, art. 163699, 2023. https://doi.org/10.1016/j.scitotenv.2023.163699.

Satterfield, T., and others. Exploring public acceptability of direct air carbon capture with storage: climate urgency, moral hazards and perceptions of the 'whole versus the parts'. Climatic Change, vol. 176(2), p.14, 2023.

Schipper, E.L.F and others. Climate Resilient Development Pathways. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner, Hans Otto, and others (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2655–2807, 2022. doi:10.1017/9781009325844.027.

Schroeder C and Stracca, L. Pollution Havens? Carbon taxes, globalization, and the geography of emissions, ECB Working Paper No. 2862, 2023. http://dx.doi.org/10.2139/ssrn.4623033

Schulz, K. G., and others. Seawater carbonate chemistry considerations for ocean alkalinity enhancement research: theory, measurements, and calculations, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-2-2023

Schupp MF, and others. Toward a Common Understanding of Ocean Multi-Use. Frontiers in Marine Science vol. 6 art. 165, 2019. https://doi.org/10.3389/fmars.2019.00165

Silverman-Roati, K and Webb, RM. Conclusion, in Webb, Romany M., and others (eds), Ocean Carbon Dioxide Removal for Climate Mitigation: The Legal Framework, Edward Elgar Publishing, 2023. http://dx.doi.org/10.4337/9781802208856

Smith, S. M., and others (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition, 2024. https://www.stateofcdr.org

Stigebrandt, A., and others. An experiment with forced oxygenation of the deepwater of the anoxic By Fjord, western Sweden. Ambio, vol. 44(1) pp.42-54, 2015. https://doi.org/10.1007/s13280-014-0524-9.

Subhas AV, and others. Microbial ecosystem responses to alkalinity enhancement in the North Atlantic Subtropical Gyre. Frontiers in Climate vol. 4, art. 784997, 2022. https://doi.org/10.3389/fclim.2022.784997

Subhas, A. V., and others. Natural analogues to ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Oschlies, A. and others (eds), Copernicus Publications, State of the Planet, vol. 2-oae2023, 3, 2023. https://doi.org/10.5194/sp-2-oae2023-8-2023

Sylvera. The State of Carbon Credits 2024. [Sylvera] State of Carbon Credits Report 2024.pdf

Tagliabue, A., and others. Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit. Global Change Biology, vol. 29, pp. 5250–5260., 2023. https://doi.org/10.1111/gcb.16854

UNEP: United Nations Environment Programme, & Yale Center for Ecosystems and Architecture Building Materials and the Climate: Constructing a New Future., 2023. https://wedocs.unep.org/handle/20.500.11822/43293

UNFCCC. United Nations Framework Convention on Climate Change, 1992. https://unfccc.int/resource/docs/convkp/conveng.pdf

UNFCCC: Paris Agreement, 2015. https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

UNFCCC. Technical dialogue of the first global stocktake FCCC/SB/2023/9. Technical dialogue of the first global stocktake. Synthesis report by the co-facilitators on the technical dialogue | UNFCCC

UNFCCC Ocean dialogue. Informal summary report of the ocean and climate change dialogue 2023 | UNFCCCUNFCCC. UNFCCC, Decision 1/CP.25: Chile Madrid Time for Action (2020), FCCC/CP/2019/13/Add.1, 2020.

UNFCCC. UNFCCC, ~~Draft~~ Decision ~~-/CP.27~~1/CMA5: Outcome of the First Global Stocktake (2023), Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its fifth session, held in the United Arab Emirates from 30 November to 13 December 2023. Addendum. Part two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement at its fifth session | UNFCCC~~FCCC/PA/CMA/2023/L.17, 2023~~

UNEP: United Nations Environment Programme. Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). Nairobi. 2023. https://doi.org/10.59117/20.500.11822/43922

Vierros, Marjo K., Promotion and Strengthening of Sustainable Ocean-based Economies 2021. https://sdgs.un.org/sites/default/files/2022-01/2014248-DESA-Oceans_Sustainable_final-WEB.pdf

Webb, Romany M. and others. International Laws Governing Ocean CDR in Webb, Romany M., and others (eds), Ocean Carbon Dioxide Removal for Climate Mitigation: The Legal Framework, Edward Elgar Publishing, **ISBN:** 978 1 80220 884 9 2023.

Webb, Romany M. International Governance of Ocean-Based Carbon Dioxide Removal: Recent Developments and Future Directions, Sabin Center for Climate Change Law, Columbia Law School, 2024 https://scholarship.law.columbia.edu/sabin_climate_change/216

Were, D., and others. Carbon sequestration by wetlands: a critical review of enhancement measures for climate change mitigation. Earth Systems and Environment, vol. 3, pp.327-340, 2019.

World Bank, Unlocking Blue Carbon Development: Investment Readiness Framework for Governments. Washington, DC: World Bank, 2023. http://hdl.handle.net/10986/40334

Wu, J., and others. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study, Earth Systems Dynamics, vol. 14, pp.185–221, 2023. https://doi.org/10.5194/esd-14-185-2023

Xi Xiao, and others. Seaweed farms provide refugia from ocean acidification, Science of The Total Environment, vol. 776, art. 145192, 2021 https://doi.org/10.1016/j.scitotenv.2021.145192.

Yau, Y. Y. Y., and others. Methane emissions in seagrass meadows as a small offset to carbon sequestration. Journal of Geophysical Research: Biogeosciences, vol. 128, art. e2022JG007295, 2023. https://doi.org/10.1029/2022JG007295

Yin, Tianya, and others. A Novel Lab-on-Chip Spectrophotometric pH Sensor for Autonomous In Situ Seawater Measurements to 6000 m Depth on Stationary and Moving Observing Platforms. Environmental Science & Technology, vol. 55 (21), pp. 14968-14978, 2021**.** https://doi.org/10.1021/acs.est.1c03517

Yool, A., and others. Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide, Journal of Geophysical. Research, vol. 114, art. C08009, 2009. https://doi.org/10.1029/2008JC004792

Zarnetske, Phoebe L., and others. Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. Proceedings of the National Academy of Sciences vol. 118, art. e1921854118, 2021. https://doi.org/10.1073/pnas.1921854118

Zeng, Y., and others. Global potential and limits of mangrove blue carbon for climate change mitigation. Current Biology, vol. 31(8), pp.1737-1743, 2021. https://doi.org/10.1016/j.cub.2021.01.070

Zhang, Xueqian and others. Blue growth and bioextraction potentials of Danish Saccharina latissima aquaculture — A model of eco-industrial production systems mitigating marine eutrophication and climate change, Algal Research, vol. 64, art. 102686, 2022. https://doi.org/10.1016/j.algal.2022.102686.

Zhou, S., and P. C. Flynn.. Geoengineering downwelling ocean currents: A cost assessment. Climatic Change vol. 71(1-2) pp. 203-220, 2005. https://doi.org/10.1007/s10584-005-5933-0.

Section 5B: One Health (introduction)

The concept of One Health involves adopting ~~undertaking~~ an integrated~~, unified~~ approach to balancing the health of the physical and chemical components of the marine environment, the inhabiting organisms and people ~~interacting with both~~. The World Health Organisation recognizes the implicit approach as ~~being~~ relevant to~~for~~ food and water safety, nutrition, the control of zoonoses, pollution management, and combatting antimicrobial resistance. This concept is based on several fundamental principles including equity, inclusivity, parity, socio-ecological equilibrium, stewardship, and trans-disciplinarity.

The concept of One Health ~~is relevant to~~ extends beyond ~~both~~ Section 5B (One Health) into Section 4 (physical and chemical environment, biodiversity and habitats) and Section 5A ~~(Socio-ecological systems), which is split into Section 5A~~ (Sustainable and Inclusive Ocean Economy)~~Ocean inclusive economy and 5B One Health~~. Under Section 5B One Health, though, more direct social components and overarching factors with consequences across socio-ecological systems are included.

The ocean provides important services to society beyond profits obtained through ocean economy sectors (Section 5A). Marine ecosystems play a significant role in the capture, storage and sequestration of carbon and, therefore, on potential climate change mitigation (Section 5B.C1). Hence, the role of marine ecosystems in the carbon cycle is intrinsically related to ecosystem health (Section 4), the modulation that climate change exerts in maritime economic sectors (Section 5B) and on the global society, as detailed in the remaining chapters of the Section One Health. The ocean also provides benefits for human health (Section 5B.C2), such as seafood ~~consumption~~, marine-derived pharmaceuticals or opportunities for exercise, and supports spiritual, cultural and recreational services, benefits on mental health or enhancement in social cohesion that contribute to a better wellbeing (Section 5B.C3). However, human activities are putting these benefits at risk through a diverse array of human pressures, such as climate change, coastal development and~~or~~ pollution.

The ocean is also a source of important natural hazards (Section 5B.C4), operating at different temporal scales and having different types of impacts. Minimizing these impacts requires different mitigation, adaptation and management measures, and the need for higher level overarching governance, institutional and social transformations.

The benefits obtained from the ocean, their deterioration by human activities, natural hazards and even the violation of human rights are unequally distributed across the global society (Section 5B.C5). Inequality is facilitated by inadequate governance and decision-making processes that remain insufficiently participatory and inclusive, and with social equity, justice and human rights inadequately integrated. This unequal distribution of benefits and disbenefits is particularly conspicuous in the case of gender (Section 5B.C6), and across sectors such as ocean science, fisheries and aquaculture, and for I~~i~~ndigenous Peoples and traditional local communities (Section 5B.C8).

The pandemic COVID19 has affected our relationship with the ocean, with some changes possibly becoming permanent. Further, some consequences remain uncertain and underscored.

The pandemic provoked high risks of infection and prolonged confinement periods in vessel crews. It also caused disruption in ocean research and observation. On the other side, human pressures were temporarily reduced, benefiting marine ecosystems.

Finally, Indigenous Peoples, Traditional ~~owner~~ and Local community Knowledges (ITLK) is increasingly acknowledged as an alternative collective source of information complementary to non-I~~i~~ndigenous or classical scientific information. ITLK must be better integrated in governance processes and in future World Ocean Assessments.

Section 5B

Chapter 1: The role of ecosystems in the carbon cycle

- Alex Poulton, UK (Lead Author Section 1)
- Natalie Hicks, UK (Lead Author Section 2)
- Patrick Martin, Singapore (Lead Author Section 3)
- Olivia Rendon, UK (Honduran/British national) (Lead Author Section 4)

- Steve Widdicombe, UK (Coordinating author)

- Lisa Levin, USA
- Punyasloke Bhadury, India
- Sevrine Sailley, UK (Frenchance national)
- Chao Liu, China
- Hiroshi Kitazato, Japan
- Udhi Eko Hernawan, Indonesia
- Catia Fernandes Barbosa, Brazil
- Ahmed Hussein Mohamed, Kenya

Key Findings

- Covering approximately~~Accounting for around~~ 71% of the Earth's surface, the open ocean contributes to around half of annual primary production, supporting around 80% of global animal biomass.
- The open ocean currently sequesters a similar amount of atmospheric CO_2 as the whole terrestrial biosphere, and the ocean has the capacity to store 40 times more CO_2 than the atmosphere.
- In coastal systems, Coastal Blue Carbon Ecosystems (CBCE's), such as seagrass, mangroves and saltmarshes, are estimated to capture and store more carbon per unit area than terrestrial forests, meaning that, despite covering an area of less than 7

million km^2, CBCE's are considered globally important areas of carbon capture and storage, as well as being of high economic value.

- Unvegetated, seafloor sediments on the continental shelf make up around 9% of the total marine area but hold the biggest carbon store in shelf systems, and over 80% of organic carbon is buried in these subtidal sediments.
- The protection and restoration of CBCEs and shelf sediment seabed habitats~~,~~ will have significant benefits for both climate mitigation and biodiversity conservation.
- Continental shelf seas are a significant source of carbon (0.95 ± 0.25 Pg~~Gt~~ C y^{-1}) to the open ocean, although this transport is largely driven by physical and geochemical processes, rather than biological. However, horizontal carbon transport *via* the migration of animals is probably widespread, but largely unquantified.
- The value of carbon cycling ecosystems has been increasingly recognised and many finance initiatives exist. However, blue carbon activities receive just 3% of total climate investment globally. This lack of financial support has been a barrier to bringing blue carbon conservation and restoration activities to scale.
- The recognition of the value of CBCE~~blue carbon ecosystem~~s in climate action has increased in recent years. However, at the time of publication, just over half (56%) of UNFCCC Parties have integrated coastal and marine nature-based solutions within new or updated NDCs as part of mitigation or adaptation measures.

Introduction

While the vast majority of the carbon in the ocean is inorganic, and many ~~some of~~ of the processes that fix, transform and transport this carbon within and through the ocean are driven by physical or chemical processes (S4.C3), there are also important ~~the majority are~~ biological processes that contribute to significant carbon cycling, and these are directly linked to the presence, function and health of marine ecosystems. Given that these same ecosystems also provide vital~~direct~~ services to humans, including ~~particularly with respect to~~ food provision (S5A.C1), understanding and protecting the role of ecosystems in driving

the carbon cycle is intrinsically linked to the health (S5B.C2) and well-being of billions of people (S5B.C3). In this chapter, we will explore the role played by biological processes of key ecosystems in cycling carbon through the two main ocean systems; the open ocean (section 1), and the near shore environment, comprising of shelf, coastal, fjordsic and estuarine systems (section 2). In section 3 we will describe the ~~dependencies and~~ transport pathways of carbon between the near shore and the open ocean. Finally, we will consider the ~~likel~~potentialy~~~~ values of these ecosystems, and the carbon cycling processes they provide, in the context of economic and non-economic valuation (section 4).

1) The Open Ocean

Carbon cycling in marine ecosystems

Accounting for around~~~~ 71% of the Earth's surface, the open ocean contributes to around half of Earth's annual primary production (~49-56 Pg C yr^{-1}; Buitenhuis et al., 2013a; Kulk et al., 2020), despite much lower levels of photosynthetic biomass in the ocean (~0.5-2.4 Pg C) than on land (~450 Pg C) (Buitenhuis et al., 2013b; Bar-On et al., 2018). Primary production is dominated by microbial phytoplankton in the open ocean (Buitenhuis et al., 201b; Bar-On et al., 2018), with lifespans ranging from a few days to weeks, leading to an inverted biomass pyramid from microbial primary producers at the base, up to higher trophic levels at the top, and a rapid turnover of photosynthetic biomass in the ocean (Fig 1.). In the wider context of the global carbon cycle, the marine biosphere represents a relatively small component; while marine biological (organic) carbon pools total ~5 Pg C, the ocean contains ~38,000 Pg C of dissolved inorganic carbon and the atmosphere ~800 Pg C (Fig. 1; Friedlingstein et al., 2023). However, this relatively small amount of biomass, with significant fluxes between biological pools (Fig. 1), supports the life and productivity of the global ocean, the largest ecosystem (biome) on the planet.

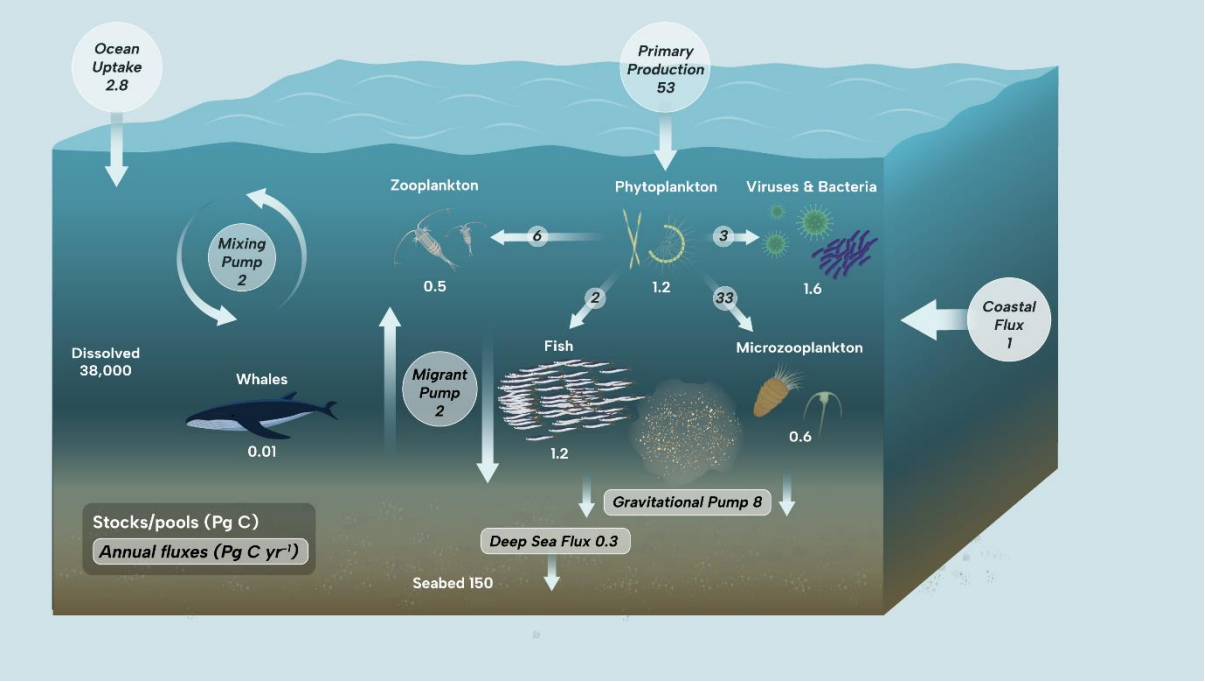


Fig. 1 – "Open Ocean ecosystem roles in the carbon cycle". Sources: Bar-On et al. (2018), Boyd et al. (2019), Friedlingstein et al. (2023), Greenspoon et al. (2023), and Siegel et al. (2022).

Significant rates of primary production and rapid turnover allow the ocean to support ~80% of global animal biomass and around half of global protist biomass, which includes significant biomass from pelagic and mesopelagic fish (0.7-1.7 Pg C), large zooplankton (e.g., copepods, krill) (0.3-0.6 Pg C) and small microzooplankton including protists like ciliates and dinoflagellates (0.5-0.7 Pg C) (Buitenhuis et al., 2013b; Bar-On et al., 2018; Bar-On and Milo, 2019; Bianchi et al., 2021; Drago et al., 2022). While marine mammal biomass is roughly twice the size of wild terrestrial mammal biomass, it represents a low level of biomass overall (~0.007 Pg C) with baleen whales making up the majority (Greenspoon et al., 2023). Globally, marine mammal biomass is an order of magnitude smaller than the human population (0.065 Pg C) or domesticated mammal biomass (0.1 Pg C) (Bar-On et al., 2018; Greenspoon et al., 2023).

Carbon fixed into marine biomass through photosynthesis in the open ocean is rapidly consumed by pelagic organisms, with ~62% lost to ingestion and respiration by

microzooplankton, ~12% directly to larger zooplankton, and ~2-10% to viral lysis and infection (Calbert et al., 2001; Schmoker et al., 2013; Gao et al., 2022). Smaller proportions of primary production are lost directly, or indirectly *via* grazing on herbivorous zooplankton, to ~~to herbivorous~~ fish (<3%; Bianchi et al., 2021) and marine mammals ~~(Bianchi et al., 2021)~~. The remaining proportion of primary production (~18% or ~11 Pg C yr^{-1}) is lost from the upper ocean through the sinking of particulate material (i.e. cells, detritus), the downward fluxes of dissolved organic material, or through the active migration of pelagic organisms from surface waters to depth (Boyd et al., 2019; Siegel et al., 2023).

Biological Carbon Pump(s)

While the open ocean lacks the immense plant biomass of land ecosystems, t~~T~~he ~~open~~ ocean currently sequesters a similar amount of anthropogenic atmospheric CO_2 (~2.8 Pg C yr^{-1}) as the whole terrestrial biosphere (Friedlingstein et al., 2023), mainly through its physical circulation and geochemical characteristics (Sabine, 2021; S4.C3), although open ocean ecosystems also play a crucial role (Boyd et al., 2019; Siegel et al., 2023; Frenger et al., 2024). Marine photosynthesis draws CO_2 from the atmosphere into surface biomass, a portion of which enters the interior ocean through one of several transport pathways (Fig. 1), driving a gradient in CO_2 from the upper ocean into the deep-sea through the collective action of ocean ecosystems, termed the biological carbon pump (Boyd et al., 2019; Siegel et al., 2023). While most of this material is typically broken down and respired by bacteria and zooplankton in the upper 1 km of the ocean, a small proportion of surface production ~~(~~(≤2%) does reach the seafloor. So, although the biological carbon pump does not actually contribute much to the net ocean C sink, largely because its vertical fluxes (export) are balanced by the release of absorbed CO_2 (outgassing) from upwelled deep waters, it does maintain the long-term store of carbon in deep waters and sediments that would otherwise reside in the atmosphere (Frenger et al. 2024).

The timescale of ocean mixing is proportional to water depth. Some deep waters can be isolated from the atmosphere for up to about 1000 years, while the upper ocean (<0.5 km)

may exchange with the atmosphere seasonally, such as during winter mixing. The deeper a sinking particle reaches into the ocean the longer the carbon associated with that particle will be sequestered from the atmosphere. As a global average, particles sinking below 500 m are sequestered for 200 years or longer (Boyd et al., 2019), but this varies geographically depending on regional ocean circulation and mixing (Baker et al., 2024).

The breakdown and respiration of organic matter supplied to the ocean's interior through the biological carbon pump contributes to the ocean's capacity to store 40 times more CO_2 than the atmosphere (Friedlingstein et al., 2023; Frenger et al., 2024) and fuels deep sea bacteria and fauna at the sea floor. An even smaller proportion (<1%) of surface production ends up sequestered into deep sea sediments through the physical activity of organisms living at the sea floor. However, the vast area of the deep sea means that this small fraction of surface production makes up a large carbon stock that contributes significantly to C cycling and sequestration on millennial scales times (150-2322 Pg C, depending on whether the upper 5 cm or 1 m is considered; Atwood et al., 2020) which is similar in size to that stored in terrestrial soils (1700 Pg C) or permafrost (1400 Pg C) (Friedlingstein et al., 2023).

Sinking particulate organic carbon falls as cells and detrital material, often aggregated into particles termed 'marine snow' or is packaged by large zooplankton as faecal pellets, and contributes to the 'gravitational pump' which is responsible for ~80% of the ~11 Pg C annually exported by the biological carbon pump (Boyd et al., 2019; Siegel et al., 2023). Often these sinking particles still hold nutrients usable by heterotrophs, and it is now recognised that zooplankton often fragment these sinking particles into smaller particles that slow their descent, keeping them in the upper ocean longer (Mayor et al., 2014). This strategy has been termed 'microbial gardening' where zooplankton promote bacterial and protist growth on fragmented particles before consuming the enriched microbial biomass (Mayor et al., 2014) which are more nutritious than the original sinking material (Cavan et al., 2020). This highlights the intricate ecological interactions in regulating carbon flow into the deep ocean.

Dissolved organic carbon, varying in form from simple metabolites such as polysaccharides and proteins to complex reworked molecules such as ~~fluvic~~ fulvic and humic acids, is an important component of the ocean's dissolved carbon pool (Friedlingstein et al., 2023) with microbial utilization of this pool as a carbon and nutrient source, responsible for breaking down the labile fractions of this material (Hansell et al., 2013; Jiao et al., 2014; Legendre et al., 2015). This 'microbial carbon pump' recycles carbon and nutrients from the dissolved pool~~,~~ but also changes the nature of the pool to a more refractory one which contributes to long-term carbon sequestration, lasting from hundreds to thousands of years (Hansell et al., 2013; Jiao et al., 2024; Legendre et al., 2015). Viral infection also plays a role in the microbial carbon pump, with viral lysis of infected plankton in the upper ocean providing a 'viral shunt' retaining carbon near the surface, where it is ~~to be~~ broken down by microbes (Suttle, 2007; Kranzler et al., 2019). Recent research shows that some viral infections do not cause immediate cell lysis. Instead, metabolically inactive infected cells may sink, creating a 'viral shuttle' that transports organic material to the deep ocean (Kranzler et al., 2021; Poulton, 2021).

The remaining carbon exported through the biological carbon pump is pumped to depth through two distinct mechanisms, one related to the physical mixing of the water column ('mixing pump') and the other related to vertical migration by zooplankton and nekton ('migrant pump') (Boyd et al., 2019; Siegel et al., 2023). The 'mixing pump' involves various oceanographic processes that transport surface water into the ocean's interior, and any dissolved and particulate carbon contained in this water thereby becomes sequestered in the deep ocean. The volume of water, and the depth to which it is transported, varies seasonally and geographically.

Many organisms in the ocean go through daily or seasonal migrations from surface waters into the ocean's interior, driven by either avoidance of visual predators during daylight or to avoid sub-optimal growth conditions. These migrations carry carbon to depth, either within their bodies to be excreted at depth as faecal pellets~~,~~ or respired over time and released as

dissolved CO_2. This 'migrant pump' transports around the same amount of carbon to depth (~2 Pg C yr^{-1}) as the physical mixing of the ocean (Boyd et al., 2019; Siegel et al., 2023). This behaviourally driven flux of carbon into the deep ocean is extremely important as these migrations are often down to significant depths (>1 km) where the carbon released may be sequestered away from the atmosphere for more than~~>~~ 500 years (Boyd et al., 2019).

Environmental controls, climate change and anthropogenic impacts

While deep remineralisation of sinking material is advantageous in terms of sequestering atmospheric CO_2 in the ocean's interior, it robs the sun-lit upper ocean of nutrients and leads to widespread nutrient limitation of primary production (Moore et al., 2013). Processes by which nutrients are returned to the surface, often through stochastic or seasonal mixing, are therefore critical to support continued production. Ocean ~~Global~~ warming, as a consequence of ~~with~~ the ocean absorbing 90% of the total energy generated by anthropogenic forcing of the climate system~~excess heat of the climate system~~ (Cheng et al., 2022), is likely to ~~radically reshape the mixing regime of the ocean~~alter ocean circulation and mixing (Melet et al., 2022; S4.C3). While the specific timing and intensity of the changes are unclear, it is likely to result in changes to the ~~and deprive ocean ecosystems of~~ physical replenishment of essential nutrients required for primary production, growth and ecosystem health (Hutchins and Tagliabue, 2024). Current IPCC-class global models vary considerably in their spatial projections~~edictions~~ of future changes in primary production. Although most exhibit only a modest reduction (~2%) in global marine productivity, ~~regionally~~ there may be strong (>20%) increases (e.g., Arctic) and decreases (e.g., subpolar Atlantic) (Tagliabue et al., 2021) in specific regions.

Another concern is that reduced ocean mixing will reduce the replenishment of oxygen to deep waters (S4.C3), essential for heterotrophic activity and higher trophic levels. The respiration of sinking organic matter requires oxygen, so there is a net oxygen consumption (deoxygenation) below the sunlit upper ocean. In shallow areas, or where there is sluggish circulation and high rates of sinking organic material and oxygen consumption, this

deoxygenation can lead to hypoxic or anoxic conditions (e.g., Meier et al., 2018), the formation of oxygen minimum zones and avoidance of these areas by aerobic organisms (Schmidtko et al., 2017). Reductions in ocean mixing due to ocean warming are predicted to lead to the expansion of oxygen minimum zones and lowering of oxygen concentrations more generally (Schmidtko et al., 2017) (S4.C3) , which will have a direct impact on ocean biology; for example, limiting the vertical migration of zooplankton (Abedi et al., 2022) and the strength of the migrant pump component of the biological carbon pump (Cavan et al., 2017). Reductions in oxygen availability in the ocean interior may also reduce respiration and remineralisation rates, acting as ~~a~~ feedback to the biological carbon pump through deeper depth penetration of sinking material (i.e. higher C sequestration) (Cavan et al., 2017).

The ocean's increased uptake of atmospheric CO_2~~–~~, relative to pre-industrial times, is primarily driven by increasing atmospheric CO_2 concentrations (Sabine, 2021), with the ocean's role in sequestrating anthropogenic CO_2 resulting in chemical changes in the ocean (Sabine, 2021). Specifically, the dissolution of CO_2 and its reaction with seawater to form carbonic acid has dramatically decreased ocean pH (by increasing proton concentrations) and reduced the saturation state of carbonate minerals (calcite, aragonite) in the ocean over the last few decades (Lauvset et al., 2015; Jiang et al., 2019). This 'ocean acidification' impacts ocean biology by making the ~~through physiological challenges in~~ balancing of cell pH (avoiding acidosis) more challenging for marine organisms and increasing the physiological costs of countering the increased dissolution rates of organism-associated bio-minerals. Ocean acidification impacts the role of marine ecosystems in the carbon cycle at multiple scales (Doney et al., 2020), for example changes in nutrient availability (e.g., Shi et al., 2010), growth, grazing and reproductive success (e.g., Keil et al., 2021), ~~calcify~~ication, plankton diversity and community composition (e.g., Taucher et al., 2017). Despite considerable knowledge of ocean acidification impacts on specific elements of marine ecosystems and the biological carbon pump (e.g., Taucher et al., 2017), a holistic understanding of its impact on the future magnitude and efficiency of the different

component pumps (gravitational, migrant, mixing) is lacking (Passow and Carlson, 2012; Wolf-Gladrow and Rost, 2014).

2) Shelf, Coasts, Fjords and Estuaries

Moving in from the open ocean, into the shallower areas around our coasts, the surface waters continue to fix and cycle carbon through many of the biological processes described in the previous section. However, unlike open ocean environments, coastal areas are more complex and varied, often made up of different, interconnected coastal habitats (such as estuaries (S4.C5f), mudflats (S4.C5b), saltmarshes (S4.C5i), seagrass meadows (S4.C5g), lagoons and mangroves (S4.C5h)), linking the terrestrial zone to the marine through rivers which meet the ocean through deltas, estuaries or fjords (S4.C5r). This riverine connection transports organic and inorganic carbon, along with ~~and~~ fine particles, into the coastal region, depositing carbon and fine sediment particles (mud) in the nearshore environment (Bianchi et al, 2024). The input of terrestrial carbon into the marine environment is reflected in the carbon sequestered in coastal habitats, which is often a mix of terrestrial and marine carbon, with the proportion of terrestrial carbon higher closer to the coast, and marine carbon dominating with greater distance from land (Wilson et al, 2018).

Additionally, in coastal zones where sufficient light can reach the seafloor~~bed~~, the seabed plays an additional role in carbon fixation (Legge et al, 2020, Gattuso et al, 2006). Coastal primary production is driven by photosynthesis in plants (S4.C4h), macroalgae (S4.C4i) or small single celled photosynthetic organisms (microphytobenthos), which inhabit the surface of soft sediment habitats, such as intertidal mudflats (Christianen et al, 2017). Microphytobenthos dominate carbon cycling in unvegetated coastal sediments (Underwood et al, 2022), play a role in pollutant remediation and form~~s~~ the basis of food webs (Hope et al, 2019). However, the complexity of coastal systems means that currently, large uncertainties remain in estimating the actual area covered by these vegetated coastal

habitats, along with considerable variability in specific carbon flux estimates, resulting in a 10-fold bracket around the estimates of their contribution to organic carbon sequestration, from 0.073 to 0.866 Pg C yr^{-1} (Duarte et al. 2017).

Coastal Blue Carbon Ecosystems

Vegetated coastal habitats such as salt marshes (S4.C5i), seagrass meadows (S4.C5g) and mangroves (S4.C5h), were first described as 'Blue Carbon' habitats in 2009 (Nellemann et al, 2009), and the term is now more generally used for biologically driven carbon fluxes and storage in marine systems that are amenable to management[111] (Lovelock and Duarte, 2019)~~used to describe the capture and storage of carbon in vegetated marine ecosystems~~. It is estimated that these three Coastal Blue Carbon Ecosystems (CBCE's) capture and store more carbon per unit area than terrestrial forests (Mcleod et al, 2011), meaning that, despite covering an area of less than 7 million km^2, (Duarte 2017), CBCE's are considered globally important areas of carbon capture and storage. The plants in these ecosystems capture CO_2 directly through photosynthesis (Figure 2), and much of the carbon remains within that ecosystem, buried in the soft sediments and root systems around the plants (Macreadie et al, 2014; Saderne et al, 2019). The sediments in these plant-rich ecosystems are key for long-term carbon accumulation and storage, and this permanence (long term storage of carbon) provides the Blue Carbon benefit, and the potential for climate mitigation (Williamson and Gattuso, 2022). However, not all the carbon stored in CBCE's is derived from that habitat (autochthonous), and allochthonous carbon (produced outside of that habitat, e.g. terrestrial origin) can make up a significant portion of carbon stocks in sediments (Cragg et

[111] IPCC, 2021: Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte,
C. Méndez, S. Semenov, A. Reisinger (eds.)]. In Climate Change 2021: The Physical Science Basis. Contribution of
Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte,
V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E.
Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press,
Cambridge, United Kingdom and New York, NY, USA, pp. 2215–2256, doi:10.1017/9781009157896.022

al, 2020; Kharbush et al, 2020). This can have implications for Blue Carbon accounting (see Section 4). In addition, a substantial contribution to the carbon sequestration potential of CBCEs can come from the export of alkalinity that is produced by anaerobic processes (especially denitrification and sulfate reduction) in sediments, and exported laterally *via* physical water movement (Santos et al. 2021).

The original definition of Bblue Ccarbon has expanded in recent years as scientific knowledge around carbon uptake and storage in marine ecosystems has increased. Unvegetated marine sediments (coastal, shelf and offshore) store significant amounts of carbon due to their geographical extent (Legge et al, 2020), despite low accumulation rates compared to coastal zones. The term Blue Carbon has broadened beyond the original CBCE's to include marine sediments (including coastal sediments such as mudflats (Brown and otherset al, 2021), and continental shelf and offshore sediments (Graves et al, 2022)), which store carbon for climate relevant (at least 100 years) and geological time periods (>1000 years?), but do not directly capture it like vegetated soft sediment habitats (EMB Policy Brief on Blue Carbon, 2023). Shelf sediments (S4.C5b) make up ~ 9% of the total marine area (Diesing et al, 2017) but hold the biggest carbon store in shelf systems (Legge et al, 2020) and over 80% of organic carbon is buried in subtidal sediments (Hedges and Keil, 1995, Diesing et al, 2021). The amount of carbon stored in shelf sediments varies with sediment type, and although finer particles and muddier sediments are associated with higher organic carbon content (Bianchi et al, 2024, Legge et al, 2020, Diesing et al, 2017), most of the continental shelf is covered by permeable, sandy sediment, or a mix of mud and sand (Diesing et al., 2021). Sandy sediments hold less organic carbon but a large amount of inorganic carbon, which is generally not considered as part of Blue Carbon. Recently, coralline algal beds found in sediments have also recently been suggested as Blue Carbon habitats, through their ability to capture and store carbon (James et al, 2024). As such, BC as a definition has also been applied to organic carbon which is stored in marine ecosystems, and is amenable to managedment to improve climate change mitigation (Lovelock and Duarte, 2019, Graves et al, 2022)

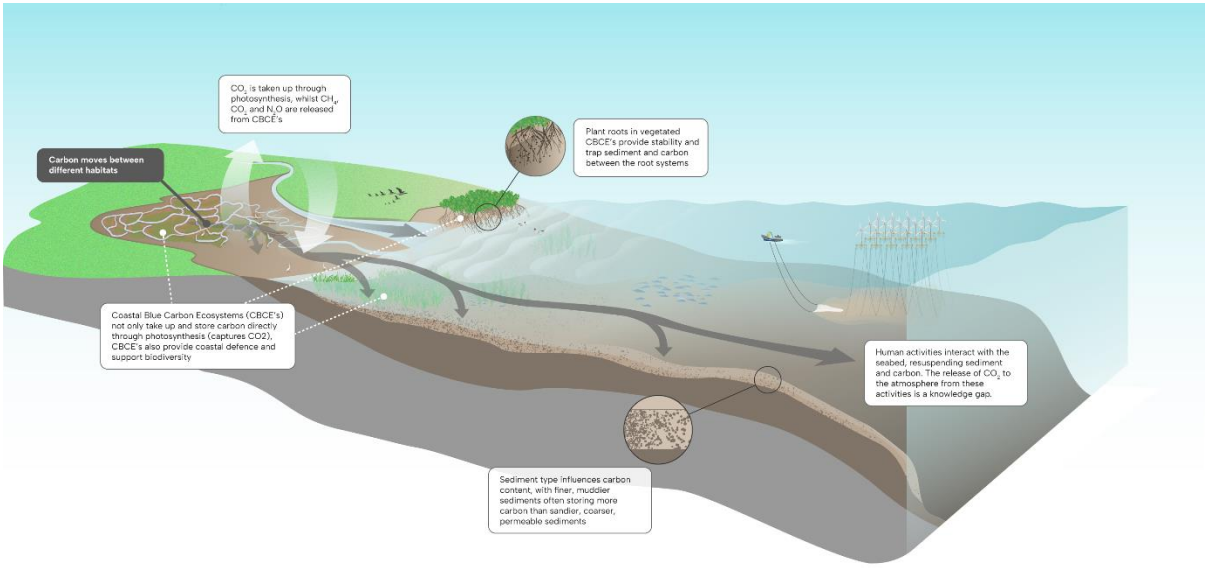


Figure 2: Carbon is directly captured by plants (as carbon dioxide (CO_2)) through photosynthesis in Coastal Blue Carbon Ecosystems (CBCE's), whilst methane (CH_4), nitrous oxide (N_2O) and CO_2 are released by CBCE's. Carbon may become stored in CBCE's, particularly in the sediment around the root systems, or may flow between the different but connected coastal ecosystems and out onto the shelf (as indicated by the arrow). The largest carbon stores are in the sediments, and carbon stocks vary with sediment type. Human activities (such as fisheries activity or energy infrastructure) that interact with the seabed resuspend sediment and carbon.

Macroalgae and calcifiers

Other organisms play a major role in the coastal biological carbon cycle, such as macroalgae (S4.C4i) and calcifying organisms. Macroalgae (such as kelp and seaweed) take up CO_2 through photosynthesis and release it at the end of a growing season when much of the algal biomass dies. Since this vegetation is not rooted in sediment, much of this biomass goes through degradation and remineralisation (microbial breakdown into CO_2). Up to 40% may be released into the coastal and open ocean (Krause-Jensen and Duarte 2016), and a small proportion may be buried in marine sediments (Queirós et al, 2023). Calcifying organisms, such as corals (S4.C5d and S4C5e) and bivalves (e.g. mussels or oysters), produce solid calcium carbonate in the form of skeletons and shells. Whilst it may seem counterintuitive,

the process of calcification actually emits CO_2~~,~~ (Pernet and others 2024) ~~because it removes more alkalinity than carbon~~, and many calcifiers additionally produce CO_2 through respiration. However, calcifying organisms do play a vital role in the biological carbon cycle, even though they ~~should~~are not ~~be~~ considered to be ~~as~~ Blue Carbon, nor ~~as~~ a nature-based solution for climate change. They are also important for many other species and provide a number of co-benefits, such as habitat provision, supporting biodiversity, and improved water quality (S4.C5d and S4C5e).~~-~~ Recently, coralline algal beds found in sediments have also ~~recently~~ been suggested to be Blue Carbon habitats, because the carbon captured and stored through photosynthesis may exceed the carbon released by calcification (James et al, 2024).

Microbial carbon cycling

As in the open ocean, microbial communities make up a significant proportion of the carbon biomass (see Section 1) and drive sedimentary carbon dynamics on the seabed (balance between sequestered and respired). Organic carbon reaches the seabed and is either remineralised through microbial breakdown or consumption of the carbon, releasing CO_2 and nutrients (Middelburg, 2018), or a small proportion may become buried in the sediment and eventually sequestered. -The proportion of carbon buried vs respired is not only driven by microbial activity, which favours aerobic respiration (Glud, 2008), but also environmental parameters like temperature and water depth (Diesing et al, 2017) and presence of macrofauna (Middelburg, 2018). Generally, warmer waters stimulate more microbial activity, and a greater proportion of carbon is converted to CO_2 whilst less is buried. T~~=t~~his has implications for reducing carbon sequestration as ocean temperatures warm. Microbial processing of organic carbon determines the flux of oxygen and carbon dioxide at the sediment-water interface (and the sea surface-air interface), and methane in coastal sediments (LaRowe et al, 2020).

Carbon is microbially mineralised in the surface oxic layers of the sediment, the depth of which varies with sediment type and season (Hicks et al., 2017), as muddy sediments with

smaller grain size have a shallower oxic depth and have higher organic carbon content than sandy sediments (Bianchi et al, 2024). Below the oxic layer in sediments, the carbon is less easily broken down by microbial communities due to the hypoxic or anoxic conditions. However, hypoxic or anoxic microbial breakdown of carbon can lead to the release of other metabolites like ammonium, hydrogen sulfide or methane, another greenhouse gas (Middelburg and Levin, 2009), although a greater proportion of carbon becomes buried in sediments under low--oxygen conditions. This has implications for warming of coastal and marine ecosystems, leading to an increase in the occurrence, duration and frequency of hypoxia (Diaz and Rosenberg, 2008).

Coastal microbial carbon cycling in CBCE's is influenced by the presence of plants roots, which provide a route for oxygen to penetrate the sediment layers beyond the oxic zone (Trevathan-Tackett et al, 2023), and microbial communities differ between the CBCE habitats. The origin of the carbon (allochthonous vs autochthonous) is also important for microbial processing, as marine microbes are less efficient at breaking down land-derived (allochthonous) carbon than marine-derived (autochthonous) carbon (Cragg et al, 2020; LaRowe et al., 2020).

Knowledge gaps and uncertainties

The protection and creation of CBCEs are seen as a Nature-based Solution (NbS) for marine climate change mitigation (Pörtner et al., 2023), and Coastal Blue Carbon Ecosystems (CBCE's) may contribute to Nationally Determined Contributions (NDC's) under the Paris Agreement 2015, for climate mitigation (Macreadie et al, 2021). Recent estimates suggest that, with full restoration of CBCEs, the total contribution to climate mitigation is around 2% globally. In temperate regions, the small geographical area of these ecosystems means that it is unlikely that they will play a significant role in meeting mitigation targets. For small island nations, which have larger geographical extent of CBCEs, their relative contribution may be significantly higher. Although Blue Carbon habitats may contribute to NDC's, for many countries, the small geographical footprint of these ecosystems means it is unlikely to play

~~a significant role in meeting climate targets, particularly in temperate regions. However, for small tropical island nations, which have larger geographical extent of BC habitats, the contribution to their NDC's may be significantly higher.~~ For example, mangroves are found in over 100 countries, but over a fifth of global mangroves are located in Indonesia (Macreadie et al, 2019, Giri et al, 2011). The huge global variability of carbon stocks in the same habitat makes it difficult to accurately assess carbon sequestration and climate change mitigation potential, and studies are often under-represented in the global south (Wasserman et al, 2023).

Recent research has focused on different approaches to restoration and conservation of CBCE~~'~~s for climate mitigation, particularly as they are vulnerable to sea level rise in the next few decades. Restoration efforts could include intentional breaching of sea defences or embankments in North West Europe (called 'managed realignment') (Burden et al, 2013; Mossman et al, 2012). Restoration approaches for CBCE~~'~~s, such as realignment, provide a Nature-based Solution for increasing carbon capture and storage, as well as providing coastal protection from floods and storm surges. However, the role of greenhouse gases in carbon cycling, particularly in CBCE~~'~~s, is not yet fully understood (Williamson and Gattuso, 2022; EMB BC Policy Brief, 2023), and the climate benefit of salt marshes (natural and restored) is variable (Mason et al, 2023; Mason et al, 2024; Williamson et al, 2024). Studies have shown that coastal wetlands can be emitters of greenhouse gases such as methane and nitrous oxide (Megonigal, 2004; Mason et al, 2023; Roth et al, 2023), although this may be linked to the health and age of the coastal wetland.

R~~Although r~~estoration of CBCE~~'~~s for climate mitigation (ability to store carbon) would lead to co-benefits such as coastal protection, increased biodiversity and improved water quality (Williamson and Gattuso, 2022). This is important to recognise because ~~However,~~ the climate benefits of restoration, or rewilding, efforts are not likely to be immediate, and the transition of ~~restoration approaches or rewilding of new~~ other habitats into CBCEs will take time for climate mitigation objectives to be met (Burden et al, 2013; Pétillon et al, 2014,

Williamson et al, 2024). CBCE's will also need to be climate resilient, in the face of warming and rising sea levels (Macreadie et al, 2019).

Coastal and shelf soft sediments are a significant repository for carbon, and shelf sediments are often highly productive systems with intensive seabed activity. Despite concerns that these carbon stocks could be remineralised into CO_2 through disturbance of the sedimentary carbon stores (Sala et al, 2021), there is limited empirical evidence on the vulnerability of this carbon to anthropogenic activity (Epstein et al, 2022, Hiddink et al, 2023). This includes trawling, dredging, installation and removal of energy structures and associated infrastructure, and deep-sea mining. The uncertainty around the vulnerability of the carbon, and limited knowledge on carbon accumulation rates and burial, makes it challenging to effectively manage the seabed.

3) Exchange between coastal and open ocean systems

In previous sections we have considered the open ocean and the coastal environment separately. However, these two systems are tightly coupled when it comes to carbon transport., with cContinental shelf seas beingare a source of 0.95 ± 0.25 PgGt C yr^{-1} to the open ocean (Regnier et al. 2022). This flux consists chiefly of dissolved inorganic and dissolved and particulate organic carbon (DIC, DOC, and POC, respectively), and is mainly driven by physical processes. The net transport of DIC is largely driven by enhanced physico-chemical dissolution of atmospheric CO_2 into shelf waters. Shelf seas also typically have higher concentrations of DOC and POC than the open ocean, because of high biological productivity and inputs of DOC and POC from land. Moreover, movement of nektonic animals to and from shelf seas contributes a carbon flux, although this remains very poorly quantified. Quantifying these carbon fluxes is challenging, in part because of the high spatial and temporal variability of shelf seas.

The purely physico-chemical mechanism of shelf-to-ocean DIC flux is mainly driven by winter-time cooling of shelf waters at temperate and higher latitudes, which lowers the partial pressure of carbon dioxide ~~CO_2 shelf sea~~ (pCO_2) in the water and results in uptake of atmospheric carbon dioxide (CO_2~~.~~). This cold, dense shelf water can then flow off the shelf and below the oceanic thermocline, a process called the "continental shelf pump" (Tsunogai et al. 1999; Cossarini et al. 2015). Conversely, in tropical shelf seas the opposite can occur: cooler oceanic water can warm up on the shelf, leading to an increase in shelf sea pCO_2 and promoting CO_2 flux to the atmosphere (Lacroix et al. 2021).

Biological production contributes to the continental shelf pump by converting CO_2 into POC and DOC~~., but only if~~However, to become part of the continental shelf pump this ~~carbon~~POC and DOC ~~is~~must either be transported below the open-ocean thermocline or be transformed into refractory DOC, so that the carbon is not remineralized back into CO_2 and exchanged with the atmosphere over short time scales ~~before it is remineralized back into CO_2 and exchanged with the atmosphere~~ (Lee et al. 2022; Holt et al. 2009). ~~Yet this transport does not always happen~~However, most of the POC and DOC produced in shelf seas is remineralized before it can become part of the continental shelf pump, and net biological production ~~is~~rates are not correlated with the strength of the CO_2 sink when comparing globally across shelf seas (Lacroix et al. 2021). Moreover, there can be seasonal and even interannual lags between biological production and physical transport, such that shelf sea carbon budgets are not necessarily balanced over a year (Chaichana et al. 2019; Humphreys et al. 2019). The production of biologically refractory ~~organic carbon~~DOC, which can accumulate and be exported off the shelf during episodic flushing events, mass transportation of both DOC and POC from shelf to the deep-sea by tectonic triggers such as big earthquakes and tsunamis (Kioka et al., 2019), is therefore important for the continental shelf pump; since this carbon is refractory it does not matter whether this material is exported above or below the thermocline (Chaichana et al. 2019; Humphreys et al. 2019). Part of the POC and DOC that is transported from shelf seas to the open ocean is terrestrial in origin. The fate of this terrestrial carbon remains poorly quantified, but roughly 50% appears to be transported off

shelf seas (Lacroix et al. 2021), including below the permanent thermocline (Medeiros et al. 2016). Turbidity currents are an important vector transferring shelf sea sedimentary POC below the oceanic thermocline (Ren et al. 2024; Gibbs et al. 2020; Talling et al. 2024). Distinct increase of coastal to upper slope temperatures gives unstable conditions of organic rich sediments under oxygen minimum zone. High rate of organic carbon deposits introduce slope failures by dissolution of gas hydrates. These non-tectonic slope failures should be important origin for lateral transportation of organic carbons to the deep in the form of turbidites (Kitazato, 2024).

Some organic matter enters the open ocean above the permanent thermocline. ~~T~~Unless it is in form of refractory DOC, this carbon is not sequestered from the atmosphere, but it can be recycled and fuel primary production off the shelf, and also contribute to the biological carbon pump in the open ocean (Frischknecht et al. 2018). This contribution is partly directly by POC and DOC originating from the shelf, and partly by POC and DOC produced from recycling of organic matter that originated from the shelf.

Horizontal carbon transport via animals is probably widespread but largely unquantified, unlike the vertical flux from animal migrations (see Section 1 of the current chapter). For example, fish contribute 16% ± 13% of downward POC flux out of the euphotic zone, but the horizontal carbon flux from fish migrations is unknown (Saba et al. 2021). Physical transport of zooplankton across the shelf break can be significant (Keister et al. 2009) and is even part of the ontogenetic migrations of some commercially important species such as rock lobsters (Phillips et al. 2007). Horizontal fluxes have only been estimated in few instances. For example, the spawning migration of the squid *Illex argentinus* on the Patagonian Shelf transfers roughly 0.09 ~~Mt~~Gg C yr^{-1} (0.09×10^{-6} Pg yr^{-1}) to the shelf slope (Arkhipkin 2013; using biomass-to-carbon conversions from Hoving et al. 2017). This is about 0.7% of the Patagonian Shelf's net biological production (Lacroix et al. 2021), although it is partly balanced by on-shelf migration of other squid species. Horizontal carbon transport *via*

nektonic animals is likely to be impacted by fishing practices and potentially by climate-induced changes in seasonal and ontogenetic migration patterns.

4) The value of Carbon Cycling Ecosystems

Ocean Nnatural Ceapital Aaccounting (NCA) encompasses the systematic measurement and reporting of the status or "health" of ocean natural capital, as well as the contributions these assets make to society and the blue economy. Through monetary quantification, the ocean NCA enables decision-makers to make trade-offs and assess impacts associated with various development scenarios and policies for ocean environmental sustainability and human well-being. Marine and coastal ecosystems form natural capital stocks that provide numerous benefits—such as food, climate regulation, and air quality control—collectively known as ecosystem services. The value of CBCEsblue carbon ecosystems can be understood as the total economic value of conserving, restoring and sustainably managing marine and coastal ecosystems. While tThe concept of Total Economic Value (TEV) comprises the use and non-use values (Zarate-Barrera et al., 2015). The valuation of the ecosystem services provided by marine and coastal ecosystems clearly evidences the links between humans and the oceans, informs policymakers for improved ocean management/planning and advance policies, and motivates the investment in ocean conservation.

Recently, a country-level Bblue Ccarbon wealth assessment showed that Coastal Bblue Ccarbon Ecosystems (CBCEs) have an average value of USD190.67±30 billion. Australia, Indonesia and Cuba were the three countries that contributed the most benefits from Bblue Bcarbon wealth and India, China and the United States are the largest beneficiaries (Bertram et al., 2021). When looking at the different types ofindividual CBCEs, the most extensively studied are mangroves (S4.C5h) and salt marshes (tidal marshes). For instance, all the ecosystem services provided byfor all mangroves worldwide have been valued at USD 69.9 billion (Sanford, 2009). Regulation services of various coastal wetlands (S4.C5i) have an

average value of USD 369.7 and a TEV value of USD 3184 ha^{-1} yr^{-1}. Mangroves have an average of USD 806 ha^{-1} yr^{-1} for provision services, USD 1446 ha^{-1} yr^{-1} for regulation services, USD113 ha^{-1} yr^{-1} for support services, USD 1721 ha^{-1} yr^{-1} for cultural services, and a TEV of USD 6553 ha^{-1} yr^{-1} (Lopez-Rivas and Cardenas 2024). Seagrass meadows (S4.C5g) are less studied but have an average USD 3226.5 ha^{-1} yr^{-1} for provision and USD 871.7 ha^{-1} yr^{-1} for regulation (Lopez-Rivas and Cardenas 2024). A study examined the ecological and economic potential of three key ecosystem services - fishery production, nutrient cycling, and carbon removal - provided by six kelp genera (*Ecklonia, Laminaria, Lessonia, Macrocystis, Nereocystis*, and *Saccharina*). The results show that the potential value of each genus was between USD 64,400 and 147,100 ha^{-1} yr^{-1} (Eger et al., 2023). There are still gaps in valuation of blue carbon ecosystems. For example, Arkema et al. (2024) found that only a third of papers quantify societal benefits of coastal ecosystems within MPAs and these tend to focus mainly on corals and mangrove ecosystems.

The value of carbon cycling ecosystems has been increasingly recognised and many finance initiatives exist i.e. voluntary and compliance carbon markets, public funding, philanthropic and other alternatives (e.g. payment for ecosystem services, ocean natural capital accounting, blue bonds). Blue Cearbon activities are one type of climate mitigation solution which currently receives just 3% of total climate investment globally. This lack of financial support has been a barrier to bringing Bblue Cearbon conservation and restoration activities to scale (First Blue Carbon Conservation Methodology Expected to Scale Up Finance for Coastal Restoration & Conservation Activities - Verra).

The recognition that marine ecosystems, other than CBCEs, also have the power to fix and transport large quantities of carbon has increased interest in using them as ~~Whilst several proposed engineered/technological~~ marine carbon dioxide removal (mCDR) measures, ~~are predicated on the use or manipulation of the carbon cycling capabilities of marine ecosystems, that topic will be covered in another chapter (ref to chapter)~~(S5A.C10). ~~However,~~ ~~i~~It should be noted that great uncertainty remains regarding the efficacy, scalability or

financial viability of many of these proposed nature-based mCDR approaches. For example, tThe estimated costs for ocean iron fertilization (OIF) vary widely, with best-case values of USD 7 per net tonne C captured versus worst-case USD 1,500 per net tonne C captured depending on oceanographic factors. OIF aerial delivery ranges between USD 21 and 2,033 per net tonne C captured inclusive of verification costs; up to 30-40% more cost-effective than ship-based OIF (Emerson et al. 2024).

Whilst seaweed aquaculture is not considered as either Bblue Ccarbon or geoengineering (S5A.C10), the additional value of such activities to carbon storage, over and above the commercial value of the seaweed product, has been noted. The levelized unit costs of CO_2eq sequestration (LCOC; USD tCO_2eq^{-1}) for kelp aquaculture at baseline were estimated at USD 17,048 tCO_2eq^{-1} with only a 39% true sequestration "additionality" rate (AR). However, by process improvement and decarbonization of production supply chains LCOC was reduced to USD 1,257 tCO_2eq^{-1} and AR increased to 91% (Coleman et al. 2022). Froehlich et al. (2019) analyzed global production data and determined that the cost of producing C credits from macroalgae ranged from USD 71 - 27,222 tCO_2eq^{-1}.

More generally, the recognition of the value of CBCEblue carbon ecosystemss in climate action has increased in recent years. However, while aA total of 81% (n=158) of Paris Agreement Parties have included an adaptation component in their NDCs, onlyof which 31% (n=49) identified ocean ecosystems as a priority sector for adaptation. Additionally; and only 21% (n=41) of all Parties included ocean or Bblue Ccarbon as a priority sector for reducing GHG emissions, of which 71% (29 Parties) of these 41 mentioned specific ocean-based mitigation measures (UNFCCC 2024).

5) References

Abedi, E., J. Seyfabadi, A. Saleh, A. Sari. 2022. Mesozooplankton community in near-hypoxic and hypoxic layers of the Persian Gulf and Gulf of Oman. Marine Pollution Bulletin 184, 114146. https://doi.org/10.1016/j.marpolbul.2022.114146.

Arkema, K.K., L. Field, L.K. Nelson, N.C. Ban, C. Gunn, S.E. Lester. 2024. Advancing the design and management of marine protected areas by quantifying the benefits of coastal ecosystems for communities. One Earth 7:989-1006. https://doi.org/10.1016/j.oneear.2024.04.019

Arkhipkin, A. I. (2013). Squid as nutrient vectors linking Southwest Atlantic marine ecosystems. Deep Sea Research Part II: Topical Studies in Oceanography, 95, 7–20. https://doi.org/10.1016/j.dsr2.2012.07.003

Atwood, T.B., Witt, A., Mayorga, J., Hammill, E., Sala, E. (2020). Global patterns in marine sediment carbon stocks. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.00165.

Baker, C.A., Martin, A.P., Yool, A., & Popova, E. (2024). Biological Carbon Pump Sequestration Efficiency in the North Atlantic: A Leaky or a Long-Term Sink? Global Biogeochemical Cycles, 36, e2021GB007286, https://doi.org/10.1029/2021GB007286.

Bar-On, Y., Phillips, R., Milo, R. (2018). The biomass on Earth. PNAS 115(25),6505-6511. https://doi.org/10.1073/pnas.1711842115.

Bar-On, Y., Milo, R. (2019). The biomass composition of the oceans: A blueprint of our blue planet. Cell 179, 1451-1454. https://doi.org/10.1016/j.cell.2019.11.018.

Bertram, C., Quaas, M., Reusch, T.B.H. *et al.* The blue carbon wealth of nations. *Nat. Clim. Chang.* **11**, 704–709 (2021). https://doi.org/10.1038/s41558-021-01089-4

Bianchi, D., Carozza, D.A., Galbraith, E.D., et al. (2021). Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. Science Advances, 7(41). https://doi.org/10.1126/sciadv.abd7554.

Bianchi, T.S., Mayer, L.M., Amaral, J.H.F., Arndt, S., Galy, V., Kemp, D.B., Kuehl, S.A., Murray, N.J., Regnier, P. (2024) Anthropogenic impacts on mud and organic carbon cycling. Nature Geoscience, 17(4), 287-297. https://doi.org/10.1038/s41561-024-01405-5.

Boyd, P.W., Claustre, H., Levy, M., Siegel, D.A., Weber, T. (2019). Multi-faceted particle pumps drive carbon sequestration in the ocean. Nature 568, 327-335. https://doi.org/10.1038/s41586-019-1098-2.

Brown, D.R., Marotta, H., Peixoto, R.B., Enrich-Prast, A., Barroso, G.C., Soares, M.L.G., Machado, W., Pérez, A., Smoak, J.M., Sanders, L.M., Conrad, S., Sippo, J.Z., Santos, I.R., Maher, D.T. & Sanders, C.J. (2021) Hypersaline tidal flats as important 'blue carbon' systems: a case study from three ecosystems. Biogeosciences, 18(8), 2527–2538. https://doi.org/10.5194/bg-18-2527-2021.

Buitenhuis, E.T., Hashioka, T., Le Quere, C.L. (2013a). Combined constraints on global ocean primary production using observations and models. Global Biogeochemical Cycles, 27, 847-858. https://doi.org/10.1002/gbc.20074.

Buitenhuis, E.T., Vogt, M., Moriarty, R., et al., (2013b). MAREDAT: towards a world atlas of MARine Ecosystem DATa. Earth System Science Data, 5(2), 227-239. https://doi.org/10.5194/essd-5-227-2013.

Burden, A., Garbutt, R.A., Evans, C.D., Jones, D.L. and Cooper, D.M. (2013) Carbon sequestration and biogeochemical cycling in a saltmarsh subject to coastal managed

realignment. Estuarine, Coastal and Shelf Science, 120, pp.12-20. https://doi.org/10.1016/j.ecss.2013.01.014

Calbert, A. (2001). Mesozooplankton grazing effect on rpimary production: A global comparative analysis in marine ecosystems. Limnology and Oceanography 46(7), 1824-1830. https://doi.org/10.4319/lo.2001.46.7.1824.

Cavan, E.L., Trimmer, M., Shelley, F., Sanders, R. (2017). Remineralization of particulate organic carbon in an ocean oxygen minimum zone. Nature Communications 8, 14847. https://doi.org/10.1038/ncomms14847.

Cavan, E.L., Kawaguchi, S., Boyd, P.W. (2020). Implications for the mesopelagic microbial gardening hypothesis as determined by experimental fragmentation of Antarctic krill fecel pellets. Ecology and Evolution 11(2), 1023-1036. https://doi.org/10.1002/ece3.7119.

Coleman S., Dewhurst T., Fredriksson D.W., St. Gelais A.T., Cole K.L., MacNicoll M., Laufer E., Brady D.C. (2022) Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal. Frontiers of Marine Science (Sec. Marine Fisheries, Aquaculture and Living Resources) 9. https://doi.org/10.3389/fmars.2022.966304

Chaichana, S., Jickells, T., & Johnson, M. (2019). Interannual variability in the summer dissolved organic matter inventory of the North Sea: Implications for the continental shelf pump. Biogeosciences, 16(5), 1073–1096. https://doi.org/10.5194/bg-16-1073-2019

Cheng, L., von Schukmann, K., Abraham, J.P., et al. (2022). Past and future ocean warming. Nature Reviews Earth and Environment 3, 776-794. https://doi.org/10.1038/s43017-022-00345-1.

Christianen, M.J., Middelburg, J.J., Holthuijsen, S.J., Jouta, J., Compton, T.J., van der Heide, T., Piersma, T., Sinninghe Damsté, J.S., van der Veer, H.W., Schouten, S. and Olff, H., (2017) Benthic primary producers are key to sustain the Wadden Sea food web: stable carbon isotope analysis at landscape scale. Ecology, 98(6), pp.1498-1512.

Cossarini, G., Querin, S., & Solidoro, C. (2015). The continental shelf carbon pump in the northern Adriatic Sea (Mediterranean Sea): Influence of wintertime variability. Ecological Modelling, 314, 118–134. https://doi.org/10.1016/j.ecolmodel.2015.07.024

Cragg, S.M., Friess, D.A., Gillis, L.G., Trevathan-Tackett, S.M., Terrett, O.M., Watts, J.E., Distel, D.L. and Dupree, P. (2020) Vascular plants are globally significant contributors to marine carbon fluxes and sinks. Annual Review of Marine Science, 12(1), pp.469-497 https://doi.org/10.1146/annurev-marine-010318-095333

Diaz, R.J. and Rosenberg, R., (2008) Spreading dead zones and consequences for marine ecosystems. science, 321(5891), pp.926-929.

Diesing, M., Kröger, S., Parker, R., Jenkins, C., Mason, C, Weston, K. (2017) Predicting the standing stock of organic carbon in surface sediments of the North–West European continental shelf. Biogeochemistry, 135 (2017), pp. 183-200

Diesing, M., Thorsnes, T., & Bjarnadóttir, L. R. (2021). Organic carbon densities and accumulation rates in surface sediments of the North Sea and Skagerrak. Biogeosciences, 18(6), 2139-2160.

Doney et al., 2020

Drago, L., Panaiotis, T., Irisson, J-O., et al. (2022). Global distribution of zooplankton biomas estimated by in situ imaging and machine learning. Front. Mar. Sci., 9, https://doi.org/10.3389/fmars.2022.894372.

Duarte, C. M. (2017). Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. Biogeosciences, 14(2), 301-310.

Eger, A.M., Marzinelli, E.M., Beas-Luna, R. *et al*. The value of ecosystem services in global marine kelp forests. *Nat Commun* **14**, 1894 (2023). https://doi.org/10.1038/s41467-023-37385-0

Emerson, D., L.E. Sofen, A.B. Michaud, S.D. Archer, B.S. Twining. 2024. A Cost Model for Ocean Iron Fertilization as a Means of Carbon Dioxide Removal That Compares Ship- and Aerial- Based Delivery, and Estimates Verification Costs. Earth's Future, 12, e2023EF003732. https://doi. org/10.1029/2023EF003732

Epstein, G., Middelburg, J.J., Hawkins, J.P., Norris, C.R. and Roberts, C.M., (2022) The impact of mobile demersal fishing on carbon storage in seabed sediments. *Global Change Biology*, *28*(9), pp.2875-2894.

European Marine Board (2023) Blue Carbon: Challenges and opportunities to mitigate the climate and biodiversity crises. EMB Policy Brief N°. 11, 2023 doi: https://doi.org/10.5281/zenodo.8314215 ISSN: 0778-3590 ISBN: 9789464206203

Faran, T.S. and L. Olsson. 2018. Geoengineering: neither economical, nor ethical-a risk-reward nexus analysis of carbon dioxide removal. Int Environ Agreements 18:63-77.

Frenger, I., Landolfi, A., Kvale, K., et al. (2024). Misconceptions of the marine biological carbon pump in a changing climate: Thinking outside the 'export' box. Global Change Biology, 30(1), e17124. https://doi.org/10.1111/gcb.17124.

First Blue Carbon Conservation Methodology Expected to Scale Up Finance for Coastal Restoration & Conservation Activities. https://verra.org/first-blue-carbon-conservation-methodology-expected-to-scale-up-finance-for-coastal-restoration-conservation-activities/

Friedlingstein, P., O'Sullivan, M., Jones, M.W., et al. (2023). Global Carbon Budget 2023. Earth System Science Data 15, 5301-5369. https://doi.org/10.5194/essd-15-5301-2023.

Frischknecht, M., Münnich, M., & Gruber, N. (2018). Origin, Transformation, and Fate: The Three-Dimensional Biological Pump in the California Current System. Journal of Geophysical Research: Oceans, 123(11), 7939–7962. https://doi.org/10.1029/2018JC013934

Froehlich H.E., Afflerbach J.C., Frazier M., Halpern B.S. (2019) Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. Current Biology 29, 3087–3093. https://doi.org/10.1016/j.cub.2019.07.041

Gao, Y., Lu, Y., Dungait, J.A.J., et al. (2022). The 'regulator' function of viruses on ecosystem carbon cycling in the Anthropocene. Front. Public. Health 10. https://doi.org/10.3389/fpubh.2022.858615.

Gattuso, J. P., Gentili, B., Duarte, C. M., Kleypas, J. A., Middelburg, J. J., & Antoine, D. (2006). Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Biogeosciences*, **3**(4), 489–513. https://doi.org/10.5194/bg-3-489-2006

Gibbs, M., Leduc, D., Nodder, S. D., Kingston, A., Swales, A., Rowden, A. A., Mountjoy, J., Olsen, G., Ovenden, R., Brown, J., Bury, S., & Graham, B. (2020). Novel Application of a Compound-Specific Stable Isotope (CSSI) Tracking Technique Demonstrates Connectivity

Between Terrestrial and Deep-Sea Ecosystems via Submarine Canyons. Frontiers in Marine Science, 7. https://doi.org/10.3389/fmars.2020.00608

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. and Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global ecology and biogeography*, *20*(1), pp.154-159.

Graves, C.A., Benson, L., Aldridge, J., Austin, W.E.N., Dal Molin, F., Fonseca, V.G., Hicks, N., Hynes, C., Kröger, S., Lamb, P.D., Mason, C., Powell, C., Smeaton, C., Wexler, S.K., Woulds, C. & Parker, R. (2022) Sedimentary carbon on the continental shelf: Emerging capabilities and research priorities for Blue Carbon. *Frontiers in Marine Science*, 9. Available online: https://www.frontiersin.org/articles/10.3389/fmars.2022.926215

Glud (2008) Oxygen dynamics of marine sediments, Marine Biology Research, 4:4, 243-289, DOI: 10.1080/17451000801888726

Greenspoon, L., Krieger, E., Sender, R., Milo, R. (2023) The global biomass of wild mammals. PNAS 120 (10), e2204862120, https://doi.org/10.1073/pnas.2204892120.

Hansell, D. A. (2013). Recalcitrant Dissolved Organic Carbon Fractions. *Annual Review of Marine Science*, *5*(1), 421–445. https://doi.org/10.1146/annurev-marine-120710-100757.

Hedges, J. I., and Keil, R. G. (1995). Sedimentary organic matter preservation: an assessment and speculative synthesis. *Marine Chemistry* 49 (2-3), 81–115

Hicks, N., Ubbara, G.R., Silburn, B., Smith, H.E., Kröger, S., Parker, E.R., Sivyer, D., Kitidis, V., Hiddink, J.G., van de Velde, S.J., McConnaughey, R.A., De Borger, E., Tiano, J., Kaiser, M.J., Sweetman, A.K. and Sciberras, M. (2023) Quantifying the carbon benefits of ending bottom trawling. Nature, 617(7960), pp.E1-E2 https://doi.org/10.1038/s41586-023-06014-7

Holt, J., Wakelin, S., & Huthnance, J. (2009). Down-welling circulation of the northwest European continental shelf: A driving mechanism for the continental shelf carbon pump. Geophysical Research Letters, 36(14). https://doi.org/10.1029/2009GL038997

Hope, J.A., Paterson, D.M. and Thrush, S.F. (2020) The role of microphytobenthos in soft-sediment ecological networks and their contribution to the delivery of multiple ecosystem services. *Journal of Ecology*, *108*(3), pp.815-830. https://doi.org/10.1111/1365-2745.13322

Hoving, H. J. T., Bush, S. L., Haddock, S. H. D., & Robison, B. H. (2017). Bathyal feasting: Post-spawning squid as a source of carbon for deep-sea benthic communities. Proceedings of the Royal Society B: Biological Sciences, 284(1869), 20172096. https://doi.org/10.1098/rspb.2017.2096

Humphreys, M. P., Achterberg, E. P., Hopkins, J. E., Chowdhury, M. Z. H., Griffiths, A. M., Hartman, S. E., Hull, T., Smilenova, A., Wihsgott, J. U., Woodward, E. M. S., & Moore, C. M. (2019). Mechanisms for a nutrient-conserving carbon pump in a seasonally stratified, temperate continental shelf sea. Progress in Oceanography, 177, 101961. https://doi.org/10.1016/j.pocean.2018.05.001

Hutchins, D.A., Tagliabue, A. (2024). Feedbacks between phytoplankton and nutrient cycles in a warming ocean. Nature Geoscience 17, 495-502. https://doi.org/10.1038/s41561-024-01451-w.

James, K., Macreadie, P. I., Burdett, H. L., Davies, I., & Kamenos, N. A. (2024). It's time to broaden what we consider a 'blue carbon ecosystem'. *Global Change Biology*, 30, e17261. https://doi.org/10.1111/gcb.17261

Jiang, L-O., Carter, B.R., Feely, R.A., Lauvset, S.K., Olsen, A. (2019). Surface ocean pH and buffer capacity: past, present, and future. Scientific Reports 9, 18624. https://doi.org/10.1038/s41598-019-55039-4.

Jiao, N., Robinson, C., Azam, F., Thomas, H., Baltar, F., Dang, H., Hardman-Mountford, N. J., Johnson, M., Kirchman, D. L., Koch, B. P., Legendre, L., Li, C., Liu, J., Luo, T., Luo, Y.-W., Mitra, A., Romanou, A., Tang, K., Wang, X., … Zhang, R. (2014). Mechanisms of microbial carbon sequestration in the ocean - future research directions. *Biogeosciences*, *11*(19), 5285–5306. https://doi.org/10.5194/bg-11-5285-2014

Jiao, N., Luo, T., Chen, Q., Zhao, Z., Xiao, X., Liu, J., Jian, Z., Xie, S., Thomas, H., Herndl, G. J., Benner, R., Gonsior, M., Chen, F., Cai, W.-J., & Robinson, C. (2024). The microbial carbon pump and climate change. Nature Reviews Microbiology, 22(7), 408–419. https://doi.org/10.1038/s41579-024-01018-0

Keil, K.E., Klinger, T., Keister, J.E., McLaskey, A.K. (2021). Comparative sensitivities of zooplankton to ocean acidification conditions in experimental and natural settings. Frontiers in Marine Science 8. https://doi.org/10.3389/fmars.2021.613778.

Kioka, A., T. Schwestermann, J. Moernaut, K. Ikehara, T. Kanamatsu, C. M. McHugh, C. dos Santos Ferreira, G. Wiemer, N. Haghipour, A. J. Kopf, T. I. Eglinton, M. Strasser 2019. Megathrust earthquake drives drastic organic carbon supply to the hadal trench, Scientific Reports 9: 1553 | https://doi.org/10.1038/s41598-019-38834-x

Kowalczyk, K.A., T. Amann, J. Strefler, M.E. Vorrath, J. Hartmann, S. De Marco, P. Renforth, S. Foteinis, E. Kriegler 2024. Marine carbon dioxide removal by alkalinization should no longer be overlooked. Environmental Research Letters 19: 074033. https://doi.org/10.1088/1748-9326/ad5192

Keister, J. E., Peterson, W. T., & Pierce, S. D. (2009). Zooplankton distribution and cross-shelf transfer of carbon in an area of complex mesoscale circulation in the northern California Current. Deep Sea Research Part I: Oceanographic Research Papers, 56(2), 212–231. https://doi.org/10.1016/j.dsr.2008.09.004

Kharbush, J.J., Close, H.G., Van Mooy, B.A., Arnosti, C., Smittenberg, R.H., Le Moigne, F.A., Mollenhauer, G., Scholz-Böttcher, B., Obreht, I., Koch, B.P. and Becker, K.W. (2020) Particulate organic carbon deconstructed: molecular and chemical composition of particulate organic carbon in the ocean. Frontiers in Marine Science, 7, p.518 https://doi.org/10.3389/fmars.2020.00518

Kitazato, H., 2024, Global warming may accelerate submarine landslides in the oceans -Possible disaster chain reactions-. *Progress in Landslide Research and Technology* (Progress-LRT), ICL Open Access Book Series, vol. 3, no. 1, 83-91. https://doi.org/10.1007/978-3-031-55120-8_4

Kranzler, C.F., Krause, J.W., Brzezinski, M.A., et al. (2019). Silicon limitation facilitates virus infection and mortality of marine diatoms. Nature Microbiology 4, 1790-1797. https://doi.org/10.1038/s41564-019-0502-x.

Kranzler, C.F., Brzezinski, M.A., Cohen, N.R., et al. (2021). Impaired viral infection and reduced mortality of diatoms in iron-limited oceanic regions. Nature Geoscience. 14, 231-237. https://doi.org/10.1038/s41561-021-00711-6.

Krause-Jensen, Dorte, and Carlos M. Duarte. "Substantial role of macroalgae in marine carbon sequestration." *Nature Geoscience* 9.10 (2016): 737-742.

Kulk, G., Platt, T., Dingle, J. (2021). Primary Production, an Index of Climate Change in the Ocean: Satellite Based Estimates over Two Decades. Remote Sensing, 12(5), 826. https://doi.org/10.3390/rs12050826.

Lacroix, F., Ilyina, T., Laruelle, G. G., & Regnier, P. (2021). Reconstructing the Preindustrial Coastal Carbon Cycle Through a Global Ocean Circulation Model: Was the Global

Continental Shelf Already Both Autotrophic and a CO2 Sink? Global Biogeochemical Cycles, 35(2), e2020GB006603. https://doi.org/10.1029/2020GB006603

LaRowe, D.E., Arndt, S., Bradley, J.A., Estes, E.R., Hoarfrost, A., Lang, S.Q., Lloyd, K.G., Mahmoudi, N., Orsi, W.D., Walter, S.S. and Steen, A.D. (2020) The fate of organic carbon in marine sediments-New insights from recent data and analysis. Earth-Science Reviews, 204, p.103146. https://doi.org/10.1016/j.earscirev.2020.103146

Lauvset, S.K., Gruber, N., Landschutzler, P., Olson, A., Tjiputra, J. (2015). Trends and drivers in global surface ocean pH over the last 3 decades. Biogeosciences 12, 1285-1298. https://doi.org/10.5194/bg-12-1285-2015.

Lee, K., Kim, J.-M., Lee, G.-S., Lee, E., Jeong, J.-Y., Lee, J., & Han, I.-S. (2022). Persistent Continental Shelf Carbon Sink at the Ieodo Ocean Research Station in the Northern East China Sea. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.919249

Legendre, L., Rivkin, R.B., Weinbauer, M.G., Guidi, L., Uitz, J. (2015). The microbial carbon pump concept: Potential biogeochemical significance in the globally changing ocean. Progress in Oceanography 134, 432-450. https://doi.org/10.1016/j.pocean.2015.01.008

Legge, O., et al., 2020. Carbon on the northwest European shelf: Contemporary budget and future influences. Frontiers in Marine Science, 7, 143. https://doi.org/10.3389/fmars.2020.00143

Lopez-Rivas, J.D., J.C. Cardenas. 2024. What is the economic value of coastal and marine ecosystem services? A systematic literature review. Marine Policy 161: 106033. https://doi.org/10.1016/j.marpol.2024.106033

Lovelock, C.E. & Duarte, C.M. (2019) Dimensions of Blue Carbon and emerging perspectives. *Biology Letters*, 15(3), 20180781. Available online: https://doi.org/10.1098/rsbl.2018.0781.

Macreadie, P.I., York, P.H., Sherman, C.D.H (2014) Resilience of Zostera muelleri seagrass to small scale disturbances: the relative importance of asexual verses sexual recovery. Ecology and Evolution 4(4), 450-461.-https://doi.org/10.1002/ece3.933

Macreadie, P.I., Anton, A., Raven, J.A. *et al*. The future of Blue Carbon science. *Nat Commun* **10**, 3998 (2019). https://doi.org/10.1038/s41467-019-11693-w

Macreadie, P.I., Costa, M.D., Atwood, T.B., Friess, D.A., Kelleway, J.J., Kennedy, H., Lovelock, C.E., Serrano, O. and Duarte, C.M. (2021) Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, *2*(12), pp.826-839.

Mason, V.G., Burden, A., Epstein, G., Jupe, L.L., Wood, K.A. and Skov, M.W. (2023) Blue carbon benefits from global saltmarsh restoration. Global Change Biology, 29(23), pp.6517-6545. https://doi.org/10.1111/gcb.16943

Mason, V. G., A. Burden, G. Epstein, L. L. Jupe, K. A. Wood, M. W. Skov. (2024) Navigating research challenges to estimate blue carbon benefits from saltmarsh restoration. Global Change Biology 30: e17526. https://doi.org/10.1111/gcb.17526

Mayor, D.J., Sanders, R., Giering, S.L.C., Anderson, T.R. (2014). Microbial gardening in the ocean's twilight zone: Detritivorous metazoans benefit from fragmenting, rather than ingesting, sinking detritus. BioEssays, 36(12), 1132-1137. https://doi.org/10.1002/bies.201400100.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. and Silliman, B.R. (2011) A blueprint for blue carbon: toward an improved

understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment* 9(10), pp.552-560 https://doi.org/10.1890/110004

Medeiros, P. M., Seidel, M., Niggemann, J., Spencer, R. G. M., Hernes, P. J., Yager, P. L., Miller, W. L., Dittmar, T., & Hansell, D. A. (2016). A novel molecular approach for tracing terrigenous dissolved organic matter into the deep ocean. Global Biogeochemical Cycles, 30(5), 689–699. https://doi.org/10.1002/2015GB005320

Megonigal, J.P., Hines, M.E. and Visscher, P.T., (2004) Anaerobic metabolism: linkages to trace gases and aerobic processes. Biogeochemistry.

Meier, H.E.M., Vali, G., Naumann, M., Eilola, K., Frauen, C. (2018). Recently accelerated oxygen consumption rates amplify deoxygenation in the Baltic Sea. Journal of Geophysical Research Oceans 123(5), 3227-3240. https://doi.org/10.1029/2017JC013686.

Melet, A.V., Hallberg, R., Marshall, D.P. (2021). Chapter 2: The role of ocean mixing in the climate system. In: Ocean Mixing: Drivers, Mechanisms, and Impacts (Ed. M. Meredith, A. Naveira Garabato). Elsevier, pg. 5-34. https://doi.org/10.1016/B978-0-12-821512-8.00009-8.

Meyers, M.T., Cohlan, W.P., Carpenter, E.J., Kimmerer, W.J. (2019). Effect of ocean acidification on the nutritional quality of marine phytoplankton for copepod reproduction. PLOS ONE 14(5): e0217047. https://doi.org/10.1371/journal.pone.0217047.

Middelburg, J. J. (2018) Reviews and syntheses: to the bottom of carbon processing at the seafloor, Biogeosciences, 15, 413–427, https://doi.org/10.5194/bg-15-413-2018

Middelburg, J. J. and Levin, L. A.(2009) Coastal hypoxia and sediment biogeochemistry, Biogeosciences, 6, 1273–1293, https://doi.org/10.5194/bg-6-1273-2009

Moore, C.M., Mills, M.M., Arrigo, K.R., et al. (2013). Processes and patterns of oceanic nutrient limitation. Nature Geoscience 6, 701-710. https://doi.org/10.1038/ngeo1765.

Mossman, H.L., Pontee, N., Born, K., Lawrence, P.J., Rae, S., Scott, J., Serato, B., Sparkes, R.B., Sullivan, M.J. and Dunk, R.M., (2012) Rapid carbon accumulation at a saltmarsh restored by managed realignment far exceeds carbon emitted in site construction. BioRxiv, pp.2021-10. https://doi.org/10.1111/j.1365-2664.2012.02198.x

Nellemann, C., et al., 2009. Blue Carbon: the role of healthy oceans in binding carbon. United Nations Environment Programme, GRIDArendal. https://wedocs.unep.org/20.500.11822/7772

Passow, U., Carlson, C.A. (2012). The biological pump in a high CO_2 world. Marine Ecology Progress Series 470, 249-271. https://doi.org/10.3354/meps09985.

Pernet, F., Dupont, S., Gattuso, J.-P., Metian, M. and Gazeau, F. (2025) Cracking the myth: Bivalve farming is not a CO 2 sink. Rev. Aquac. 2025;17:e12954. https://doi.org/10.1111/raq.12954.

Petillon, J., Potier, S., Carpentier, A. and Garbutt, A., 2014. Evaluating the success of managed realignment for the restoration of salt marshes: Lessons from invertebrate communities. Ecological Engineering, 69, pp.70-75. https://doi.org/10.1016/j.ecoleng.2014.03.085

Phillips, B. F., Booth, J. D., Cobb, J. S., Jeffs, A. G., & McWilliam, P. (2006). Larval and Postlarval Ecology. In Lobsters: Biology, Management, Aquaculture and Fisheries (pp. 231–262). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470995969.ch7

Pörtner, H.-O., et al., 2023. Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science,* 380 (6642). https://10.1126/science.abl4881

Poulton, A.J. (2021). Shunt or Shuttle. Nature Geoscience 14, 181-183. https://dio.org/10.1038/s41561-021-00718-z.

Queirós, Ana M., et al. (2023) "Identifying and protecting macroalgae detritus sinks toward climate change mitigation." *Ecological Applications* 33.3: e2798.

Roth, F., Broman, E., Sun, X., Bonaglia, S., Nascimento, F., Prytherch, J., Brüchert, V., Lundevall Zara, M., Brunberg, M., Geibel, M.C. and Humborg, C. (2023) Methane emissions offset atmospheric carbon dioxide uptake in coastal macroalgae, mixed vegetation and sediment ecosystems. Nature Communications, 14(1), p.42.. https://doi.org/10.1038/s41467-022-35673-9

Regnier, P., Resplandy, L., Najjar, R. G., & Ciais, P. (2022). The land-to-ocean loops of the global carbon cycle. Nature, 603(7901), 401–410. https://doi.org/10.1038/s41586-021-04339-9

Ren, X., Xu, J., Wang, H., Liu, M., Liu, X., Li, Y., & Wu, X. (2024). The depositional characteristics of turbidity current in Manila Trench: Sediment provenance, geochemical elements and organic carbon burial. Journal of Asian Earth Sciences, 264, 106074. https://doi.org/10.1016/j.jseaes.2024.106074

Saba, G. K., Burd, A. B., Dunne, J. P., Hernández-León, S., Martin, A. H., Rose, K. A., Salisbury, J., Steinberg, D. K., Trueman, C. N., Wilson, R. W., & Wilson, S. E. (2021). Toward a better understanding of fish-based contribution to ocean carbon flux. Limnology and Oceanography, 66(5), 1639–1664. https://doi.org/10.1002/lno.11709

Sabine, C. (2021). The role of the ocean in the global carbon cycle. In: Integrated Ocean Carbon Research: A summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade. (Eds Wanninkof, Sabine, and Arico). IOC Technical Series 158, Paris, UNESCO, 7-9. https://doi.org/10.25607/h0gj-pq41.

Saderne, V., Geraldi, N.R., Macreadie, P.I. et al. (2019) Role of carbonate burial in Blue Carbon budgets. Nat Commun 10, 1106. https://doi.org/10.1038/s41467-019-08842-6
Sala et al., 2021

Sanford, M.P. (2009) Valuating Mangrove Ecosystems as Coastal Protection in Post-Tsunami South Asia. Natural Areas Journal 29(1), 91-95/. https://doi.org/10.3375/043.029.0111

IR Santos, DJ Burdige, TC Jennerjahn, S Bouillon, A Cabral, O Serrano, T Wernberg, K Filbee-Dexter, JA Guimond, JJ Tamborsk (2009) The renaissance of Odum's outwelling hypothesis in 'Blue Carbon' science, Estuarine, Coastal and Shelf Science Volume 255, 5 July 2021, 107361
https://doi.org/10.1016/j.ecss.2021.107361

Schmidtko, S., Stramma, L., Visbeck, M. (2017) Decline in global oceanic oxygen content during the past five decades. Nature 542, 335–339. https://doi.org/10.1038/nature21399

Schmoker, C., Hernandez-Leon, S., Calbert, A. (2013). Microzooplankton grazing in the oceans: impacts, data variability, knowledge gaps and future directions. Journal of Plankton Research 35(4), 691-706. https://doi.org/10.1093/plankt/fbt023.

Shi, D., Zu, Y., Hopkinson, B.M., Morel, F.M.M. (2010). Effect of ocean acidification on iron availability to marine phytoplankton. Science 327 (5966), 676-679. https://doi.org/10.1126/science.1183517.

Siegel, D.A., DeVries, T., Cetinic, I., Bisson, K.M. (2023). Quantifying the ocean's biological pump and its carbon cycle impacts on global scales. Annual Review of Marine Science 15, 329-356. https://doi.org/10.1146/annurev-marine-040722-115226.

Suttle, C. (2007). Marine viruses – major players in the global ecosystems. Nature Reviews Microbiology 5, 801-812. https://doi.org/10.1038/nrmicro1750.

Tagliabue, A., Kwiatkowski, L., Bopp, L., et al. (2021). Persistent uncertainties in ocean net primary production climate change projections at regional scales raise challenges for assessing impacts on ecosystem services. Front. Climate 3. https://doi.org/10.3389/fclim.2021.738224.

Talling, P. J., Hage, S., Baker, M. L., Bianchi, T. S., Hilton, R. G., & Maier, K. L. (2024). The Global Turbidity Current Pump and Its Implications for Organic Carbon Cycling. Annual Review of Marine Science, 16(Volume 16, 2024), 105–133. https://doi.org/10.1146/annurev-marine-032223-103626

Taucher, J., Haunost, M., Boxhammer, T., Bach, L.T., Alguero-Muniz, M., Riebesell, U. (2017). Influence of ocean acidification on plankton community structure during a winter-to-summer succession: An imaging approach indicates that copepods can benefit from elevated CO2 via indirect food web effects. PLOS ONE 12(2): e0169737. https://doi.org/10.1371/journal.pone.0169737.

Trevathan-Tackett, S.M., Callahan, D.L., Connolly, R.M. and Macreadie, P.I., (2023) Dual indicators link geochemistry to microbiota in blue carbon soils. *Estuarine, Coastal and Shelf Science*, *285*, p.108307.

Tsunogai, S., Watanabe, S., & Sato, T. (1999). Is there a “continental shelf pump” for the absorption of atmospheric CO2? Tellus B: Chemical and Physical Meteorology, 51(3), 701–712. https://doi.org/10.3402/tellusb.v51i3.16468

Underwood, G.J., Dumbrell, A.J., McGenity, T.J., McKew, B.A. and Whitby, C., 2022. The microbiome of coastal sediments. *The marine microbiome*, pp.479-534 https://doi.org/10.1007/978-3-030-90383-1_12

UNFCCC. 2024. Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat. Conference of the Parties serving as the meeting of the Parties to the Paris Agreement Sixth session, Baku, 11 to 22 November 2024. FCCC/PA/CMA/2024/10.

Wasserman, J., Human, L.R.D. and Adams, J.B. (2023) Blue carbon stocks in southern Africa's Endangered seagrass Zostera capensis. Estuarine, Coastal and Shelf Science, 284, p.108296. https://doi.org/10.1016/j.ecss.2023.108296

Williamson, P. & Gattuso, J.-P. 2022. Carbon removal using coastal Blue Carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate* 4. https://doi.org/10.3389/fclim.2022.853666

Williamson, P., R. W. Schlegel, J.-P. Gattuso, J. E. Andrews & T. D. Jickells. (2024) Climate benefits of saltmarsh restoration greatly overstated by Mason et al. (2023). Global Change Biology 30: e17525. https://doi.org/10.1111/gcb.17525

Wilson, R. J., Speirs, D. C., Sabatino, A., & Heath, M. R. (2018) A synthetic map of the north-west European Shelf sedimentary environment for applications in marine science, Earth System Science Data 10, 109–130 https://doi.org/10.5194/essd-10-109-2018

Wolf-Gladrow, D.A., Rost, B. (2014). Ocean Acidification and oceanic carbon cycling. In: Global Environmental Change: Handbook of Global Environmental Pollution, vol 1. (Ed. B. Freedman). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-5784-4_79.

Zarate-Barrera TG, Maldonado JH (2015) Valuing Blue Carbon: Carbon Sequestration Benefits Provided by the Marine Protected Areas in Colombia. PLoS ONE 10(5): e0126627. doi:10.1371/journal. pone.0126627

Section 5B
Chapter 2: The ocean and human health

Writing Team Members:

Professor Michael Moore (UK) - Co-ordinating Author

1. **Dr Lorraine Backer (USA)**
2. **Dr Elisa Berdalet (Spain)**
3. **Dr Timothy Bouley (USA)**
4. **Professor Alistair Boxall (UK)**
5. **Professor Lora Fleming (US)**
6. **Professor Will Gaze (UK)**
7. **Professor William Gerwick (USA)**
8. **Professor Awadhesh Jha (UK)**
9. **Dr Hanna Joerss (Germany)**
10. **Dr Jae Ryoung Oh (Republic of Korea)**
11. **Professor Francesco Regoli (Italy)**
12. **Professor Aldo Viarengo (Italy)**
13. **Dr Zhiyong Xie (China)**

Key Findings

1. Health of the Ocean and the human population are inextricably linked within a highly complex network that is global as well as regional~~Health of the Ocean and the human population are inextricably linked within a highly complex network that is global as well as regional~~.

2. ~~Benefits include seafood, medicines from marine organisms, and wellbeing opportunities ofpopulations living near the sea.~~ Benefits include seafood, medicines from marine organisms, and wellbeing opportunities of populations living near the sea.

3. Harmful effects arise from exposures to algal toxins, pathogens, combustion-derived and synthetic chemicals, micro-/nanoparticles (particularly plastics), coupled with climate change, biodiversity loss and ecosystem degradation due to excess nutrients (N&P), diffuse waste, contaminant mixtures, as well as natural threats.

4. Despite various international agreements, marine biodiversity continues to decline, and several ecosystems, such as the Atlantic cod fishery, Black Sea fishery, and northern Benguela upwelling system, have collapsed.

~~4. Numerous international agreements have failed to prevent progressive loss of marine biodiversity and collapse of several marine ecosystems (e.g., Atlantic cod fishery, Black Sea fishery and the northern Benguela upwelling ecosystem).~~

5. **Identifying single causative factor~~s~~ for many adverse health effects is overly simplistic: a holistic interdisciplinary approach to Ocean and Human Health is required to focus on integrated impact of pollutants and environmental factors, including temperature, salinity, hypoxia and acidification.**

2.1. Introduction

For millennia humans have lived in close proximity to the sea, and the Global Coastal Zone (within 100 km from the coast) population is currently 38% o~~0~~f the human population~~.~~ (C~~c~~osby et al., 2024). This trend reflects the range of benefits coastal living offers, including access to marine resources, opportunities to trade by sea and a sense of wellbeing that many coastal dwellers derive. However, the trend has already resulted in severe damage to marine ecosystems worldwide as humanity has not interacted sustainably with the oceans; and the more benefits acquired, the greater the damage, in turn threatening future benefits (Fig. 1; Depledge, 2024; Depledge et al., 2013; Moore et al., 2013, 2014). Unfortunately, numerous international agreements have failed to prevent the progressive loss of marine biodiversity and the collapse of several marine ecosystems through overfishing and introduction of alien species (e.g., Atlantic cod fishery, Black Sea fisheries and the northern Benguela upwelling ecosystem; Depledge, 2024).

Human health and wellbeing are intrinsically linked with marine ecosystem integrity, depending on the global Ocean for food, oxygen, water and climate regulation (Fleming et al., 2019, 2023, 2024). Human health linkages were first promulgated in the UNESCO-IOC Health of the Oceans (HOTO) Component of the multi-Agency GOOS Programme in the 1990's (Health of the Oceans (HOTO) Panel of the Global Ocean Observing System (GOOS): report - UNESCO Digital Library). World Ocean Assessment II (WOA II) highlighted the complex network of interactions with Ocean and Human Health, and Figure 1 demonstrates these linkages in much greater detail. Many of these health-related interactions are beneficial, while others can be detrimental (Fig. 1, adapted from Fleming et al., 2019, 2023, 2024; Landrigan et al., 2020).

INSERT Fig. 1

Linkages between human health and well-being (S5B-C3; S5B.C4) and the Ocean have been known for a long time. New information and understanding by environmental scientists and epidemiologists reinforce the importance of these linkages (Planetary Health Alliance, https://www.planetaryhealthalliance.org; UN Right to Healthy Environment, https://press.un.org/en/2022/ga12437.doc.htm; Convention on Biological Diversity, Biodiversity and Health). Linkages include benefits, such as seafood as a source of protein and micronutrients: at least 3.3 billion people obtain about 20% of their dietary protein from this resource (Fleming et al., 2023). Additional health-related benefits are derived from medicines ~~produced by~~from marine organisms, and opportunities to enhance well-being by living near the sea (Fleming et al. 2024; Maycock et al. 2024).

Conversely, negative linkages include adverse impacts on health from exposure to natural- and/or anthropogenically-sourced events such as exposure to biotoxins from harmful algal blooms (HABs; S4.C4h); microbial pathogens from sewage and agricultural runoff, agricultural pesticides, offensive odours and pathogens from the presence of animal carcasses/abattoirs, pathogens from hospital waste; chemical/particle pollutants, including nano-/micro-plastics (S4-C6); and radiological contamination (Fig. 2).

INSERT Fig. 2

This chapter assesses benefits and adverse impacts from selected ocean-human interactions that are generally global and regional in scope; and also identifies emerging health-related issues and problems of future concern (Tables 1 & 2). Major health challenges discussed below include: anti-microbial resistance (AMR), toxic chemical and pharmaceutical contaminants, nano-/microparticles and environmental radiation, all within the context of climate change, biodiversity loss and environmental degradation (e.g. habitat loss, coastal zone destruction). Socio-economic decline is associated with marine ecosystem degradation and gives rise to, or exacerbates, pre-existing human physical and mental health issues (S5B.C1; S5B.C3). Concerns about pollutant mixtures and their potential interactions are also discussed, as harmful contaminants are rarely found in isolation. Finally, key knowledge and capacity-building gaps are identified, as well as possible actions to effectively monitor/measure risks and benefits of linked health of the Ocean and of the human population (Fig. 1). 'The ocean's degradation is affecting the enjoyment of human rights, including the rights to health and a clean, healthy and sustainable environment. ('The ocean and human rights', Report of the Special Rapporteur on the human right to a clean, healthy and sustainable environment, Astrid Puentes Riaño, https://docs.un.org/en/A/HRC/58/59)'

2.2. General Aspects of the Relationship between the Ocean and Human Health

Our human health and wellbeing depend upon the health of the global Ocean. The Ocean provides food and livelihoods (e.g., transport and leisure) for >3 billion people (40% of the world's population), and is a source of cultural, spiritual and artistic expression (Fleming et al., 2023 Chapter 1, with permission; Fig. 3).

INSERT Fig. 3

These interactions can be directly beneficial to human health and wellbeing in many ways, such as development of marine-derived pharmaceuticals. Biotechnology and economic benefits can also foster better health and wellbeing and there is growing evidence of physical health and mental wellbeing benefits of blue spaces (Table 1). On the other hand, the Ocean can pose severe human health risks because of environmental stressors (e.g., climate change, HABs and anthropogenic pollution) (Table 1; S4.C4b; S4.C6.sub1; S4.C6.sub5). These and other changes may diminish ocean

biodiversity, and subsequently fisheries and human nutrition, and decrease the potential for discovery and development of marine drugs and beneficial biotechnology (Fig. 3).

The complex interactions (Fig. 1; Table1) between the Ocean and human health highlight existing challenges and provide insight into emergent and perceived future health challenges, while identifying key knowledge and capacity-building gaps. Ultimately, policies and approaches already exist to address many of these Ocean-borne challenges to human health and well-being. It is critical that we acknowledge the vital importance of a healthy Ocean to support human health and well-being now and in the future and have the will to act sustainably and equitably to protect this relationship

2.3. Assessment of Health Benefits (Table 1)

2.3.1. Health of Coastal Communities Relative to Inland Communities

The Global Burden of Disease study (https://www.healthdata.org/research-analysis/gbd#:~:text=The%20 GBD%20study%20is%20the,outcome%20and%20health%20system%20measures) found that the relative burden of disease has already shifted from infectious to non-communicable diseases (NCDs) (e.g. cardiovascular diseases, diabetes, depression) in many countries. It is in the prevention of NCDs that living near the ocean may offer important human health benefits (Fleming et al 2024).

Relatively poorer coastal communities may benefit most from interactions with the ocean (Garrett et al. 2019) and people living nearer the coast report better overall health (Elliott et al. 2023; Geiger et al. 2023). The benefits of residing near a coast can be seen globally (Maharja et al. 2023b), and are enhanced during times of stress, such as the COVID-19 pandemic (Pouso et al. 2021; S5B-C4). Nevertheless, there are challenges associated with coastal living, as noted in a recent report by the UK Chief Medical Officer (2021), even in a relatively high-income country such as the United Kingdom. Challenges include rapid and human generated environmental change, social and environmental inequalities, poor investment in infrastructure, and a lack of a long-term vision.

Research is beginning to show that communities near marine protected areas (MPAs) and other areas designated as 'protected' experience diverse human health and wellbeing benefits, including decreased overall national mortality and improved child health, as well as positive ecosystem impacts (Madarcos et al. 2021; Haque et al. 2023; Nowakowski et al. 2023). It is clear that collaborative, equitable and effective management of these areas with ongoing involvement and economic improvement of local communities is essential to creating and sustaining these ocean and human health benefits (Ban et al. 2019; Gollan and Barclay 2020; Rasheed 2020).

2.3.2. Pharmaceuticals from the Sea

Marine-derived pharmaceuticals are currently valued at $4.1 billion (USD) and are anticipated to reach $9.1 billion by 2033 (Fact.MR 2023). As of 2024, there are some 56 marine natural product-

inspired pharmaceuticals in use or in human clinical trials (Antunes et al., 2023). For example, one of the fastest growing classes of anticancer agent, an Antibody-Drug Conjugate (ADC), immunologically directs a toxin to selectively kill cancer cells. The toxic component was inspired by dolastatin 10, a natural product of a marine cyanobacterium (Singh, 2022).

The health of functional marine ecosystems is in danger, and numerous marine species, some of which we do not even know about, are rapidly disappearing (del Monte-Luna, 2023). What unique adaptations do these species possess, and how could they benefit human health? This is a loss of unknowable yet presumably vast impact and consequence.

There is an urgent need to characterize, catalogue and use the DNA genetic blueprints of at least representative marine life.

2.3.4. Marine Biotechnology

"Biotechnology," broadly defined, encompasses exploration and application of biological processes for innovation across medicine, agriculture, manufacturing, and any other sector that involves living systems. "Marine Biotechnology" refers to those innovations derived from, or applied to, the ocean.

For thousands of years, humans have used marine resources for land-based biologic needs (Dias et al., 2012), long before "biotechnology" became an established term. Medicines, foods and food supplements, topical ointments, colours and dyes – each are examples of innovative adaptation of local marine resources and are precursors to the advanced technologies that have emerged over the past century.

Building on traditional knowledge, anatomists and physiologists have used marine species to achieve greater understanding of basic biomedical processes~~n~~. Biochemists extracted and isolated compounds for use in modern medicine and cosmetics. And molecular biologists and geneticists developed marine-based laboratory tests, applied enzymes for gene sequencing, and are building reference libraries, which hold untold biomedical value. Aqua-culturists and conservationists are increasingly adopting sophisticated biotechnological techniques to optimize ~~–~~feeding, reproduction, and health of farmed species and wild marine life.

The explosive growth of synthetic biology, artificial intelligence and data science, and new genetic tools means that the potential for new biotechnological adaptation of marine resources has never been greater, underscoring the continued importance of protecting and preserving a healthy ocean (Bouley et al. 2023).

2.3.5. Seafood Security – Sea Fisheries and Aquaculture

The role oceans play as a source of healthy food is widely recognized. Foods from the ocean are considered among the most healthy foods providing a wide range of essential nutrients, some even difficult to find in natural forms in other foods. Seafood provides high-quality proteins; omega-3 fatty acids (n-3 polyunsaturated fatty acids, PUFAs); and other nutrients, such as iodine and other trace elements, and vitamins (Liu & Ralston, 2021; The Role of Seafood in Child Growth and Development | National Academies; S4.C4d; S5A.C1a; S5A.C1b; S5A.C1c; S5A.C1d). The conclusion

from the recent FAO/WHO expert consultation on the risks and benefits of fish consumption is very clear. Consumption of aquatic foods is highly beneficial for people at all ages, even when considering potential hazards: (https://openknowledge.fao.org/items/5430199e-8e5d-43d7-87b0-ee78a4f5658d and https://files.nettsteder.regjeringen.no/wpuploads01/blogs.dir/213/files/2021/05/The-role-of-aquatic-foods-in-sustainable-healthy-diets-UNnutrition-May-2021.pdf).

2.3.6. Blue Gym and Mental and Physical Wellbeing

There is growing research evidence that interacting recreationally with unpolluted blue spaces (including the coasts and seas) can have beneficial effects on human physical health and mental well-being (e.g., anti-depression effects; Britton et al., 2020; Depledge & Bird, 2009; Fleming et al., 2024; White et al. 2020).

Coastal residents are more likely than inland dwellers to meet recommended levels of physical activity through recreational exercise (Pasanen et al. 2019), reducing the risk of many NCDs. After correcting for income and other factors, longitudinal studies demonstrate that moving to the coast is associated with sustained improvements in mental health (White et al. 2023). Because of these and other factors (e.g., generally lower levels of air pollution), several comparative studies across multiple countries indicate that many people living nearer the coast report better overall health and well-being (Elliott et al. 2023; Geiger et al. 2023).

2.4. Assessment of Adverse Health Impacts (Table 2)

2.4.1. Harmful Effects of Exposure to Contaminated Seawater, Marine Aerosols & Contaminated Seafood

Despite health benefits, many microbial, chemical and particle pollutants, and toxins can contaminate seafood. These include marine biotoxins, chemicals produced by certain marine organisms, that cause adverse health effects such as gastrointestinal and neurological symptoms and, therefore, pose unique food safety concerns (US EPA, Should I Be Concerned about Eating Fish and Shellfish? | US EPA; Hites et al., 2004; Mol et al., 2022). According to the World Health Organization (WHO), food-borne illnesses are responsible for about 600 million cases and 420,000 deaths each year.

New marine biotoxins and other pollutants are continually being identified, and global demand for seafood continues to grow., Thus, oversight and quality control of seafood should be a priority to prevent future contamination and ensure safe, nutritious, and high-quality seafood for consumers (FAO, 2020; S5A.C1e).

2.4.1.1. Harmful biological agents (Table 2)

2.4.1.1.1. Harmful algal blooms (HABs), respiratory distress and toxicity

The term Harmful Algal Blooms (HABs) refers to a wide range of natural events that occur in aquatic systems that have negative impacts on humans, animals and/or ecosystems (Table 2; Fig. 3; Global HAB, 2017; Gobler et al. 2017; **S4.C4h**; **S4.C6.**sub1; **S5B.C1**). Some HABs, through their production of natural toxins, cause massive mortalities of wild and cultured animals (GlobalHAB 2023). Although these toxic compounds can target certain organisms, they can also be transferred through food webs by non-affected vectors and induce adverse health effects in other animals and humans –(**Table 2**; Berdalet et al. 2016; Berdalet et al. 2022; Lefevre et al. 2016; Zingone et al. 2021).

~~Major HABs,~~ M~~m~~ajor efforts in interdisciplinary research and monitoring of cells and toxic compounds have targetted those HABs with demonstrated human health impacts (Hallegraeff et al. 2021). There were 11,000 hospital admissions and 4000 emergency department visits in 2012 related to HABs in Florida (Lim et al., 2023), likely only the "tip of the iceberg" because of misdiagnosis and underreporting. However, in the last 40 years, progress in understanding HAB species-specific dynamics, bloom prediction and effective regulations have been successful –in preventing seafood poisonings, and mitigating illnesses associated with dermal contact from contaminated water or from inhalation of aerosolised toxins (**S4.C4h**; **S4.C6.sub1**).

INSERT Fig. 4

Paralytic shellfish Toxins (PST) were dominant in East and West Coast America, South America, South East and North East Asia; diarrhetic shellfish toxins (DST) in the Mediterranean and Europe; and Ciguatera in the Indian Ocean and tropical Pacific/Australia/New Zealand and Central America/Caribbean. Currently, adequate monitoring or regulatory tools are in place for DST, PST and amnesic shellfish toxins (AST).~~DST, PST and amnesic shellfish toxins (AST) have adequate monitoring or regulatory tools in place.~~ However, this is not true for fish killing HABS (Trainer et al. 2020) nor for ciguatera toxins with neither easy nor reliable toxin detection tools (Chinain et al. 2021).

2.4.1.1.2. Allergies, food sensitivities & poisonings from consumption of seafood

Seafood can be contaminated by naturally occurring or anthropogenic chemicals and toxins, including agents that cause poisonings, allergic reactions, and other food sensitivities. This section (Table 2) focuses on natural toxins (e.g., saxitoxin, ciguatoxin; Backer et al., 2005) and chemicals that may naturally occur and/or be anthropogenic (e.g., mercury; Takahashi and Shimohata 2019). These chemical agents are responsible for both acute poisonings and– exacerbation of chronic illnesses. Landrigan et al. (2020) published an extensive review of human health and ocean pollutants, including adverse health impacts from exposure to industrial discharges, pharmaceutical wastes, pesticides, persistent organic pollutants, mercury, and micro- and nanoplastics.

Allergic reactions may occur after eating seafood (e.g., shrimp; Ruethers et al., 2018) or fish that has been improperly handled (American Academy of Allergy Asthma and Immunology, 2024). Food protein-induced enterocolitis syndrome in adulthood can be triggered by consuming seafood, particularly in the presence of other gastrointestinal pathologies such as irritable bowel syndrome symptoms (Gonzales-Delgado et al., 2022). These immune-mediated reactions typically occur quickly after consuming seafood.

Seafoods may also induce or exacerbate chronic health conditions. Non-immune-mediated reactions are known as "food sensitivity" or "intolerance" and comprise a delayed response involving the digestive system (Muthukumar et al, 2020; Anibarro et al., 2023).

2.4.1.1.3. Microbial infections and parasitic infestations from consumption of seafood and seawater exposure (mainly from human sewage and agricultural runoff)

Marine environments including recreational waters are polluted by human, animal and industrial waste containing diverse microorganisms including viruses, bacteria and single-celled and multicellular parasites. A systematic review of self-reported symptoms of recreational coastal water users in OECD (Organisation for Economic Co-operation and Development) Countries indicated that marine recreational water users are approximately twice as likely to report symptoms of illness than non-marine water users (Leonard et al., 2018). The relationship is strengthened in low and middle-income countries (LMICs) where untreated sewage may be discharged to the Ocean and elevated temperatures from climate change favour survival and growth of indigenous marine pathogens such as *Vibrio* bacteria (Baker-Austin et al., 2024).

A comprehensive literature review on viruses and bacteria in seafood reported 371,962 cases, 18,723 hospitalizations and 445 deaths associated with 19,554 outbreaks in the US from 2001 to 2021 recorded by the US national Outbreak Reporting System (Fig. 5). Over 450 pathogenic viruses have been detected in sewage and in sewage-contaminated sea water (Fig. 5; Tisza et al, 2023). Norovirus is an important cause of recreational waterborne gastrointestinal illness (Kennedy et al., 2023) due to high loads in wastewater combined with a very low infective dose.

INSERT Fig. 5

Infection risks associated with seafood consumption vary by type of organism and mode of preparation prior to consumption. Bivalve molluscs are of particular concern as they filter large volumes of water and concentrate viral and bacterial pathogens as well as waterborne parasites (Merks et al., 2023). A study of retail mussels in Canada reported between 1.6-5.2%, 3.4-10.4% and 0-3.3% of packages of fresh mussels and oysters PCR positive for *Giardia, Cryptosporidium and Toxoplasma*, respectively. Bivalves such as oysters and clams are often consumed raw, increasing the likelihood of pathogen transmission and human infection.

Finfish are the primary source of parasitic worms (Fig. 6); and infection is associated with eating

raw or undercooked fish (Shamsi 2019). Larval stages of tapeworms and Anisakid nematodes infect humans from contaminated raw, pickled, smoked or undercooked fish and cause gastrointestinal pathologies and allergic reactions (Audicana *et al.,* 2002).

INSERT Fig. 6

2.4.1.1.4. Anti-microbial resistance

Anti-microbial resistance (AMR) is the ability of microorganisms to withstand drugs used to treat infections. AMR refers to antiviral, antibacterial (or antibiotic), antifungal resistance (specifically AFR) and antiparasitic drug resistance. Antibiotic resistant bacterial infections are a growing pandemic, with 1.27 million directly attributable deaths and 4.95 million deaths associated with antibiotic resistant infections globally in 2019. Antibiotic resistance is often considered to be a clinical phenomenon; however, antibiotic resistance genes frequently acquired by bacteria through horizontal gene transfer are predominantly of environmental origin (Wright, 2007).

Many antibiotic drugs are natural products produced by environmental bacteria and fungi. However, less understood is that bacteria have evolved resistance mechanisms in deep evolutionary history, and these are now emerging in human pathogens relevant to global pandemics.

Antibiotic resistance has long been found in soil bacteria. When marine environments are screened for resistance using functional metagenomics, antibiotic resistance genes were found at all sites with only 28% identified as known resistance genes. There was a high diversity of previously uncharacterized genes, demonstrating the scale of the marine environment as a reservoir of novel resistance genes (Hatosy et al., 2015), with the potential risk of spreading to seafood and humans. For example, bacteria such as *Aeromonas* species are opportunistic human pathogens of aquatic (including marine) origin and are the origin of clinical important resistance genes that have subsequently spread to other human pathogens at a global scale (Ebmeyer *et al.,* 2021).

A subset of these bacterial pathogens (and accompanying non-pathogenic commensal bacteria) is resistant to antibiotics. For example, a study by Leonard *et al.* (2015) estimated that 6 million exposure events to a clinically important resistant type of the bacterium occurred (i.e., *E. coli* alone in UK bathing waters). Further work illustrated an association between frequent coastal water exposure and gastro-intestinal occupation of the same clinically important resistant *E. coli* (Leonard *et al.,* 2018). In addition to being a reservoir of antibiotic resistance and facilitating environmental transmission to humans, the coastal environment may be impacted by pharmaceutical and antibiotic pollution that can select for antibiotic resistance, even at the very low concentrations present.

INSERT Fig. 7

A recent study of over 2,000 metagenomic DNA samples sequenced from marine environments revealed that over 50% of distinct gene clusters were fungal (Cardoso et al., 2020; Laiolo et al., 2024; Ribeiro et al., 2022). In estuarine and coastal environments anti-fungal residues from human and animal usage and crop applications may be at sufficient concentrations to select for resistance. However, our understanding of minimal selective concentrations of antifungals required to drive evolution of resistance is just emerging (Fig. 7; Stevenson et al., 2022). There are also health concerns around antifungal resistant fungal pathogens in wastewater inputs in coastal waters with the presence of *Aspergillus* and *Fusarium* isolates resistant to antifungals (Assress et al, 2020).

2.4.1.2. Harmful non-biological pollutants (Table 2)

2.4.1.2.1. Toxicity from chemical, particle and radiological contaminants

Non-biological pollutants in seafood can represent a serious health risk (Tacon et al., 2023). Although industrial production of potential toxic chemicals is estimated to be over 400,000 substances (https://www.cas.org/press-releases/common-chemistry): only a minimal number of these have been identified and quantified in the environmental matrices by national environmental agencies. Seafood animals accumulate chemicals from seawater, sediments and/or diet with different outcomes according to tissues and species. Specific classes of chemicals (e.g., persistent organic pollutants (POPs) and mercury) represent a higher risk for human consumption (Al-Sulaiti et al., 2022; See specific Subsections below).

Environmental pollutants can be classified according to the biological mechanisms leading to chronic rather than acute health conditions (Mezzelani & Regoli, 2022). Exposure over time to endocrine disruptors in seawater, sediments, aerosols and seafood can alter hormonal balance in both animals and people. Other chemicals can interact with several cellular receptors to alter biological pathways, including those of lipid metabolism with obesogenic effects. Carcinogenic substances can damage DNA following their biotransformation or through oxidative mechanisms with increased production of reactive oxygen species (ROS).

Particles (e.g. microplastics and nanoplastics) have been increasingly reported in all species of marine food webs and in human tissues (Vital et al 2021; Tan et al, 2023). Toxicological potential of micro- and nano-particles is inversely related to size, below 20 μm down to nanoscale, alterations of immune system, inflammation, decreased growth rate, and energy imbalance have been reported (Nardi et al., 2024).

Radioactive contaminants in seafood might potentially affect human health because of the intrinsic long-termrisk potential of radiation to cause mutations and an increased risk of cancer (Smith et al., 2023).

2.4.1.2.2. Metals

Many metals and metalloids can impact health of both aquatic organisms and humans, therefore

maximum permissible concentrations in fish and shellfish exist for mercury (Hg), arsenic (As; metalloid), cadmium (Cd) and lead (Pb) (EC, 2023; Raj & Das, 2023).

The main ocean-related toxicity of mercury derives from its bacterial methylation to MeHg, rapidly accumulated and biomagnified, and accounting for up to 100% of total mercury in seafood. MeHg is neurotoxic for the developing nervous systems, and dietary guidelines have been provided for a safe fish consumption by pregnant women (US-EPA & FDA, 2024). Long-term exposure to cadmium (Cd) results in renal dysfunction, osteoporosis and some cancers in humans (Satarug et al., 2017). Humans can be exposed to arsenic through the consumption of fish contaminated with arsenic. However, non-toxic organic species of arsenic are believed to be the dominant form of arsenic in fish and shellfish, although other organic metabolites produced by gut mictobes may be more toxic (Chandel et al., 2024).

~~**Consequently, there are increasing health risks from endocrine disruptors by being exposed to concentrated emerging chemicals through the consumption of contaminated seafood (Alvarez-Muñoz et al., 2018; Landrigan et al., 2020).**~~

2.4.1.2.3. Petrochemicals & combustion products

Petrochemical and combustion products such as polycyclic aromatic hydrocarbons (PAHs) are ubiquitous substances in the marine environment (Hassaan et al., 2024; Landrigan et al., 2020; Montuori et al., 2021; Speight, 2019). Contamination problems are due to human activities such as petroleum extraction, transport, shipping, chemical transformation and their use (International Energy Agency - IEA, 2018; Rovira et al., 2021; UNEP/RAMOGE, 1999; **S5A.C3b**). .

Petrochemical and PAH combustion product contamination may be used to evaluate risk for human health from exposure to petrochemicals and combustion processes (Long et al., 1995; Ma et al., 2017; Montuori et al., 2021; Nourian et al., 2024). However, the risk related to these products should be considered as a component of the general evaluation of human health risk due to the mixture of contaminants present in a particular marine environment, along with other factors such as climate change (see Pollutant interactions, *2.4.1.2.10*).

2.4.1.2.4. Persistent organic pollutants

Persistent organic pollutants (POPs) are hazardous chemicals that threaten human health and ecosystems (e.g., polychlorinated biphenls; Ritter et al., 1995; Stockholm Convention – pops.int). POPs remain intact for a long time, are widely distributed throughout the environment, bioaccumulate and biomagnify in living organisms through the food chain, and are toxic to both humans and wildlife (S4.C6.sub5). Furthermore, as a result of releases to the environment over the past several decades due to human activities, POPs are now widely distributed over large regions. This extensive contamination of both the environment and living organisms includes many foodstuffs, resulting in sustained exposure of many species (including humans) for periods of time

that span generations, leading to both acute and chronic health effects.

2.4.1.2.5. Neurotoxic pesticides and agrochemicals

Wastewater and land runoff of the most common insecticides, herbicides, fungicides and rodenticides represent a significant environmental and health threat because the same molecular targets attacked in pests are also present in other species, including diverse marine life and humans (Richardson et al., 2019). Neurotoxic effects in humans are supported by their detection in brains of patients affected by Alzheimer's and Parkinson's disease (Paul et al., 2024). Acaracides, such as rotenone and pyridaben can cause human neurological disorders, including the possible pathogenesis of Parkinson's disease.

2.4.1.2.6. Pharmaceuticals and endocrine disruptors

Over 2000 active pharmaceutical ingredients (APIs) are approved for use around the globe. APIs which can be released to the environment during their production, patient and veterinary use, and their ultimate disposal.

Monitoring of APIs in the marine environment has been done in North America, Asia, Africa, Europe, Latin America and Antarctica (UBA, 2024). Substances detected in seawater and, estuarine waters, including compounds from analgesic, antibiotic, antidepressant, anti-inflammatory, β-blocker, estrogen, and lipid lowering agent classes (UBA, 2024). Concentrations in water are typically in the low ng/L range or below (UBA, 2024; Leonard et al., 2020; Section *2.4.1.1.5*).

Monitoring of fish and shellfish demonstrates that many of these APIs are taken up by these organisms and potentially enter the food chain, therefore human exposure is possible (Madikezela and Ncube, 2022). Assessments have estimated the toxicological risks of seafood contamination to human health; these indicate that, in some instances, concentrations of APIs are at levels that might cause harm to humans (Fehrenbach et al., 2022).

Consequently, there are increasing health risks from endocrine disruptors by being exposed to concentrated emerging chemicals through the consumption of contaminated seafood (Alvarez-Muñoz et al., 2018; Landrigan et al., 2020).

2.4.1.2.7. Contaminants of emergent concern

Emerging contaminants in marine environments (e.g. detergents, personal care products [PCPs], per- and polyfluoroalkyl substances [PFAS - "Forever Chemicals"; Fig. 8], and plastic additives pose significant threats to marine organisms and human health (Combi et al., 2022; Guo et al., 2023). PCPs (including triclosan, UV blockers, parabens, and oxybenzone) are commonly found in sunscreens, shampoos and lotions (Chakraborty et al., 2023; Pironti et al., 2021; Vuckovic et al., 2022; Xue et al., 2017).

Flame retardants and plastic additives are widespread in the ocean; and can cause reproductive

and gender abnormalities in marine life due to their endocrine-disrupting properties (Cocchetti et al., 2022; Liu et al., 2023; Xie et al., 2022).

INSERT Fig. 8

PFAS are ubiquitous in coastal waters and are bioaccumulated in the human seafood chain (~~Fig. 9;~~ Sonne et al., 2023). Exposure to all pollutants is particularly concerning for Indigenous Peoples and other coastal communities with high seafood diets: they face significant health risks, including immune suppression as identified by the European Food Safety Authority (Fig. 8; Bilela et al., 2023; Chen et al., 2023; Ford & Ginley, 2024).

2.4.1.2.8. Micro-/ nanoparticles (including plastics) and from road runoff

Nanotechnology is generating increasing amounts of nanomaterials that enter the marine environment (Gonçalves & Bebianno, 2021). Other nano- and micromaterials are generated by various combustion and frictional processes: of particular concern is what is known as "hidden plastics" (Mayer et al., 2024). These nano- and microplastics are produced by frictional and partial combustion of vehicle tyres/tires. Tyres are approximately 25% plastic and tyre dust contributes to particulate air pollution and road runoff draining into marine environments and comprises approximately 28% of all nano-/microplastic pollution (Fig. 9; Mayer et al., 2024; Obanya et al., 2024; Sieber at al., 2022).

INSERT Fig. 9

Evidence for harmful human health effects of these particles, as well as other various nanoparticles (NPs), is growing rapidly, with ingested and inhaled particles finding their way into most human organ systems as well as emerging evidence for endocrine-disrupting effects (Fig. 10; Leso et al., 2023; Wang et al., 2024; Yee et al., 2021). Routes of particle uptake include consumption of seafood and inhalation/ingestion of NPs in marine aerosols (i.e., sea spray) (Fig. 2 & 10; Lambert et al., 2024; Luo et al., 2025; Patil et al., 2022; Li & Liu, 2024).

INSERT Fig. 10

Micro-/nanoplastics (MPs & NPs) serve as transport vectors for many chemical additives and adsorbed chemicals in the ocean which are persistent, bioaccumulative, mobile, and toxic to the marine fish and other organisms (Amelia et al., 2021; Andrade et al., 2021). Consequently, NPs and MPs, chemical additives and adsorbed chemicals (e.g., polycyclic aromatic hydrocarbons) can lead to potential adverse health effects in marine organisms and humans (Aatmeeyata, 2010; Megha et al., 2024).

A new issue of health concern is the presence of micro- and nanofibres of glass in edible filter-feeding molluscs from degradation of fibreglass hulls of boats, including derelict boats (Ciocan et

al., 2024).

2.4.1.2.9. Environmental radiation

Along with other contaminants, the seas and global ocean are the ultimate recipient of anthropogenic radionuclides. For example, 5.9 x 10^{18} Bq of tritium, is discharged in quantities much larger than any other radionuclide (Fig. 2; Ferreira et al., 2023, 2024; Matsumoto et al., 2021). 90% of this radionuclide is present in the oceans compared to 9% and 1% in continental waters and atmosphere respectively. In this context, the Pacific Ocean currently contains 500,000 TBq of natural and 2,500,000 TBq of anthropogenic tritium, the latter mostly from past atmospheric nuclear weapon testing (Smith et al., 2023).

~~Concerns arising after the Fukushima (Japan) nuclear power accident in 2011 revealed that exposure levels in marine organisms were too low to cause adverse effects. However, levels slightly above the regulatory limits were occasionally found in some species close to the plant, although to date radioactivity in seafood outside this area has been below any public health concern (Smith et al., 2023).~~

~~According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), DNA is the most important target for the action of ionising radiations. Damage to DNA, if not repaired, is the ultimate cause of many cancers and is associated with many other harmful health impacts. Exposure to radionuclides through different routes (e.g., consumption of seafood, inhalation, or skin penetration), therefore, poses health risks (Matsumoto et al., 2021). To protect human health, biokinetic models have been developed for specific radionuclides, within specific organs. Data from biokinetic models are then used to calculate absorbed radiation doses and potential biological effects for each target organ (Paquet et al., 2017).~~

~~Concerns arising after the Fukushima (Japan) nuclear power accident in 2011 revealed that exposure levels in marine organisms were too low to cause adverse health effects (Japan's Discharge of ALPS Treated Water in Line with International Safety Standards, New IAEA Task Force Report Confirms | IAEA). However, levels slightly above the international regulatory limits were occasionally found in some species close to the plant, although to date radioactivity in seafood outside this area has been below any public health concern (Smith et al., 2023). There are however many unresolved issues in relation to potential short- and long-term impact related to controlled release of radioactive water following the Fukushima Daiichi nuclear accident (Ferreira et al., 2024).~~

~~According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), DNA is the most important target for the action of ionising radiations. Damage to DNA, if not repaired, is the ultimate cause of many cancers and is associated with many other harmful health impacts. Exposure to radionuclides through different routes (e.g., consumption of seafood, inhalation, or skin penetration), therefore, poses health risks (Matsumoto et al., 2021). To protect human health, biokinetic models have~~

~~been developed for specific radionuclides, within specific organs. Data from biokinetic models are then used to calculate absorbed radiation doses and potential biological effects for each target organ (Paquet et al., 2017). It is being emphasized that in order to minimise presence of hazardous wastes, UN Sustainable Development Goals (SDG) 12 and environmental sound technologies, SDG 17 should be redefined to include radioactive wastes (Wimmers & von Hirschhausen, 2024; Wimmers et al., 2023).~~

Concerns arising after the Fukushima (Japan) nuclear power accident in 2011 revealed that exposure levels in marine organisms were too low to cause adverse health effects (Japan's Discharge of ALPS Treated Water in Line with International Safety Standards (IAEA, 2023). However, levels slightly above the international regulatory limits were occasionally found in some species close to the plant, although to date radioactivity in seafood outside this area has been below any public health concern (Smith et al., 2023). There are however many unresolved issues in relation to potential short- and long-term impact related to controlled release of radioactive water following the Fukushima Daiichi nuclear accident (Ferreira et al., 2024).

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), DNA is the most important target for the action of ionising radiations. Damage to DNA, if not repaired, is the ultimate cause of many cancers and is associated with many other harmful health impacts. Exposure to radionuclides through different routes (e.g., consumption of seafood, inhalation, or skin penetration), therefore, poses health risks (Matsumoto et al., 2021). To protect human health, biokinetic models have been developed for specific radionuclides, within specific organs. Data from biokinetic models are then used to calculate absorbed radiation doses and potential biological effects for each target organ (Paquet et al., 2017). It is being emphasized that in order to minimise presence of hazardous wastes, UN Sustainable Development Goals (SDG) 12 and environmental sound technologies, SDG 17 should be redefined to include radioactive wastes (Wimmers & von Hirschhausen, 2024; Wimmers et al., 2023).

2.4.1.2.10. Pollutant interactions

It is now well established that biological effects of environmental contaminants are due to their cumulative actions (Bopp et al., 2018; Kienzler et al., 2016). The toxic effects of contaminants present in a mixture may be additive, and even in some cases antagonistic (Forest, 2021; Moore et al., 2021); however, synergistic effects of toxic chemicals are also well demonstrated (Albani et al., 2023; Gauthier et al., 2014; Martin, 2023; Moore et al., 2018). Obviously, there is a clear need to estimate risk for human health from marine pollution that ~~takes into account~~considers all available chemical data in terms of contaminant concentrations in waters, sediments, aerosol and seafood. It is important to evaluate biological effects of contaminants on seafood organisms exposed to all bioavailable contaminants (Dagnino and Viarengo, 2014; Davies and Vethaak, 2012; Viarengo et. 2008) to gain a more complete overview of toxicity and risk.

2.5. Key Remaining Knowledge and Capacity-Building Gaps

There clearly remain many unknowns in the field of human health-marine environmental interactions (Fig.1). However, there is considerable evidence for research progress and a better understanding of the many and often interconnected areas of interest to scientists and regulators (Fig. 11).

INSERT Fig. 11

Continuing emphasis should be placed on the following key problem areas and issues of emerging concern given the socio-economic importance of environmental interactions with human health:

1. **Current lack of an effective International Interdisciplinary Panel/Forum that includes environmental epidemiologists; public health, biomedical and environmental scientists; clinicians, environmental psychologists, lawyers and economists; marine ecologists and oceanographers, as well as environmental regulators and managers;**
2. "The High Level Ocean Panel for a Sustainable Ocean Economy " https://oceanpanel.org has created many reports on various aspects related to human health; but only one specific report (https://oceanpanel.org/ publication/ocean-human-health/);
3. Important to start linking human health and wellbeing indicators with ocean "health" indicators, and exploring long term impacts (risks and benefits) of changing ocean health on human health; and recommended in the Ocean Panel OHH Report (https://oceanpanel.org/publication/ocean-human-health/) as one of 3 major recommendations;
4. ~~An explicit transdisciplinary framework has been proposed by Everaert et al. (2025) to accelerate research on Ocean–Human Health Connections: this could help to form the basis of an OHH Forum;~~
5. Recognition that actions intended to ameliorate risk from particular factors may have unintended adverse consequences for ecosystems and human health;
6. **The evidence indicates that pollution is causing serious health issues, so why are many national authorities not taking action to protect people?;**
7. Promotion of sustainable and equitable use of decreasing marine resources as a result of increasing population and demand;
8. Recognition of the benefits of increasing interdisciplinary research efforts into Oceans and Human Health;
9. **Suggest effective monitoring and quantitative assessment (where possible) of risks and benefits of interlinked human and ocean health;**
10. **Try to ensure data are truly available and transparent for use by communities and others;**
11. Increase sustainable and equitable efforts to identify potential marine pharmaceuticals and other natural products;

12. **Try to ensure seafood monitoring programmes are effective and up to date for biotoxins, pollutant chemicals and micro-/nanomaterials;**
13. Suggest increasing efforts to reduce impact of antimicrobial/antifungal resistance in relation to seafood and aquatic systems;
14. Aim to end microbial, chemical (including pharmaceuticals) and particulate pollution of the oceans;
15. Suggest support for a global ban on production of single-use plastic and promote effective plastic waste management;
16. **Recognise that unpredictable emergent Future Health Challenges will occur;**
17. Recognise that climate change will result in the geographical redistribution of human pathogens; and that enhanced storm-related disturbance of coastal sediments, and erosion of nearshore landfill sites, will release chemical pollutants and other types of waste;
18. Recognise the importance of serendipity in scientific discovery, such as production of "dark" oxygen from seafloor metal-rich nodules (Sweetman et al., 2024); possible role of algal toxins in inhaled/ingested sea spray aerosols having a beneficial health effect (Van Acker et al., 2021); and role of environmental endocrine disrupters in gender dysphoria (Cocchetti et al., 2022);
19. Recognise the benefits of developing an integrated modelling capacity for predicting environmental impacts on human health (Allen, 2011; Moore et al., 2014);
20. **Suggest extending regional and international marine pollution control programmes to all countries.**

2.6. Conclusions & Vision

The global Ocean provides humans with many benefits including production of healthy seafood. The marine environment can also be the source of potential health benefits by providing novel pharmaceuticals and related natural products derived from marine organisms, as well as contributing to disease prevention and treatments through encouraging physical activity and enhancing psychological wellbeing (Table 1).

The complexity of ocean-human interactions is increasing, with mixed exposures from contaminated environments to harmful algal toxins, pathogenic bacteria and viruses, anthropogenic (man-made) chemicals (including micro-/nanoplastics), as well as other types of pollution. Untangling relative contributions and interactions of these stressors is challenging, particularly when coupled with climate change, biodiversity loss and ecosystem degradation of the Global Ocean (Table 2; Figs. 1, 12; Allen, 2011).

INSERT Fig. 12

It is crucial that all of these stressors be considered in depth globally to understand the complexity

of interactions between the Ocean and Human Health (see Figs.1, 2, 12). At its core, there must be a well thought out and clearly articulated vision of what would be an acceptable relationship between humans and the Oceans in the future. This means accepting and embracing that the current and future state of the Global Ocean will in large part determine current and future sustainability, health and well-being of all humans on Earth.

~~**To achieve the above-mentioned goals, consideration should be given to establishing an International Interdisciplinary Forum, perhaps under the auspices of the United Nations. Such a Forum could prioritise:**~~

Attainment of such a vision requires an appropriate International Interdisciplinary Forum or Panel. However, a one-off report on ocean and human health from "The High Level Panel for a Sustainable Ocean Economy (Ocean Panel)" could provide the example for a potential way forward (https://oceanpanel.org/publication/ocean-human-health/).

Such a Panel/Forum could prioritise:

1. Failure of numerous international agreements to prevent progressive loss of marine biodiversity and collapse of several marine ecosystems with implications for human health, and explore strategies to reverse this situation;
2. **Effective protection of coastal communities from natural threats including flooding and tsunamis/hurricanes;**
3. **Knowledge of interactions between natural and anthropogenic stressors that impact ocean and human health;**
4. **Most issues are associated with both benefits and threats – it often depends on the context as to whether we sacrifice a benefit to remove a threat or accept a threat to gain a benefit: who then decides and on what basis?;**
5. **Awareness of health professionals and documentation of environmentally related illnesses;**
6. **Exploring potential unique medicines and other natural marine products, while ensuring a sustainable use and protection of marine life and habitats (Papon et al., 2022);**
7. **Developing an integrated modelling capacity for predicting environmental impacts on human health (Figs. 11 & 12; Allen, 2011; Moore et al., 2014).**

Acknowledgements: **The authors wish to thank Professor Ralf Ebinghaus (Germany, POE member) and Professor Michael Depledge (UK) for their insightful and very helpful comments during the preparation of this chapter.**

References

Aatmeeyata, SM (2010). Polycyclic aromatic hydrocarbons, elemental and organic carbon emissions from tire-wear. Sci Total Environ. 2010 Sep 15;408(20):4563-8. doi: 10.1016/j.scitotenv.2010.06.011. Epub 2010 Jul 10. PMID: 20624631.

Abdel-Shafy, H.I., Mansour, M.S.M., 2016. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egypt. J. Pet. 25, 107-123.

Adeniji, A.O., Okoh, O.O. & Okoh, A.I., 2019. Distribution pattern and health risk assessment of polycyclic aromatic hydrocarbons in the water and sediment of Algoa Bay, South Africa. Environ Geochem Health 41, 1303-1320.

Adhikari PL, Maiti K, Overton EB, Rosenheim BE, Marx BD., 2016. Distributions and accumulation rates of polycyclic aromatic hydrocarbons in the northern Gulf of Mexico sediments. Environ Pollut. 212, 413-423.

Albani G, Asiedu D, Abrokwah S, Jónasdóttir SH, Nielsen TG, Acheampong E, Ruiz LH, Ekumah B, Koski M., 2023. Synergistic and additive effects of microplastic, nickel and pyrene on survival, reproduction, and egestion of a tropical copepod. Aquat Toxicol. 265, 106737.

Allen JI, 2011. Marine Environment and Human health: An Overview In: Environmental Science and Technology, 33 Marine Pollution and Human Health, pp. 1-24 (Eds.R.E. Hester and R.M. Harrison). Royal Society of Chemistry, 2011.

Al-Sulaiti M.M., Soubra L., Al-Ghouti M.A. (2022). The Causes and Effects of Mercury and Methylmercury Contamination in the Marine Environment: A Review. Current Pollution Reports, 8:249–272, https://doi.org/10.1007/s40726-022-00226-7

Alvarez-Muñoz, D., Rodríguez-Mozaz, S., Jacobs, S., Serra-Compte, A., Cáceres, N., Sioen, I., Verbeke, W., Barbosa, V., Ferrari, F., Fernández-Tejedor, M., Cunha, S., Granby, K., Robbens, J., Kotterman, M., Marques, A., Barceló, D., 2018. Pharmaceuticals and endocrine disruptors in raw and cooked seafood from European market: Concentrations and human exposure levels. Environment International 119, 570-581.

Amelia, T.S.M., Khalik, W., Ong, M.C., Shao, Y.T., Pan, H.J., Bhubalan, K., 2021. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. Progress in Earth and Planetary Science 8.

American Academy of Allergy Asthma and Immnology, 2024 Histamine Toxicity Symptoms, Diagnosis, Treatment & Management (aaaai.org). Updated 2024. Accessed 7-1-24.

Andrade, H., Glüge, J., Herzke, D., Ashta, N.M., Nayagar, S.M., Scheringer, M., 2021. Oceanic long-range transport of organic additives present in plastic products: an overview. Environmental Sciences Europe 33.

Ansdell, V., 2019. 49 - Seafood Poisoning, In: Travel Medicine (Fourth Edition), Editor(s): Jay S. Keystone, Phyllis E. Kozarsky, Bradley A. Connor, Hans D. Nothdurft, Marc Mendelson, Karin Leder, pp. 449-456, Elsevier. doi.org/10.1016/B978-0-323-54696-6.00049-5.

Añibarro B, Feijoo L, de Las Cuevas N, Seoane FJ. Occupational asthma induced by fish exposure. Occup Med (Lond). 2023 Dec 30;73(9):581-583. doi: 10.1093/occmed/kqad127. PMID: 38016183.

Antunes C, Aleem A, Curtis SA. Gastroesophageal Reflux Disease. 2023 Jul 3. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan–. PMID: 28722967.

Archer EJ, Baker-Austin C, Osborn TJ, Jones NR, Martínez-Urtaza J, Trinanes J, Oliver JD, González FJC, Lake IR. Climate warming and increasing Vibrio vulnificus infections in North America. Sci Rep. 2023 Mar 23;13(1):3893. doi: 10.1038/s41598-023-28247-2.

Assress, H.A., Nyoni, H., Mamba, B.B. and Msagati, T.A., 2020. Occurrence and risk assessment of azole antifungal drugs in water and wastewater. Ecotoxicology and environmental safety, *187*, p.109868.

Atlas, E., Giam, C.S., 1981. Global transport of organic pollutants: ambient concentrations in the remote marine atmosphere. Science. 211(4478),163-165.

Ausili A., Gabellini M., Cammarata G., Fattorini D., Benedetti M., Pisanelli B, Gorbi S., Regoli F. (2008). Ecotoxicological and human health risk in a petrochemical district of southern Italy. Mar. Environ. Res. 66, 215–217, https://doi.org/10.1016/j.marenvres.2008.02.062

Backer, LC, Schurz-Rogers, H, Fleming, LE, Kirkpatrick, B, Benson, J, 2004. Marine phycotoxins in seafood. In: Toxins in Food (Eds. Waldemar M. Dabrowski, Zdzislaw E. Sikorski), pp. 155-190. CRC Press, Boca Raton, 376p.

Baker-Austin C, Lake I, Archer E, Hartnell R, Trinanes J, Martinez-Urtaza J. Stemming the rising tide of Vibrio disease. Lancet Planet Health. 2024 Jul;8(7):e515-e520. doi: 10.1016/S2542-5196(24)00124-4. PMID: 38969478.

Ban, N.C., Gurney, G.G., Marshall, N.A. et al. Well-being outcomes of marine protected areas. Nat Sustain 2, 524–532 (2019). https://doi.org/10.1038/s41893-019-0306-2.

Barakat, A. O., Mostafa, A., Wade, T. L., Sweet, S. T., El Sayed, N., 2011. Distribution and characteristics of PAHs in sediments from the Mediterranean coastal environment of Egypt. Mar. Pollut. Bull. 62, 1969-1978.

Baumard, P., Budzinski H., Michon, Q., et al., 1998. Origin and Bioavailability of PAHs in the Mediterranean Sea from Mussel and Sediment Records. Estuar. Coast. Shelf Sci. 47(1), 77-90.

Bellinger D.C. (2008). Very low lead exposures and children's neurodevelopment. Curr. Opin.

Pediatr. 20, 172–177. https://doi.org/10.1097/MOP.0b013e3282f4f97b

Benedetti M., Giuliani M.E., Regoli F. (2015). Oxidative metabolism of chemical pollutants in marine organisms: Molecular and biochemical biomarkers in environmental toxicology. Annals of the New York Academy of Sciences, 1340 8 – 19, https://doi.org/10.1111/nyas.12698

Berdalet, E., Fleming, L. E., Gowen, R., Davidson, K., Hess, P., Backer, L. C., Moore, S. K., Enevoldsen, H., Hoagland, P. (2016) Marine Harmful Algal Blooms, Human Health and Wellbeing: challenges and opportunities in the 21st century. Journal of the Marine Biology Association of the United Kingdom, 96 (Special Issue 01): 61-96, doi:10.1017/S0025315415001733

Berdalet, E., Pavaux, A.-S, Abós-Herràndiz, R., Travers, M., Appéré, G., Vila, M., Thomas, J., de Haro, L., Estrada, M., Medina-Pérez, N.-I., Viure, L., Karlson, B., Lemée, R. (2022). Environmental, human health and socioeconomic impacts of *Ostreopsis* spp. blooms in the NW Mediterranean. Harmful Algae 119, 102320. https://doi.org/10.

Berdalet, E, Chinain, M, Kirkpatrick, B, Tester, PA, 2023. Harmful algal blooms cause ocean illnesses affecting human health. In: Oceans and Human Health: Opportunities and Impacts, second edition (Eds. Fleming L, Creencia LA, Gerwick WH, Goh HC, Gribble MO, Maycock B, Solo-Gabriele H), Cambridge: Academic Press, 2023. doi.org/10.1016/B978-0-323-95227-9.09990-5.

Bergamasco, A., Culotta, L., De Stefano, C., Orecchio, S., Sammartano, S., Barreca, S., 2014. Composition, Distribution, and Sources of Polycyclic Aromatic Hydrocarbons in Sediments of the Gulf of Milazzo (Mediterranean Sea, Italy). Polycyclic Aromatic Compounds 34(4), 397-424.

Bilela, L.L., Matijosyte, I., Krutkevicius, J., Alexandrino, D.A.M., Safarik, I., Burlakovs, J., Gaudencio, S.P., Carvalho, M.F., 2023. Impact of per- and polyfluorinated alkyl substances (PFAS) on the marine environment: Raising awareness, challenges, legislation, and mitigation approaches under the One Health concept. Marine Pollution Bulletin 194.

Boonyatumanond R, Wattayakorn G, Togo A, Takada H., 2006. Distribution and origins of polycyclic aromatic hydrocarbons (PAHs) in riverine, estuarine, and marine sediments in Thailand. Mar Pollut Bull. 52, 942-956.

Bopp SK, Barouki R, Brack W, Dalla Costa S, Dorne JCM, Drakvik PE, Faust M, Karjalainen TK, Kephalopoulos S, van Klaveren J, Kolossa-Gehring M, Kortenkamp A, Lebret E, Lettieri T, Nørager S, Rüegg J, Tarazona JV, Trier X, van de Water B, van Gils J, Bergman Å., 2018. Current EU research activities on combined exposure to multiple chemicals. Environ Int. 120, 544-562.

Bouley, TA, Machalaba, C, Keast, J, Gerwick, WH, Fleming, LE 2023. Chapter 6 - Marine biotechnology: A One Health approach to linking life on land to life underwater. In: Oceans and Human Health (Second Edition), Editor(s): Lora E. Fleming, Lota B. Alcantara Creencia, William H. Gerwick, Hong Ching Goh, Matthew O. Gribble, Bruce Maycock, Helena Solo-Gabriele. Academic Press, pp. 149-180. doi.org/10.1016/B978-0-323-95227-9.00024-5.

Bowley, J., Baker-Austin, C., Porter, A., Hartnell, R., Lewis, C., 2021. Oceanic hitchhikers–assessing pathogen risks from marine microplastic. Trends in microbiology, 29(2), pp.107-116. doi.org/10.1016/j.tim.2020.06.011

Campos, C.J., Lees, D.N., 2014. Environmental transmission of human noroviruses in shellfish waters. Applied and environmental microbiology, 80(12), 3552-3561. doi.org/10.1128/AEM.04188-13

Cardoso J, Nakayama DG, Sousa E, Pinto E. Marine-Derived Compounds and Prospects for Their Antifungal Application. Molecules. 2020 Dec 11;25(24):5856. doi: 10.3390/molecules25245856. PMID: 33322412; PMCID: PMC7763435.

Carvalho RN, Arukwe A, Ait-Aissa S, Bado-Nilles A, Balzamo S, Baun A, Belkin S, Blaha L, Brion F, Conti D, Creusot N, Essig Y, Ferrero VE, Flander-Putrle V, Fürhacker M, Grillari-Voglauer R, Hogstrand C, Jonáš A, Kharlyngdoh JB, Loos R, Lundebye AK, Modig C, Olsson PE, Pillai S, Polak N, Potalivo M, Sanchez W, Schifferli A, Schirmer K, Sforzini S, Stürzenbaum SR, Søfteland L, Turk V, Viarengo A, Werner I, Yagur-Kroll S, Zounková R, Lettieri T., 2014. Mixtures of chemical pollutants at European legislation safety concentrations: how safe are they? Toxicol Sci. 141, 218-233.

Castro-Jiménez, J., Berrojalbiz, N., Wollgast, J., Dachs, J., 2012. Polycyclic aromatic hydrocarbons (PAHs) in the Mediterranean Sea: atmospheric occurrence, deposition and decoupling with settling fluxes in the water column. Environ. Pollut. 166, 40-47.

Chakraborty, A., Adhikary, S., Bhattacharya, S., Dutta, S., Chatterjee, S., Banerjee, D., Ganguly, A., Rajak, P., 2023. Pharmaceuticals and Personal Care Products as Emerging Environmental Contaminants: Prevalence, Toxicity, and Remedial Approaches. Acs Chemical Health & Safety 30, 362-388.

Chandel M, Sharma AK, Thakur K et al., 2024. Poison in the water: Arsenic's silent assault on fish health. J Appl Toxicol 44:1282–1301

CHEMnetBASE 2023. RGL22-0697 (taylorandfrancis.com).

Chen F, Lin Y, Cai M, Zhang J, Zhang Y, Kuang W, Liu L, Huang P, Ke H., 2018. Occurrence and Risk Assessment of PAHs in Surface Sediments from Western Arctic and Subarctic Oceans. Int J Environ Res Public Health. 15, 734.Cedergreen N., 2014. Quantifying synergy: a systematic review of mixture toxicity studies within environmental toxicology. PLoS One. 9(5):e96580.

Chen, Z.W., Zhan, X.Y., Zhang, J.R., Diao, J.Y., Su, C.H., Sun, Q.P., Zhou, Y.Q., Zhang, L.L., Bi, R., Ye, M., Wang, T.Y., 2023. Bioaccumulation and risk mitigation of legacy and novel perfluoroalkyl substances in seafood: Insights from trophic transfer and cooking method. Environment International 177.

Chinain, M., Gatti, C. M. i., Darius, H. T., Quod, J.-P., Tester, P. A. (2021). Ciguatera poisonings: a global review of occurrences and trends. Harmful Algae 102, https://doi.org/10.1016/j.hal.2020.101873.

Ciocan C, Annels C, Fitzpatrick M, Couceiro F, Steyl I, Bray S. Glass reinforced plastic (GRP) boats and the impact on coastal environment – Evidence of fibreglass ingestion by marine bivalves from natural populations. Journal of Hazardous Materials, 472, 2024, 134619, https://doi.org/10.1016/j.jhazmat.2024.134619.

Cocchetti, C., Rachoń, D., Fisher, A.D. (2022). Environmental Impact on Sexual Response. In: Pivonello, R., Diamanti-Kandarakis, E. (eds) Environmental Endocrinology and Endocrine Disruptors. Endocrinology. Springer, Cham. https://doi.org/10.1007/978-3-030-38366-4_11-1

Combi, T., Montone, R.C., Corada-Fernández, C., Lara-Martín, P.A., Gusmao, J.B., Santos, M.C.D., 2022. Persistent organic pollutants and contaminants of emerging concern in spinner dolphins (Stenella longirostris) from the Western Atlantic Ocean. Marine Pollution Bulletin 174.

Corminboeuf A, Montero-Serrano JC, St-Louis R., 2021. Spatial and temporal distributions of polycyclic aromatic hydrocarbons in sediments from the Canadian Arctic Archipelago. Mar Pollut Bull. 171, 112729.

Cosby, A.G., Lebakula, V., Smith, C.N. *et al.*, 2024. Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. *Sci Rep* **14**, 22489 (2024). https://doi.org/10.1038/s41598-024-73287-x

Dagnino A, Viarengo A., 2014. Development of a decision support system to manage contamination in marine ecosystems. Sci Total Environ. 466-467, 119-126.

Das, J, (2023). Blue Economy, Blue Growth, Social Equity and Small-scale Fisheries: A Global and National Level Review. Studies in Social Science Research. 4. p38. 10.22158/sssr.v4n1p38.

Davies I. M., Vethaak, D., 2012. Integrated marine environmental monitoring of chemicals and their effects. ICES Cooperative Research Reports (CRR).de Almeida M, do Nascimento DV, de Oliveira Mafalda P Jr, Patire VF, de Albergaria-Barbosa ACR., 2018. Distribution and sources of polycyclic aromatic hydrocarbons (PAHs) in surface sediments of a Tropical Bay influenced by anthropogenic activities (Todos os Santos Bay, BA, Brazil). Mar Pollut Bull. 137,399-407.

Depledge MH. 2024 Re thinking human interactions with the oceans. R. Soc. Open Sci. 11: 240808. https://doi.org/10.1098/rsos.240808

Depledge MH, Bird WJ (2009) The blue gym: health and wellbeing from our coasts. Mar Pollut Bull 58:947–948 https://doi.org/10.1016/j.marpolbul.2009.04.01

Dhananjayan, V., Muralidharan, S., Peter, V. R., 2012. Occurrence and distribution of polycyclic aromatic hydrocarbons in water and sediment collected along the Harbour Line, Mumbai, India. International Journal of Oceanography 2012, 403615.

Dias DA, Urban S, Roessner UL: A historical overview of natural products in drug discovery, *Metabolites* 2(2):303-36, 2012. doi: 10.3390/metabo2020303. PMID: 24957513; PMCID: PMC3901206.

Dodd R, Reeve E, Sparks E, George, A, Vivili, P, Tin, STW, Buresova, D, Webster, J, Thow, A-M, 2020. The politics of food in the Pacific: coherence and tension in regional policies on nutrition, the food environment and non-communicable diseases. Public Health Nutrition, 23(1), 168-180. doi:10.1017/S1368980019002118

Dong CD, Chen CF, Chen CW., 2012. Determination of polycyclic aromatic hydrocarbons in industrial harbor sediments by GC-MS. Int J Environ Res Public Health. 9, 2175-2188.

Dudhagara DR, Rajpara RK, Bhatt JK, Gosai HB, Sachaniya BK, Dave BP., 2016. Distribution, sources and ecological risk assessment of PAHs in historically contaminated surface sediments at Bhavnagar coast, Gujarat, India. Environ Pollut. 213, 338–346.

EC (2023). European Union Commission Regulation 2023/915 on Maximum levels for certain contaminants in food. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32023R0915

El-Maradny A, Radwan IM, Amer M, Fahmy MA, Mohamed LA, Ibrahim MIA, 2023. Spatial distribution, sources and risk assessment of polycyclic aromatic hydrocarbons in the surficial sediments of the Egyptian Mediterranean coast. Mar Pollut Bull. 188, 114658.

El-Maradny, A., Ibrahim, M.I.A., Radwan, I.M. et al., 2022. Horizontal and vertical segregation of polycyclic aromatic hydrocarbons in the Egyptian Mediterranean coast. Environ Sci Pollut Res 29, 86707-86721.

European Environment Agency, 2023; Emerging chemical risks in Europe — 'PFAS'; Emerging chemical risks in Europe — 'PFAS' — European Environment Agency (europa.eu)

Everaert G, Aerts R, Bourgois JG, Buysse A, Covaci A, De Rijcke M, Diopere E, Hooyberg A, Lachat C, Lahousse L, Mees J, Michels N, Plusquin M, Raes F, Rappé K, Roose H, Severin M, Van Campenhout K, Vanhaecke L, Janssen C, Asselman J. Ocean for Health: A Transdisciplinary Framework to Accelerate Research on Ocean-Human Health Connections. Environ Sci Technol. 2025 Jul 1. doi: 10.1021/acs.est.5c05463. Epub ahead of print. PMID: 40592480.

FAO (2020). The State of World Fisheries and Aquaculture 2020 (fao.org)Umweltbundesamt (2024) Database- pharmaceuticals in the environment. https://www.umweltbundesamt.de/en/database-pharmaceuticals-in-the-environment-0#undefined

FAO (2022). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation.https:// openknowledge.fao.org/handle/20.500.14283/cc0461en.

Falkenberg LJ, Bellerby RGJ, Connell SD, Fleming LE, Maycock B, Russell BD, Sullivan FJ, Dupont S. Ocean Acidification and Human Health. Int J Environ Res Public Health. 2020 Jun 24;17(12):4563.

doi: 10.3390/ijerph17124563. PMID: 32599924; PMCID: PMC7344635.

Falkenberg, L.J. and Joyce, P.W., 2023. Internationalisation at Home: Developing a Global Change Biology Course Curriculum to Enhance Sustainable Development. Sustainability, 15(9), p.7509.

Fattorini D., Notti A., Regoli, F. (2006). Characterization of arsenic content in marine organisms from temperate, tropical, and polar environments. Chemistry and Ecology, 22(5), 405–414, https://doi.org/10.1080/02757540600917328

Fehrenbach G.W., Pogue R., Carter F., Clifford E., Rowan N. (2022) Implications for the seafood industry, consumers and the environment arising from contamination of shellfish with pharmaceuticals, plastics and potentially toxic elements: A case study from Irish waters with a global orientation. Sci Total Environ, 844:157067.

Ferreira MF, A Turner, AN Jha (2024) The controlled release of radioactive water from Fukushima Daiichi nuclear power plant: Should we be concerned? Environmental Science and Technology, 58, 4840−4843. https://doi.org/10.1021/acs.est.3c08702.

Ferreira MF, A Turner, EL Vernon, C Grisolia, L Lebaron-Jacobs, V Malard, AN Jha (2023) Tritium: Its relevance, sources and impacts on non-human biota. Sci Total Environ, 876, 162816*; http://dx.doi.org/10.1016/j.scitotenv.2023.162816.*

Fleming L, Creencia LA, Gerwick WH, Goh HC, Gribble MO, Maycock B, Solo-Gabriele H, 2023. Editors: Oceans and Human Health: Opportunities and Impacts, second edition. Cambridge: Academic Press, 2023. https://doi.org/10.1016/B978-0-323-95227-9.09990-5

Fleming, LE, Kirkpatrick, B, Backer, LC, Walsh, CJ, Nierenberg, K, Clark, J, Reich, A, Hollenbeck, J, Benson, J, Cheng, YS, Naar, J, Pierce, R, Bourdelais, AJ, Abraham, WM, Kirkpatrick, G, Zaias, J, Wanner, A, Mendes, E, Shalat, S, Hoagland, P, Stephan, W, Bean, J, Watkins, S, Clarke, T, Byrne, M, Baden, DG, 2011. Review of Florida red tide and human health effects. Harmful Algae, 10, I224-233. doi.org/10.1016/j.hal.2010.08.006.

Fleming LE, Landrigan PJ, Gerwick W, Heymans JJ, Hicks CC, Morrissey K, White MP, Alcantara-Creencia L, Alexander KA, Ashford OS, Astell-Burt T, Berlinck RGS, Cohen PJ, Hixson R, Islam MM, Iwasaki A, Praptiwi RA, Raps H, Remy JY, Sowman G, Swift A, Ternon E, Thiele T, Thilsted SH, Whitman EM, 2024. How can a healthy ocean improve human health and enhance wellbeing on a rapidly changing planet? Washington, DC: World Resources Institute (WRI). 2024. https://oceanpanel.org/publications/ocean-human-health/;

Fleming LE, Maycock B, White MP, Depledge MH. Fostering human health through ocean sustainability in the 21st century. People Nat. 2019;00:1–8. https://doi.org/10.1002/pan3.10038.

Ford AT, Ginley F, 2024. Insights into PFAS contaminants before and after sewage discharges into a marine protected harbour. Chemosphere. 2024 Oct 10:143526. doi: 10.1016/j.chemosphere.2024.143526. Epub ahead of print. PMID: 39395480.

Forest V., 2021. Combined effects of nanoparticles and other environmental contaminants on human health - an issue often overlooked. NanoImpact. 23, 100344.

Friedman MA, Fernandez M, Backer LC, Dickey RW, Bernstein J, Schrank K, Kibler S, Stephan W, Gribble MO, Bienfang P, Bowen RE, Degrasse S, Flores Quintana HA, Loeffler CR, Weisman R, Blythe D, Berdalet E, Ayyar R, Clarkson-Townsend D, Swajian K, Benner R, Brewer T, Fleming LE. An Updated Review of Ciguatera Fish Poisoning: Clinical, Epidemiological, Environmental, and Public Health Management. Mar Drugs. 2017 Mar 14;15(3):72. doi: 10.3390/md15030072.

Funari, E., Manganelli, M. and Testai, E., 2015. *Ostreopsis* cf. *ovata* blooms in coastal water: Italian guidelines to assess and manage the risk associated to bathing waters and recreational activities. Harmful Algae, 50, 45-56. doi.org/10.1016/j.hal.2015.10.008.

Garcia-Bustos, V., Acosta-Hernández, B., Cabañero-Navalón, M.D., Ruiz-Gaitán, A.C., Pemán, J. and Rosario Medina, I., 2024a. Potential Fungal Zoonotic Pathogens in Cetaceans: An Emerging Concern. *Microorganisms*, *12*(3), p.554.

Garcia-Bustos, V., 2024b. Is Candida auris the first multidrug-resistant fungal zoonosis emerging from climate change? *Mbio*, *15*(4), pp.e00146-24.

Gauthier PT, Norwood WP, Prepas EE, Pyle GG., 2014. Metal-PAH mixtures in the aquatic environment: a review of co-toxic mechanisms leading to more-than-additive outcomes. Aquat Toxicol. 154, 253-269.

Germond-Duret, C. (2022), Framing the Blue Economy: Placelessness, Development and Sustainability. Development and Change, 53, 308-334. https://doi.org/10.1111/dech.12703

GlobalHAB, 2017. Global Harmful Algal Blooms, Science and Implementation Plan. E. Berdalet et al. (eds.). SCOR and IOC, Delaware and Paris, 64 pp

Gnandi K, Musa Bandowe BA, Deheyn DD, Porrachia M, Kersten M, Wilcke W., 2011. Polycyclic aromatic hydrocarbons and trace metal contamination of coastal sediment and biota from Togo. J Environ Monit. 13, 2033-2041.

Gobler, C. J., Doherty, O.M., Hattenrath- Lehmann, T. K., Griffith, A. W., Kang, Y., Litaker, R. W., 2017.Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. Proceedings of the National Academy of Sciences of the USA 114 (19): www.pnas.org/cgi/doi/10. 1073/pnas.1619575114

Golden, C., Allison, E., Cheung, W. et al. 2016. Nutrition: Fall in fish catch threatens human health. Nature 534, 317–320 (2016). https://doi.org/10.1038/534317a

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA, Fluet-Chouinard E, Nyboer EA, 2021. Aquatic foods to nourish nations. Nature. 2021 Oct 14;598(7880):315-20.

Gollan N, Barclay K (2020) 'It's not just about fish': Assessing the social impacts of marine protected areas on the wellbeing of coastal communities in New South Wales. PLOS ONE 15(12): e0244605. doi.org/10.1371/journal.pone.0244605

González-Delgado P, Muriel J, Jiménez T, Cameo JI, Palazón-Bru A, Fernández J, 2022. Food Protein-Induced Enterocolitis Syndrome in Adulthood: Clinical Characteristics, Prognosis, and Risk Factors. J Allergy Clin Immunol Pract. 2022 Sep;10(9):2397-2403. doi: 10.1016/j.jaip.2022.05.006. Epub 2022 May 19. PMID: 35598865.

Grégoire M, Oschlies A, Canfield D, Castro C, Ciglenecki I, Croot P, Salin K, Schneider B, Serret P, Slomp C, Tesi T. Ocean Oxygen: the role of the Ocean in the oxygen we breathe and the threat of deoxygenation. Future Science Brief, 10 . European Marine Board, Ostend, Belgium, 82 pp. ISBN 9789464206180 doi10.5281/zenodo.7941157.

Guo, X.T., Lv, M., Song, L.H., Ding, J., Man, M.S., Fu, L.W., Song, Z.H., Li, B.Q., Chen, L.X., 2023. Occurrence, Distribution, and Trophic Transfer of Pharmaceuticals and Personal Care Products in the Bohai Sea. Environmental Science & Technology 57, 21823-21834.

Habibullah-Al-Mamun M, Kawser Ahmed M, Hossain A, Masunaga S., 2019. Distribution, Source Apportionment, and Risk Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) in the Surficial Sediments from the Coastal Areas of Bangladesh. Arch Environ Contam Toxicol. 76, 178-190.

Hallegraeff, G. M., Anderson, D. M., Belin, C., Dechraoui Bottein, M-Y., Bresnan, E., Chinain, M., Enevoldsen, H., Iwataki, M., Karlson, B., Cynthia H. McKenzie, C. H., Sunesen, I., Pitcher, G. C., Provoost, P., Anthony Richardson, A., Schweibold, L., Tester, P. A., Trainer, V. L., Yñiguez, A. T., Zingone, A. (2021) Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. Communications Earth & Environment, 2,117. doi.org/10.1038/s43247-021-00178-8

Hamley GJ, 2022. The implications of seabed mining in the Area for the human right to health. *RECIEL,* 31(3), 389-398. doi:10.1111/reel.12471.

Han Y, Nambi IM, Prabhakar Clement T., 2018. Environmental impacts of the Chennai oil spill accident - A case study. Sci Total Environ. 626, 795-806.

Haque, S.S., Bennett, B.J., Brewer, T.D., Morrissey, K, Fleming, LE, Gribble, MO, 2023. Marine Protected Area expansion and country-level age-standardized adult mortality. EcoHealth 20, 236–248. doi.org/10.1007/s10393-023-01658-3

Hassaan MA, Ragab S, Sikaily AE, Nemr AE., 2024. Sources of hydrocarbons and their risk assessment in seawater and sediment samples collected from the Nile Delta coast of the Mediterranean Sea. Sci Rep. 14, 5082.

Hatami Manesh, M., Haghshenas, A., Mirzaei, M. et al., 2021. Seasonal variations of polycyclic aromatic hydrocarbons in coastal sediments of a marine resource hot spot: the case of pars special economic energy zone, Iran. Environ Geochem Health 43, 3897-3919.

Hites, R.A. et al. "Global Assessment of Organic Contaminants in Farmed Salmon."Science, vol. 303, January 2004.

Hoegh-Guldberg, O, Dove, SG, Spady, BL, Skirving, W, Geiger, EF, Liu, G, De La Cour, J, Manzello, D, 2023. Coral reefs in peril in a record-breaking year.*S*cience382,1238-1240. doi:10.1126/science.adk4532

International Energy Agency (IEA), 2018. The future of petrochemicals: Towards more sustainable plastics and fertilisers, IEA, Paris, .https://doi.org/10.1787/9789264307414-en

Iwamoto M, Ayers, T, Mahon, BE, Swerdlow, DL. 2010. Epidemiology of Seafood-Associated Infections in the United States. Clin Microbiol Rev 23, 399-411. doi.org/10.1128/cmr.00059-09.

Jernelöv A., Lindén O., 1981. Ixtoc I: A Case Study of the World's Largest Oil Spill. Ambio, 10, 299-306.

Jinshu, Z., Richardson, B.J., Shouming, O. et al., 2004. Distribution and sources of polycyclic aromatic hydrocarbon (PAH) in marine environment of China. Chin. J. Ocean. Limnol. 22, 136-145.

Johnson M.D., Kenney N., Stoica A., Hilakivi-Clarke L., Singh B., Chepko G., Clarke R., Sholler P.F., Lirio A.A., Foss C., Reiter R., Trock B., Paik S., Martin M.B. (2003). Cadmium mimics the in vivo effects of estrogen in the uterus and mammary gland. Nat. Med., 9, 1081-1084. https://doi.org/10.1038/nm902

Johnson-Restrepo B, Olivero-Verbel J, Lu S, Guette-Fernández J, Baldiris-Avila R, O'Byrne-Hoyos I, Aldous KM, Addink R, Kannan K., 2008. Polycyclic aromatic hydrocarbons and their hydroxylated metabolites in fish bile and sediments from coastal waters of Colombia. Environ Pollut. 151, 452-459.

Kanungo S, Azman AS, Ramamurthy T, Deen J, Dutta S, 2022. Cholera. Lancet. 2022 9;399(10333):1429-1440. doi: 10.1016/S0140-6736(22)00330-0.

Kennedy LC, Costantini VP, Huynh KA, Loeb SK, Jennings WC, Lowry S, Mattioli MC, Vinjé J, Boehm AB., 2023. Persistence of human norovirus (GII) in surface water: Decay rate constants and inactivation

mechanisms. Environmental Science and Technology. 2023;57(9):3671–3679. doi: 10.1021/acs.est.2c09637.

Kienzler A, Bopp SK, van der Linden S, Berggren E, Worth A, 2016. Regulatory assessment of chemical mixtures: Requirements, current approaches and future perspectives. Regul Toxicol Pharmacol. 80, 321-334.

~~Koudryashova, Y., Chizhova, T., Zadorozhny, P., Ponomareva, A.; Eskova, A., 2023. Occurrence and Sources of Polycyclic Aromatic Hydrocarbons and Factors Influencing Their Accumulation in Surface Sediment of a Deep-Sea Depression, Namely, the Tatar Trough (Tatar Strait, the Sea of Japan). Water 15, 4151.~~

Laiolo, E., Alam, I., Uludag, M., Jamil, T., Agusti, S., Gojobori, T., Acinas, S.G., Gasol, J.M. and Duarte, C.M., 2024. Metagenomic probing toward an atlas of the taxonomic and metabolic foundations of the global ocean genome. *Frontiers in Science*, *1*, p.1038696.

Lakhmanov DE, Kozhevnikov AY, Pokryshkin SA, Semiletov IP, Kosyakov DS., 2022. Polycyclic aromatic hydrocarbons in the Siberian Arctic seas sediments. Mar Pollut Bull. 180, 113741.

Lambert, S., Vercauteren, M., Catarino, A.I., Li, Y., Van Landuyt, J., Boon, N., Everaert, G., De Rijcke, M., Janssen, C.R. and Asselman, J., 2024. Aerosolization of micro-and nanoplastics via sea spray: Investigating the role of polymer type, size, and concentration, and potential implications for human exposure. *Environmental Pollution*, *351*, p.124105.

Landrigan PJ, Raps H, Cropper M, Bald C, Brunner M, Canonizado EM, Charles D, Chiles TC, Donohue MJ, Enck J, Fenichel P, Fleming LE, Ferrier-Pages C, Fordham R, Gozt A, Griffin C, Hahn ME, Haryanto B, Hixson R, Ianelli H, James BD, Kumar P, Laborde A, Law KL, Martin K, Mu J, Mulders Y, Mustapha A, Niu J, Pahl S, Park Y, Pedrotti ML, Pitt JA, Ruchirawat M, Seewoo BJ, Spring M, Stegeman JJ, Suk W, Symeonides C, Takada H, Thompson RC, Vicini A, Wang Z, Whitman E, Wirth D, Wolff M, Yousuf AK, Dunlop S 2023. The Minderoo-Monaco Commission on Plastics and Human Health. Ann Glob Health. 2023 Mar 21;89(1):23. doi: 10.5334/aogh.4056. Erratum in: Ann Glob Health. 2023 Oct 11;89(1):71. doi: 10.5334/aogh.4331.

Landrigan PJ, Stegeman JJ, Fleming LE, Allemand D, Anderson DM, Backer LC, Brucker-Davis F, Chevalier N, Corra L, Czerucka D, Bottein MD, Demeneix B, Depledge M, Deheyn DD, Dorman CJ, Fénichel P, Fisher S, Gaill F, Galgani F, Gaze WH, Giuliano L, Grandjean P, Hahn ME, Hamdoun A, Hess P, Judson B, Laborde A, McGlade J, Mu J, Mustapha A, Neira M, Noble RT, Pedrotti ML, Reddy C, Rocklöv J, Scharler UM, Shanmugam H, Taghian G, van de Water JAJM, Vezzulli L, Weihe P, Zeka A, Raps H, Rampal P., 2020. Human Health and Ocean Pollution. Ann Glob Health. 86, 151.

Lawal, A. T., Fantke, P., 2017. Polycyclic aromatic hydrocarbons. A review. Cogent Environmental Science, 3(1).

Lefebvre, K. A., Quakenbush, L., Frame, E., Huntington, K. B., Sheffield, G., Stimmelmayr, R., Bryan, A., Kendrick, P., Ziel, H., Goldstein, T., Snyder, J. A., Gelatt, T., Gulland, F., Dickerson, B., Gill, V. (2016) Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae 55, 13–24.

Lelieveld et al 2019Lelieveld J, Klingmüller K, Pozzer A, Burnett RT, Haines A, Ramanathan V. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. Proc Natl Acad Sci U S A. 2019 Apr 9;116(15):7192-7197. doi: 10.1073/pnas.1819989116.

Lemée, R., 2023. https://anses.hal.science/anses-04169914 Lemee, R., Humbert, J.-F., Abadie, E., Amzil, Z., Berdalet, E., et al.. Avis de l'Anses relatif aux risques pour la santé humaine liés aux proliférations d'*Ostreopsis* spp. sur le littoral basque. Saisine n°2021-SA-0212, Anses. 2023, 40 p. ⟨anses-04169914⟩.

Leonard, A.F., Singer, A., Ukoumunne, O.C., Gaze, W.H., Garside, R. 2018. Is it safe to go back into the water? A systematic review and meta-analysis of the risk of acquiring infections from recreational exposure to seawater, *International Journal of Epidemiology*, 47, 572–586, https://doi.org/10.1093/ije/dyx281.

Leonard, A.F., Garside, R., Ukoumunne, O.C. and Gaze, W.H., 2020. A cross-sectional study on the prevalence of illness in coastal bathers compared to non-bathers in England and Wales: Findings from the Beach User Health Survey. *Water Research*, *176*, p.115700.

Leso V, Battistini B, Vetrani I, Reppuccia L, Fedele M, Ruggieri F, Bocca B, Iavicoli I, 2023 The endocrine disrupting effects of nanoplastic exposure: A systematic review. Toxicol Ind Health. 2023 Nov;39(11):613-629. doi: 10.1177/07482337231203053. Epub 2023 Sep 27. PMID: 37753827.

Li, P., Liu, J., (2024). Micro(nano)plastics in the human body: sources, occurrences, fates, and health risks. Environ. Sci. Technol. 2024, 58, 7, 3065–3078. doi.org/10.1021/acs.est.3c08902

Lim CC, Yoon J, Reynolds K, Gerald LB, Ault AP, Heo S, Bell ML. Harmful algal bloom aerosols and human health. EBioMedicine. 2023 Jul;93:104604. doi: 10.1016/j.ebiom.2023.104604. Epub 2023 May 8. PMID: 37164781; PMCID: PMC10363441.

Liu C, Ralston NVC. Seafood and health: What you need to know? Adv Food Nutr Res. 2021;97:275-318. doi: 10.1016/bs.afnr.2021.04.001. Epub 2021 May 6. PMID: 34311902.

Liu, J.Y., Gao, D., Wang, H., Li, Y.H., Chen, M.M., Ma, Q., Wang, X.X., Cui, M.J., Chen, L., Zhang, Y., Guo, T.J., Yuan, W., Ma, T., Jiang, J.N., Dong, Y.H., Zou, Z.Y., Ma, J., 2023. Long-term exposure to exogenous phthalate, masculinity and femininity trait, and gender identity in children: a Chinese 3-year longitudinal cohort study. Environmental Health 22.

Liu LY, Wang JZ, Wei GL, Guan YF, Zeng EY., 2012. Polycyclic aromatic hydrocarbons (PAHs) in continental shelf sediment of China: implications for anthropogenic influences on coastal marine environment. Environ Pollut. 167, 155-162.

Liu M., Zheng H., Cai M, Leung KMY, Li Y, Yan M., Zhang Z, Zhang K, Chen M., Ke H., 2023. Ocean Stratification Impacts on Dissolved Polycyclic Aromatic Hydrocarbons (PAHs): From Global Observation to Deep Learning. Environ. Sci. Technol. 57, 46, 18339-18349.

Long E.R., Macdonald D.D., Smith S.L., Calder F.D., 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environmental Management 19, 81-97.

Lunde Hermansson A, Hassellöv IM, Jalkanen JP, Ytreberg E., 2023. Cumulative environmental risk assessment of metals and polycyclic aromatic hydrocarbons from ship activities in ports. Mar Pollut Bull. 189, 114805.

Lunde Hermansson A., Hassellöv I-M, Moldanová J., Ytreberg E., 2021. Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers. Transportation Research Part D: Transport and Environment 97, 102912.

Lunde Hermansson, A., Hassellöv, IM., Grönholm, T. et al., 2024. Strong economic incentives of ship scrubbers promoting pollution. Nat Sustain 7, 812-822.

Luo, Y, Xu, X, Yin, Q, Liu, S, Xing, S, Jin, M, et al., 2025. Mapping micro(nano)plastics in various organ systems: their emerging links to human diseases? Trends Anal Chem, 183 (2025), Article 118114, 10.1016/j.trac.2024.118114.

Ma, Y., Halsall, C. J., Xie, Z., Koetke, D., Mi, W., Ebinghaus, R., Gao G., 2017. Polycyclic aromativc hydrocarbons in ocean sediments from the North Pacific to the Arctic Ocean. Environ. Poll. 227, 498-504.

Macías-Zamora J V., Mendoza-Vega E, Villaescusa-Celaya JA., 2002. PAHs composition of surface marine sediments: a comparison to potential local sources in Todos Santos Bay, B.C., Mexico. Chemosphere. 46, 459-468.

Madarcos, JRV, Creencia, LA, Roberts, BR, White, MP, Noyoan,J, Morrissey, K, Fleming, LE, 2021. Understanding local perceptions of the drivers/pressures on the coastal marine environment in Palawan, Philippines. Frontiers in Marine Science, 8. doi:10.3389/fmars.2021.659699.

Madikezela, L.M., Ncube, S. (2022) Health effects and risks associated with the occurrence of pharmaceuticals and their metabolites in marine organisms and seafood. Science of the Total Environment 837: 155780.

Martin OV, 2023. Synergistic effects of chemical mixtures: How frequent is rare? Curr Opin Toxicol 36, 100424.

Martins CC, Bícego MC, Tanigichi S, Montone RC., 2004. Aliphatic and polycyclic aromatic hydrocarbons in surface sediments in Admiralty Bay, King George Island, Antarctica. Antarctic Science16, 117-122.

Matsumoto H, Shimada Y, Nakamura AJ, Usami N, Ojima M, Kakinuma S, Shimada M, Sunaoshi M, Hirayama R, Tauchi H. Health effects triggered by tritium: how do we get public understanding based on scientifically supported evidence? J Radiat Res. 2021 Jul 10;62(4):557-563. doi: 10.1093/jrr/rrab029. PMID: 33912931; PMCID: PMC8273802.

Maycock B, Then AY, Taufek NM, Mills DJ, Blackford K, 2023. Food from the ocean. In: Oceans and Human Health: Opportunities and Impacts, second edition (Eds. Fleming L, Creencia LA, Gerwick WH, Goh HC, Gribble MO, Maycock B, Solo-Gabriele H), pp. 71-101. Cambridge: Academic Press.

Mayer PM, Moran KD, Miller EL, Brander SM, Harper S, Garcia-Jaramillo M, Carrasco-Navarro V, Ho KT, Burgess RM, Thornton Hampton LM, Granek EF, McCauley M, McIntyre JK, Kolodziej EP, Hu X, Williams AJ, Beckingham BA, Jackson ME, Sanders-Smith RD, Fender CL, King GA, Bollman M, Kaushal SS, Cunningham BE, Hutton SJ, Lang J, Goss HV, Siddiqui S, Sutton R, Lin D, Mendez M. Where the rubber meets the road: Emerging environmental impacts of tire wear particles and their chemical cocktails. Sci Total Environ. 2024 Jun 1;927:171153. doi: 10.1016/j.scitotenv.2024.171153. Epub 2024 Mar 7. PMID: 38460683; PMCID: PMC11214769.

Megha, K.B., Anvitha, D., Parvathi, S., Neeraj, A., Sonia, J., Mohanan, P.V., 2024. Environmental impact of microplastics and potential health hazards. Critical Reviews in Biotechnology.

Mezzelani M., Regoli, F. (2022). The Biological Effects of Pharmaceuticals in the Marine Environment. Annual Review of Marine Science, 14, 105–128, https://doi.org/10.1146/annurev-marine-040821-075606

Miller, R.L., G.A. Schmidt, L. Nazarenko, S.E. Bauer, M. Kelley, R. Ruedy, G.L. Russell, A. Ackerman, I. Aleinov, M. Bauer, R. Bleck, V. Canuto, G. Cesana, Y. Cheng, T.L. Clune, B. Cook, C.A. Cruz, A.D. Del Genio, G.S. Elsaesser, G. Faluvegi, N.Y. Kiang, D. Kim, A.A. Lacis, A. Leboissetier, A.N. LeGrande, K.K. Lo, J. Marshall, E.E. Matthews, S. McDermid, K. Mezuman, L.T. Murray, V. Oinas, C. Orbe, C. Pérez García-Pando, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, D.T. Shindell, S. Sun, N. Tausnev, K. Tsigaridis, G. Tselioudis, E. Weng, J. Wu, and M.-S. Yao, 2021: CMIP6 historical simulations (1850-2014) with GISS-E2.1. *J. Adv. Model. Earth Syst.*, 13, no. 1, e2019MS002034, doi:10.1029/2019MS002034.

Mol, S., Coşansu, S. (2022). Seafood Safety, Potential Hazards and Future Perspective. Turkish Journal of Fisheries and Aquatic Sciences, 22(6), TRJFAS20533. http://doi.org/10.4194/TRJFAS20533
Fehrenbach G.W., Pogue R., Carter F., Clifford E., Rowan N. (2022) Implications for the seafood industry, consumers and the environment arising from contamination of shellfish with

pharmaceuticals, plastics and potentially toxic elements: A case study from Irish waters with a global orientation. Sci Total Environ. 844:157067.

Montuori P, De Rosa E, Di Duca F, Provvisiero DP, Sarnacchiaro P, Nardone A, Triassi M., 2021. Estimation of Polycyclic Aromatic Hydrocarbons Pollution in Mediterranean Sea from Volturno River, Southern Italy: Distribution, Risk Assessment and Loads. Int J Environ Res Public Health. 18(4):1383.

Moore, M.N., Depledge, M.H., Fleming, L., Hess, P., Lees, D., Leonard, P., Madsen, L., Owen, R., Pirlet, H., Seys, J., Vasconcelos, V., Viarengo, A. (2013). Oceans and human health (OHH): a European perspective from the Marine Board of the European Science Foundation (Marine Board-ESF). *Microbial Ecol*., 65, 889-900.

Moore, M.N., Depledge, M.H., Fleming, L., Hess, P., Lees, D., Leonard, P., Madsen, L., Owen, R., Pirlet, H., Seys, J., Vasconcelos, V., Viarengo, A. (2014). Linking Oceans & Human Health: A strategic research priority for Europe. Position Paper 19. European Marine Board, Ostend, Belgium, 111p.

Moore M.N., Lowe D., Köhler, A., 2004. Biological effects of contaminants: measurement of lysosomal membrane stability. ICES Techniques in Marine Environmental Sciences, No. 36. 31pp.

Moore, M.N., Sforzini, S., Viarengo, A., Barranger, A., Aminot, Y., Readman, J.W., Khlobystov, A.N., Arnt, V.M.;Banni, M., Jha, A.N., 2021. Antagonistic cytoprotective effects of C60 fullerene nanoparticles in simultaneous exposure to benzo [a] pyrene in a molluscan animal model. Sci Total Environ, 755:1-27; https:// doi.org/10.1016/j.scitotenv.2020.142355.

Moore MN, Wedderburn RJ, Clarke KR, McFadzen IRB, Lowe DM, Readman JW., 2018. Emergent synergistic lysosomal toxicity of chemical mixtures in molluscan blood cells (hemocytes). Environ Pollut. 235, 1006-1014.

Muthukumar J, Selvasekaran P, Lokanadham M, Chidambaram R, 2020. Food and food products associated with food allergy and food intolerance - An overview. Food Res Int. 2020 Dec;138(Pt B):109780. doi: 10.1016/j.foodres.2020.109780.

Nardi A., Pittura L., d'Errico G., Cesaroni D., Mongera F., Gorbi S., Benedetti M., Regoli F. (2024). Cellular effects of microplastics are influenced by their dimension: Mechanistic relationships and integrated criteria for particles definition. Environmental Pollution, 344, 123327, https://doi.org/10.1016/j.envpol.2024.123327

Nash AK, Auchtung TA, Wong MC, Smith DP, Gesell JR, Ross MC, Stewart CJ, Metcalf GA, Muzny DM, Gibbs RA, Ajami NJ, Petrosino JF. The gut mycobiome of the Human Microbiome Project healthy cohort. Microbiome. 2017 Nov 25;5(1):153. doi: 10.1186/s40168-017-0373-4.

Nash, K.L., et al. Oceans and society: feedbacks between ocean and human health. *Rev Fish Biol Fish.* 32(1):161-187 (2022b). doi: 10.1007/s11160-021-09669-5.

Nourian G, Jaafarzadeh Haghighi Fard N, Pazira AR, Kohgardi E., 2024. An extensive investigation on human risk associated with PAHs in fish and sediment in Bushehr, Northern of Persian Gulf. Sci Rep. 14(1):10585.

Nowakowski GS, Yoon DH, Mondello P, Joffe E, Peters A, Fleury I, Greil R, Ku M, Marks R, Kim K, Zinzani PL, Trotman J, Sabatelli L, Waltl EE, Winderlich M, Sporchia A, Kurukulasuriya NC, Cordoba R, Hess G, Salles G. RE-MIND2: comparative effectiveness of tafasitamab plus lenalidomide versus polatuzumab vedotin/bendamustine/rituximab (pola-BR), CAR-T therapies, and lenalidomide/rituximab (R2) based on real-world data in patients with relapsed/refractory diffuse large B-cell lymphoma. Ann Hematol. 2023 Jul;102(7):1773-1787. doi: 10.1007/s00277-023-05196-4. Epub 2023 May 12. Erratum in: Ann Hematol. 2023 Sep;102(9):2643-2644. doi: 10.1007/s00277-023-05321-3.

Obanya HE, Khan FR, Carrasco-Navarro V, Støhle Rødland E, Walker-Franklin I, Thomas J, Cooper A, Molden N, Amaeze NH, Patil RS, Kukkola A, Michie L, Green-Ojo B, Rauer Ct, Couceiro F, Hutchison GR, Tang J, Ugor J, Lee S, Hofmann T, Ford AT, 2024. Priorities to inform research on tire particles and their chemical leachates: A collective perspective. Environmental Research, 263 (3). doi.org/10.1016/j.envres.2024.120222.

Ocean Panel, 2020. High Level Panel for a Sustainable Ocean Economy | World Resources Institute (wri.org).

Olayinka OO, Adewusi AA, Olujimi OO, Aladesida AA., 2019. Polycyclic Aromatic Hydrocarbons in Sediment and Health Risk of Fish, Crab and Shrimp Around Atlas Cove, Nigeria. J Health Pollut. 9, 191204.

Oliva AL, Quintas PY, Ronda AC, Marcovecchio JE, Arias AH., 2020. First evidence of polycyclic aromatic hydrocarbons in sediments from a marine protected area within Argentinean Continental Shelf. Mar Pollut Bull. 158, 111385.

Overstreet, R, 2013. Waterborne Parasitic Diseases waterborne parasitic diseases in Ocean. In: Infectious Diseases: SelectedEntries from the Encyclopedia of Sustainability Science and Technology (Eds. P. Kanki and D.J. Grimes), Springer Science+Business Media New York 2013. doi 10.1007/978-1-4614-5719-0_15.

Papon N, Copp BR, Courdavault V., 2022. Marine drugs: Biology, pipelines, current and future prospects for production. Biotechnol Adv. 2022 Jan-Feb;54:107871. doi: 10.1016/j.biotechadv.2021.107871. Epub 2021 Nov 19. PMID: 34801661.

Paquet F et al., (2016) ICRP, 2016. Occupational intakes of radionuclides: Part 2. ICRP Publication 134. Ann. ICRP 45(3/4), 1–352.

Pascual-Alonso A, Xiol C, Smirnov D, Kopajtich R, Prokisch H, Armstrong J, 2024. Multi-omics in MECP2 duplication syndrome patients and carriers. Eur J Neurosci, 60(2), :4004-4018. doi: 10.1111/ejn.16389.

Patel AB, Shaikh S, Jain KR, Desai C, Madamwar D., 2020. Polycyclic Aromatic Hydrocarbons: Sources, Toxicity, and Remediation Approaches. Front Microbiol. 11, 562813.

Patil, P.B., Maity, S., Sarkar, A., 2022. Potential human health risk assessment of microplastic exposure: current scenario and future perspectives. Environ Monit Assess 194, 898. https://doi.org/10.1007/s10661-022-10539-1

Paul KC, Cockburn M, Gong Y, Bronstein J, Ritz B, 2024. Agricultural paraquat dichloride use and Parkinson's disease in California's Central Valley. Int J Epidemiol. 2024 Feb 1;53(1):dyae004. doi: 10.1093/ije/dyae004.

Pironti, C., Ricciardi, M., Proto, A., Bianco, P.M., Montano, L., Motta, O., 2021. Endocrine-Disrupting Compounds: An Overview on Their Occurrence in the Aquatic Environment and Human Exposure. Water 13, 1347; https://doi.org/10.3390/w13101347.

Planetary Health Alliance, https://www.planetaryhealthalliance.org.

Popowich A, Zhang Q, Chris Le X, 2016. Arsenobetaine: the ongoing mystery, *National Science Review*, Volume 3, Issue 4, December 2016, Pages 451–458, https://doi.org/10.1093/nsr/nww061.

Pozo K, Perra G, Menchi V, Urrutia R, Parra O, Rudolph A, Focardi S., 2011. Levels and spatial distribution of polycyclic aromatic hydrocarbons (PAHs) in sediments from Lenga Estuary, central Chile. Mar Pollut Bull. 62, 1572-1576.

Préndez M, Barra C, Toledo C, Richter P., 2011. Alkanes and polycyclic aromatic hydrocarbons in marine surficial sediment near Antarctic stations at Fildes Peninsula, King George Island. Antarctic Science 23, 578-588.

Queb-Suarez JE, Ruiz-Marin A, Canedo-Lopez Y, Aguilar-Ucan CA, Montalvo-Romero C, Flores-Trujillo JG, Perez-Morga N., 2022. Source Identification, Toxicity, and Persistence of PAHs in Sediment Core from a Natural Protected Area in Mexico. Energies. 15, 7116.

Raj, K. and Das, A.P., 2023. Lead pollution: Impact on environment and human health and approach for a sustainable solution. Environmental Chemistry and Ecotoxicology, *5*, pp.79-85.

Rasheed, AR, 2020. Marine protected areas and human well-being – A systematic review and recommendations. Ecosystem Services, 41, 2020, 101048, ISSN 2212-0416. doi.org/10.1016/j.ecoser.2019.101048.

Reguera B, García-Portela, M, Velasco-Senovilla, E, Rial P, Escalera, L, Díaz PA, Rodríguez, F, 2024. *Dinophysis*, a highly specialized mixoplanktonic protist. Frontiers in Protistology, 1.*doi.org/10.3389/frpro.2023.1328026*

Ribeiro, R., Pinto, E., Fernandes, C. and Sousa, E., 2022. Marine cyclic peptides: Antimicrobial activity and synthetic strategies. Marine Drugs, *20*(6), p.397.

Richardson J. R., Fitsanakis V., Westerink R., Kanthasamyet A.G. (2019). Neurotoxicity of Pesticides. Acta Neuropathol. 2019 Sep; 138(3): 343–362. doi: 10.1007/s00401-019-02033-9

Ritter, L., Solomon, K., Forget, J., Stemeroff, M. and O'leary, C. (1995) A Review of Selected Persistent Organic Pollutants. International Programme on Chemical Safety (IPCS). PCS/95.39. World Health Organization, Geneva, Vol. 65, 66.

Rovira J, Nadal M, Schuhmacher M, Domingo JL., 2021. Environmental impact and human health risks of air pollutants near a large chemical/petrochemical complex: Case study in Tarragona, Spain. Sci Total Environ. 787, 147550.

Ruethers T, Taki AC, Johnston EB, Nugraha R, Le TTK, Kalic T, McLean TR, Kamath SD, Lopata AL. Seafood allergy: A comprehensive review of fish and shellfish allergens. Mol Immunol, 100:28-57. doi: 10.1016/j.molimm.2018.04.008.

Satarug S., Vesey D.A., Gobe G.C. (2017). Current health risk assessment practice for dietary cadmium: Data from different countries. Food Chem. Toxicol., 106, 430–445. https://doi.org/ 10.1016/j.fct.2017.06.013

Savinov, V. M., Savinova, T. N., Carroll, J., Matishov, G. G., Dahle, S., Næs, K., 2000. Polycyclic aromatic hydrocarbons (PAHs) in sediments of the White Sea, Russia. Mar. Pollut. Bull. 40, 807-818.

Savinov VM, Savinova TN, Matishov GG, Dahle S, Naes K., 2003. Polycyclic aromatic hydrocarbons (PAHs) and organochlorines (OCs) in bottom sediments of the Guba Pechenga, Barents Sea, Russia. Sci Total Environ. 306, 39-56.

Schøyen M, Green NW, Hjermann DØ. , Tveiten L, Beylich B, Øxnevad S, Beyer J, 2019. Levels and trends of tributyltin (TBT) and imposex in dogwhelk (*Nucella lapillus*) along the Norwegian coastline from 1991 to 2017, Marine Environmental Research, 144, 1-8. https://doi.org/10.1016 /j.marenvres.2018.11.011.

Shi W, Xu M, Liu Q, Xie S., 2022. Polycyclic aromatic hydrocarbons in seawater, surface sediment, and marine organisms of Haizhou Bay in Yellow Sea, China: Distribution, source apportionment, and health risk assessment. Mar Pollut Bull. 174, 113280.

Shi W., Xu M., Liu Q., Xie S., 2022. Polycyclic aromatic hydrocarbons in seawater, surface sediment, and marine organisms of Haizhou Bay in Yellow Sea, China: Distribution, source apportionment, and health risk assessment. Mar. Poll. Bull. 174, 113280.

Short, R.E., Gelcich, S., Little, D.C., Micheli, F, et al., 2021. Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. Nat Food, 2, 733–741. doi.org/10.1038/s43016-021-00363-0

Shreadah, M., Moneim, M., Said, T., Fathallah, E., Mahmoud, M., 2013. PAHs in Seawater of the Semi-Closed Areas along the Alexandria Coast of Egyptian Mediterranean Sea. Journal of Environmental Protection 4, 1307-1317.

Sieber, G., Beisser, D., Rothenberger, J., Shah, M., Schumann, M., Sures, B., Boenigk, J. (2022). Microbial community shifts induced by plastic and zinc as substitutes of tire abrasion. *Sci Rep* 12, 18684 (2022). https://doi.org/10.1038/s41598-022-22906-6

Smith J., Marks N., Irwin, T. (2023). The risks of radioactive waste water release, Science, 382(6666), 31–33, https://doi.org/10.1126/science.adi5446

Sonne, C., Desforges, J.P., Gustavson, K., Bossi, R., Bonefeld-Jorgensen, E.C., Long, M.H., Rigét, F.F., Dietz, R., 2023. Assessment of exposure to perfluorinated industrial substances and risk of immune suppression in Greenland and its global context: a mixed-methods study. Lancet Planetary Health 7, E570-E579.

Speight, J., 2019. Title: Handbook of petrochemical processes / James G. Speight. Description: Boca Raton, FL: CRC Press/Taylor & Francis Group, Series: Chemical industries.

Stevenson, E.M., Gaze, W.H., Gow, N.A., Hart, A., Schmidt, W., Usher, J., Warris, A., Wilkinson, H. and Murray, A.K., 2022. Antifungal exposure and resistance development: defining minimal selective antifungal concentrations and testing methodologies. *Frontiers in Fungal Biology*, *3*, p.918717.

Stockholm Convention. https://www.pops.int/Home/tabid/2121/Default.aspx

Sun RX, Lin Q, Ke CL, Du FY, Gu YG, Cao K, Luo XJ, Mai BX., 2016. Polycyclic aromatic hydrocarbons in surface sediments and marine organisms from the Daya Bay, South China. Mar Pollut Bull. 103, 325-332.

Sweetman, A.K., Smith, A.J., de Jonge, D.S.W. *et al.* Evidence of dark oxygen production at the abyssal seafloor. *Nat. Geosci.* 17, 737–739 (2024). https://doi.org/10.1038/s41561-024-01480-8

Tacon A.G.J., Coelho R.T.I, Levy J., Machado T.M., Neiva C.R.P., Lemos D. (2023). Annotated Bibliography of Selected Papers Dealing with the Health Benefits and Risks of Fish and Seafood Consumption.

Reviews in Fisheries Science & Aquaculture, 32, 211-305, https://doi.org/10.1080/23308249.2023.2238821

Takahashi, T, Takayoshi S, 2019. Vascular Dysfunction Induced by Mercury Exposure. *International Journal of Molecular Sciences,* 20(10), 2435. doi.org/10.3390/ijms20102435.

Tan Z, Berry A, Charalambides M, Mijic A, Pearse W, Porter A, Ryan MP, Shorten RN, Stettler MEJ, Tetley TD, Wright S, Masen MA. Tyre wear particles are toxic for us and the environment. Imperial College London (2023). doi: https://doi.org/10.25561/101707

Taylor V., Goodale B., Raab A. , Schwerdtle T. , Reimer K. , Conklin S. , Karagas M.R., Francesconi K.A. (2017). Human exposure to organic arsenic species from seafood. Sci. Total Environ., 580, 266–282, https://doi.org/10.1016/j.scitotenv.2016.12.113

Tigchelaar M, Leape J, Micheli F, Allison EH, Basurto X, Bennett A, Bush SR, Cao L, Cheung WW, Crona B, DeClerck F, 2022. The vital roles of blue foods in the global food system. Global Food Security, 33:100637. *doi.org/10.1016/j.gfs.2022.100637.*

Trainer, V, Moore, S, Hallegraeff, G, Kudela, R, Clement, A, Mardones, J, Cochlan, W, 2019. Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. Harmful Algae, 91. 10.1016/j.hal.2019.03.009. et al., 2019. doi.org/10.1016/j.hal.2019.03.009.

Trainer, V. L., Moore, S. K., Hallegraeff, G.,Kudela, R. M., Clement, A., Mardones, J. I., Cochlan, W. P. (2020). Pelagic harmful algal blooms and climate change: lessons from nature's experiments with extremes. Harmful Algae 91, 101591.

Tsapakis, M., Apsotolaki, M., Eisenreich, S. & Stephanou, E. G., 2006. Atmospheric deposition and marine sedimentation fuxes of polycyclic aromatic hydrocarbons in the eastern Mediterranean Basin. Environ. Sci. Technol. 40, 4922-4927.

UBA - Umweltbundesamt (2024). Database- pharmaceuticals in the environment. https://www.umweltbundesamt.de/en/database-pharmaceuticals-in-the-environment-0#undefined

UK Chief Medical, 2021. Chief Medical Officer's annual report 2021: health in coastal communities; Chief Medical Officer's annual report 2021: health in coastal communities - GOV.UK

UN Right to Healthy Environment https://www.undp.org/sites/g/files/zskgke326/files/2023-01/UNDP-UNEP-UNHCHR-What-is-the-Right-to-a-Healthy-Environment.pdf

UNEP/RAMOGE, 1999. Manual on the Biomarkers Recommended for the MED POL Biomonitoring Programme. UNEP, Athens.

U.S. EPA, 2001. Water Quality Criterion for the Protection of Human Health - Methylmercury. Federal

Register / Vol. 66, No. 5, EPA-823-R-01-001. https://www.epa.gov/sites/default/files/2020-01/documents/methylmercury-criterion-2001.pdf

U.S. EPA & FDA, 2024. Joint Federal Advisory for Mercury in Fish, https://www.fda.gov/media/102331/download.

Van Acker E, Huysman S, De Rijcke M, Asselman J, De Schamphelaere KAC, Vanhaecke L, Janssen CR. Phycotoxin-Enriched Sea Spray Aerosols: Methods, Mechanisms, and Human Exposure. Environ Sci Technol. 2021 May 4;55(9):6184-6196. doi: 10.1021/acs.est.1c00995. Epub 2021 Apr 12. PMID: 33843191.

Viarengo A, Lowe D, Bolognesi C, Fabbri E, Koehler A. 2007. The use of biomarkers in biomonitoring: a 2-tier approach assessing the level of pollutant-induced stress syndrome in sentinel organisms. Comp Biochem Physiol C Toxicol Pharmacol. 2007 Sep;146(3):281-300. doi: 10.1016/j.cbpc.2007.04.011. Epub 2007 May 3. PMID: 17560835.

Villasante, S, Ainsworth, GB, Pita, P, Belgrano, A, Bennett, N, Sumaila, UR, 2023. The role of marine protected areas (MPAs) in providing ecosystem services to improve ocean and human health. In : Oceans and Human Health (Second Edition), (Eds. Lora E. Fleming, Lota B. Alcantara Creencia, William H. Gerwick, Hong Ching Goh, Matthew O. Gribble, Bruce Maycock, Helena Solo-Gabriele), pp. 23-37. Academic Press, 2023, ISBN 9780323952279. doi.org/10.1016/B978-0-323-95227-9.00013-0.

Viñas L, Pérez-Fernandez B, Besada V, Gago J, McHugh B, Parra S., 2023. PAHs and trace metals in marine surficial sediments from the Porcupine Bank (NE Atlantic): A contribution to establishing background concentrations. Sci Total Environ. 856(Pt 2), 159189.

Vital, S.A., Cardoso, C., Avio, C., Pittura L., Regoli, F., Bebianno, M.J. (2021) Do microplastic contaminated seafood consumption pose a potential risk to human health? Marine Pollution Bulletin, 2021, 171, 112769, https://doi.org/10.1016/j.marpolbul.2021.112769

Vuckovic, D., Tinoco, A.I., Ling, L., Renicke, C., Pringle, J.R., Mitch, W.A., 2022. Conversion of oxybenzone sunscreen to phototoxic glucoside conjugates by sea anemones and corals. Science 376, 644-+.

Wai HA, Lord J, Lyon M, Gunning A, Kelly H, Cibin P, Seaby EG, Spiers-Fitzgerald K, Lye J, Ellard S, Thomas NS, Bunyan DJ, Douglas AGL, Baralle D, 2020. Splicing and disease working group. Blood RNA analysis can increase clinical diagnostic rate and resolve variants of uncertain significance. Genet Med, 22(6), 1005-1014. doi: 10.1038/s41436-020-0766-9.

Wang XC, Zhang YX, Chen RF., 2001. Distribution and partitioning of polycyclic aromatic hydrocarbons (PAHs) in different size fractions in sediments from Boston Harbor, United States. Mar Pollut Bull. 42, 1139-1149.

Wang Z, Liu Z, Xu K, Mayer LM, Zhang Z, Kolker AS, Wu W., 2014. Concentrations and sources of polycyclic aromatic hydrocarbons in surface coastal sediments of the northern Gulf of Mexico. Geochem Trans. 15, 2.

WHO (2012) Pharmaceuticals in drinking water. https://iris.who.int/bitstream/handle/10665/44630/9789241502085_eng.pdf;jsessionid=A04913BAAEDED316C54839D2D9A8404F?sequence=1

White PA, 2002. The genotoxicity of priority polycyclic aromatic hydrocarbons in complex mixtures. Mutat Res. 515, 85-98.

Willetts, L, Fleming, LE, Morgera, E, 2025. Biodiversity, health science, and the human right to a healthy environment. The Lancet (Planetary Health), 9: e553-e569; doi: 10.1016/S2542-5196(25)00092-0

Wimmers, A., Bärenbold, R., Bah, M.M., Lordan-Perret, R., Steigerwald, B., von Hirschhausen, C.R., Weigt, H. and Wealer, B., 2023. Decommissioning of nuclear power plants: Regulation, financing, and production (No. 104). DIW Data Documentation.

Wimmers, A, von Hirschhausen, C, 2024. Organizational models for the decommissioning of nuclear power plants: Lessons from the United Kingdom and the United States. Utilities Policy, 91, 2024, 101843, doi.org/10.1016/j.jup.2024.101843.

Winther JG, Dai M, Rist T, Hoel AH, Li Y, Trice A, Morrissey K, Juinio-Meñez MA, Fernandes L, Unger S, Scarano FR, 2020. Integrated ocean management for a sustainable ocean economy. Nature ecology & evolution, 4(11), 1451-8. doi.org/10.1038/s41559-020-1259-6.

Xie, Z.Y., Wang, P., Wang, X., Castro-Jiménez, J., Kallenborn, R., Liao, C.Y., Mi, W.Y., Lohmann, R., Vila-Costa, M., Dachs, J., 2022. Organophosphate ester pollution in the oceans. Nature Reviews Earth & Environment 3, 309-322.

Xue R, Chen L, Lu Z, Wang J, Yang H, Zhang J, Cai M., 2016. Spatial distribution and source apportionment of PAHs in marine surface sediments of Prydz Bay, East Antarctica. Environ. Pollut. 219, 528-536.

Xue, X.H., Xue, J.C., Liu, W.B., Adams, D.H., Kannan, K., 2017. Trophic Magnification of Parabens and Their Metabolites in a Subtropical Marine Food Web. Environmental Science & Technology 51, 780-789.

Ytreberg E., Eriksson M., Maljutenko I, Jalkanen J-P, Johansson L, Hassellöv I-M, Granhag L, 2020. Environmental impacts of grey water discharge from ships in the Baltic Sea. Mar. Poll. Bull. 152, 110891.

Zaghden H, Tedetti M, Sayadi S, Serbaji MM, Elleuch B, Saliot A., 2017. Origin and distribution of hydrocarbons and organic matter in the surficial sediments of the Sfax-Kerkennah channel (Tunisia, Southern Mediterranean Sea). Mar Pollut Bull. 117(1-2), 414-428.

Zingone, A., Escalera, L., Aligizaki, K., Fernández-Tejedor, M., Ismael, A., Montresor, M., Mozetič, P., Taş, S., Totti, C. (2021). Toxic microalgae and noxious blooms in the Mediterranean Sea: a contribution to the global HAB status report. Harmful Algae 102, https://doi.org/10.1016/j.hal.2020.101843. 1016/j.hal.2022.102320

Zuloaga O, Prieto A, Ahmed K, Sarkar SK, Bhattacharya A, Chatterjee M, et al., 2013. Distribution of polycyclic aromatic hydrocarbons in recent sediments of Sundarban mangrove wetland of India and Bangladesh: a comparative approach. Environ Earth Sci 68, 355-367.

Detailed Supplemental Material:

Fleming L, Creencia LA, Gerwick WH, Goh HC, Gribble MO, Maycock B, Solo-Gabriele H, 2023. Editors: Oceans and Human Health: Opportunities and Impacts, second edition. Cambridge: Academic Press, 2023. https://doi.org/10.1016/B978-0-323-95227-9.09990-5

Fleming LE, Landrigan PJ, Gerwick W, Heymans JJ, Hicks CC, Morrissey K, White MP, Alcantara-Creencia L, Alexander KA, Ashford OS, Astell-Burt T, Berlinck RGS, Cohen PJ, Hixson R, Islam MM, Iwasaki A, Praptiwi RA, Raps H, Remy JY, Sowman G, Swift A, Ternon E, Thiele T, Thilsted SH, Whitman EM. How can a healthy ocean improve human health and enhance wellbeing on a rapidly changing planet? Washington, DC: World Resources Institute (WRI). 2024. https://oceanpanel.org/publications/ocean-human-health/;

Fleming LE, Maycock B, White MP, Depledge MH. Fostering human health through ocean sustainability in the 21st century. People Nat. 2019;00:1–8. https://doi.org/10.1002/pan3.10038.

FIGURES

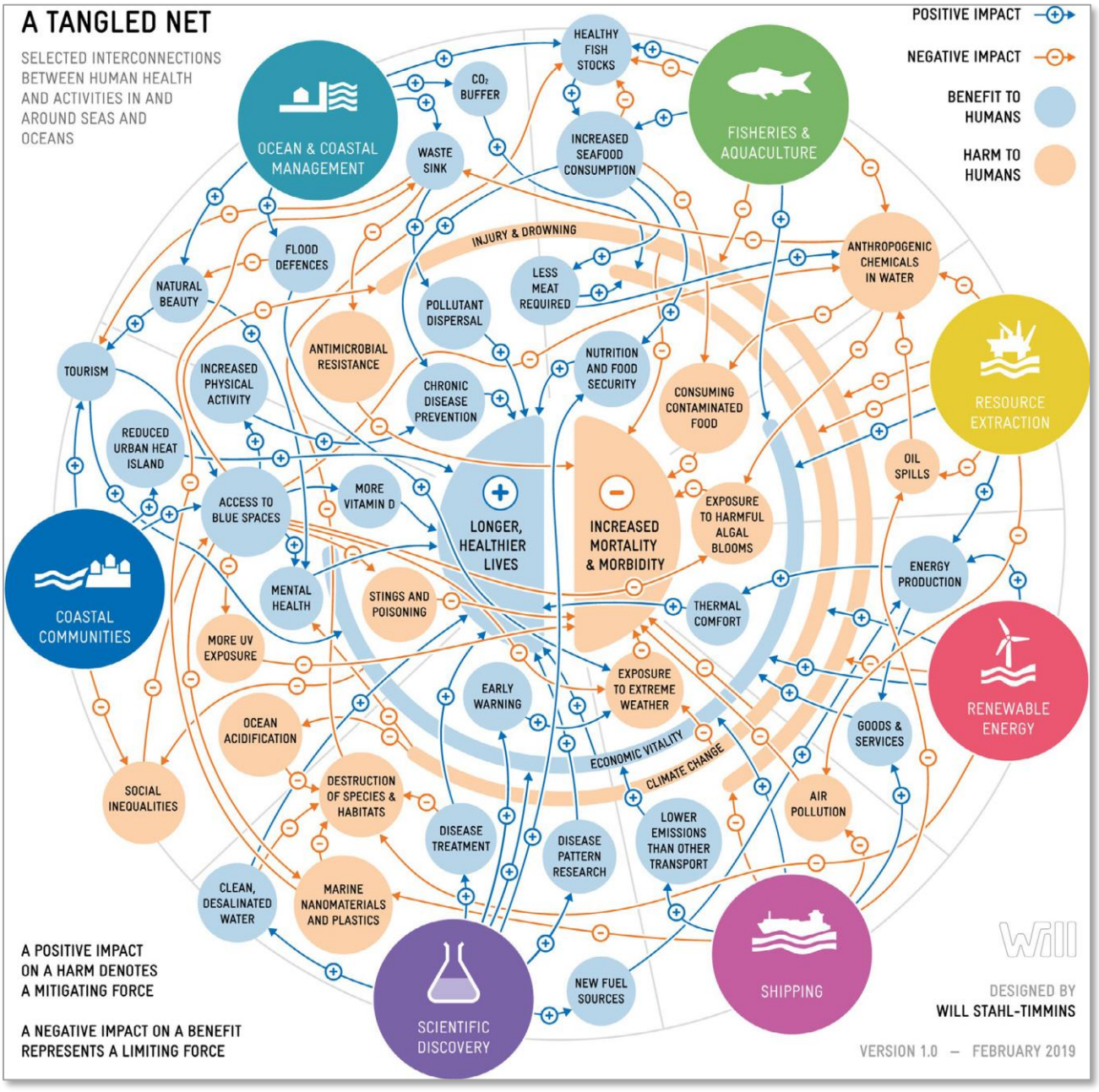


Fig. 1. A tangled net: selected interactions between human health and activities in the marine and coastal environment (adapted from Fleming et al., 2019; with permission from Prof. Lora Fleming).

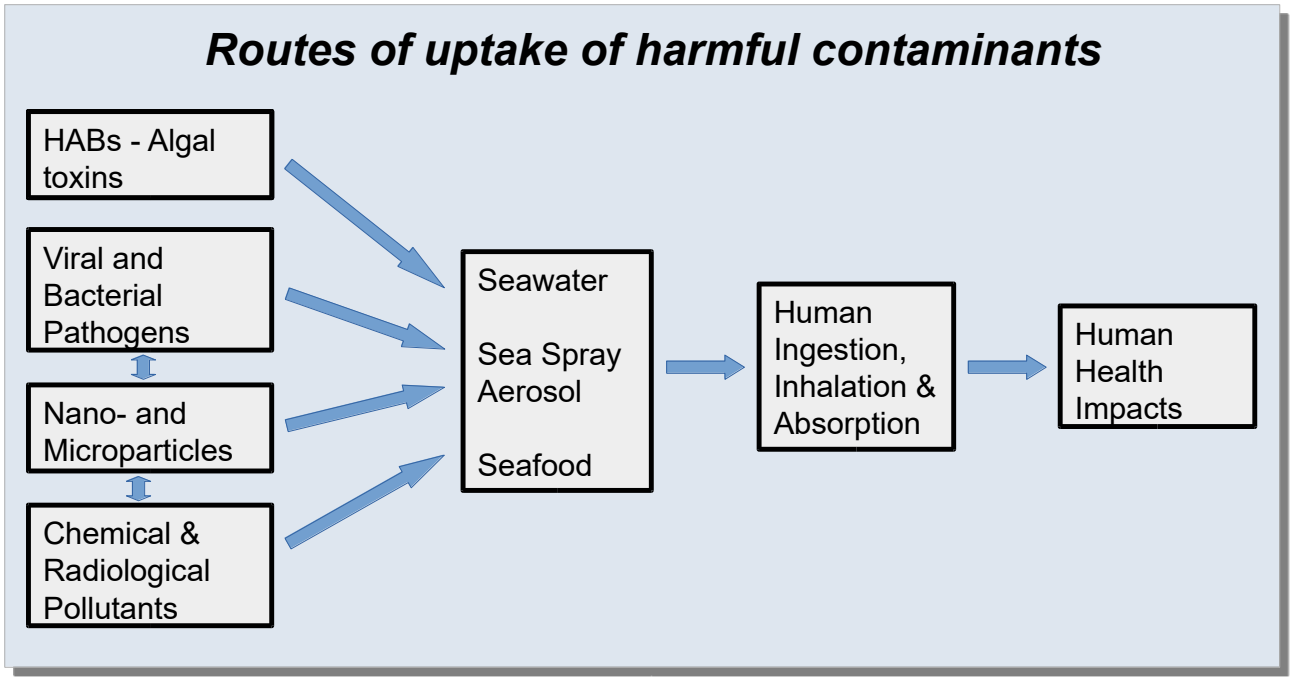


Fig. 2. Routes of human uptake of harmful biogenic toxins, pathogens, particles and chemicals.

Fig. 3. The Global Challenges Research Fund (UKRI – GCRF) Blue Communities Project examined the "health" of the environment and the people living in and around Marine Protected Areas (MPAs) in four SE Asian Countries (Blue Communities - University of Plymouth; with permission from Prof. Lora Fleming.

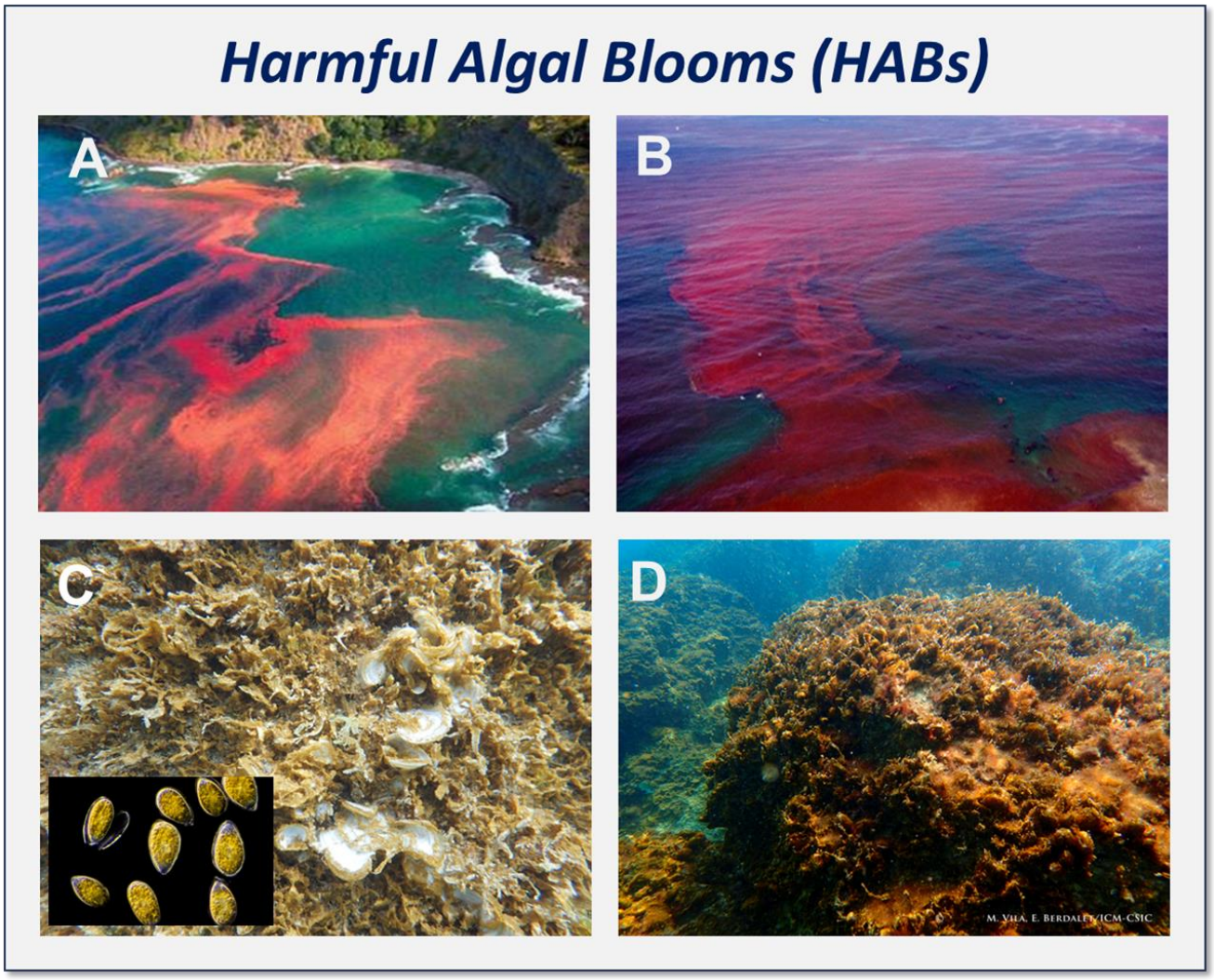
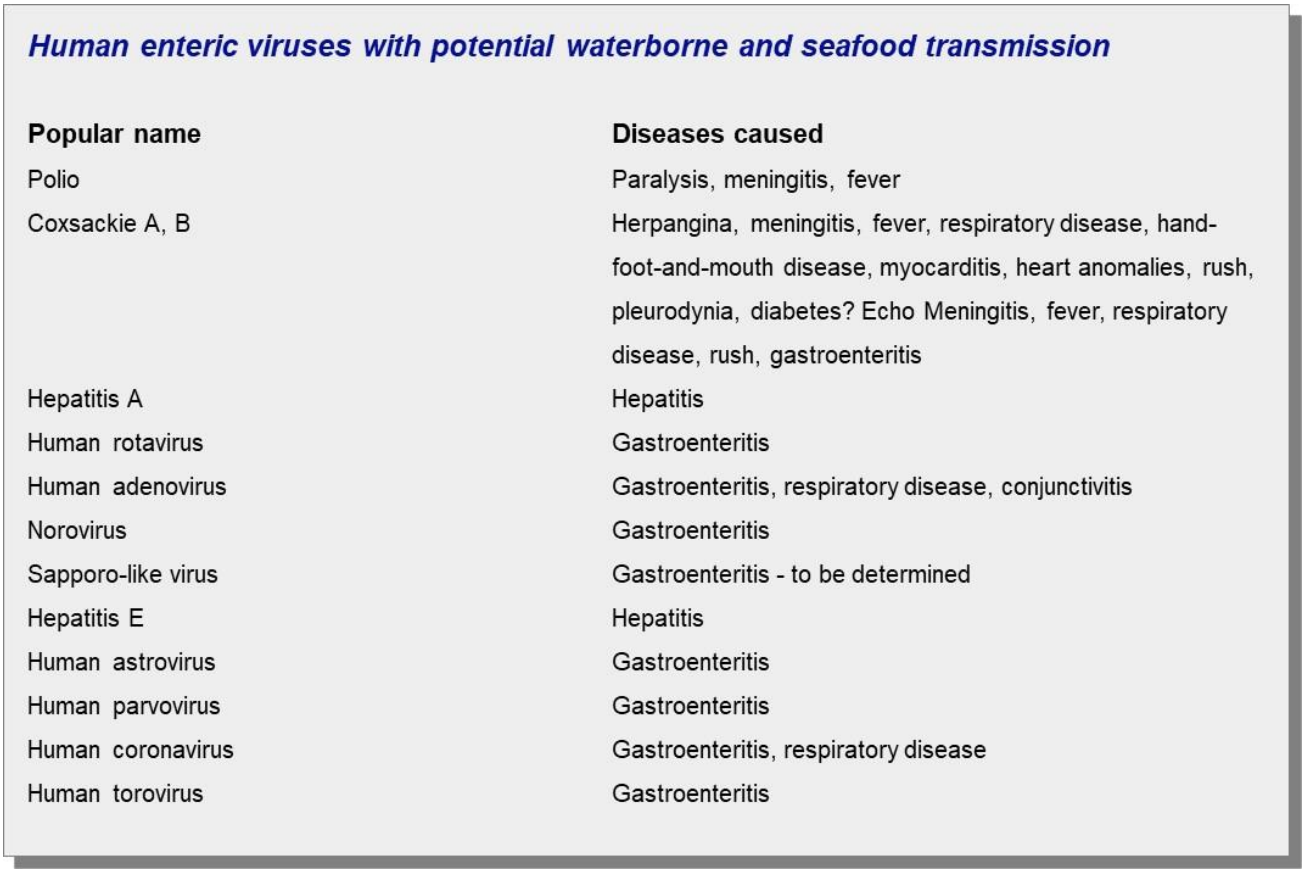


Fig. 4. A. Red algal bloom at Leigh, near Cape Rodney, New Zealand (Miriam Godfrey for New Zealand's National Institute of Water and Atmospheric Research); B. Red harmful algae, called *Lingulodinium polyedra*, often produces brightly bioluminescent coloured water discoloration. It has been associated with fish and shellfish mortality events, but its direct threat to human health is still being evaluated. (Photo credit: Kai Schumann, California Department of Public Health volunteer, www.noaa.gov/what-is-harmful-algal-bloom); C. Images of bloom of *Ostreopsis* cf. *ovata* that causes mortalities among sessile organisms and produces aerosolised toxins (Inset - Microphotography of the benthic dinoflagellate *Ostreopsis* cf. *ovata*, made by a professional, @RUBENDURO/SCIENCE INTO IMAGES); D. detail of the bloom covering macroalgae (NW Mediterranean Coast, July 2024 taken by Dr. E. Berdalet).



Human enteric viruses with potential waterborne and seafood transmission

Popular name	Diseases caused
Polio	Paralysis, meningitis, fever
Coxsackie A, B	Herpangina, meningitis, fever, respiratory disease, hand-foot-and-mouth disease, myocarditis, heart anomalies, rush, pleurodynia, diabetes? Echo Meningitis, fever, respiratory disease, rush, gastroenteritis
Hepatitis A	Hepatitis
Human rotavirus	Gastroenteritis
Human adenovirus	Gastroenteritis, respiratory disease, conjunctivitis
Norovirus	Gastroenteritis
Sapporo-like virus	Gastroenteritis - to be determined
Hepatitis E	Hepatitis
Human astrovirus	Gastroenteritis
Human parvovirus	Gastroenteritis
Human coronavirus	Gastroenteritis, respiratory disease
Human torovirus	Gastroenteritis

Fig. 5. Human pathogenic enteric viruses in seawater and seafood.

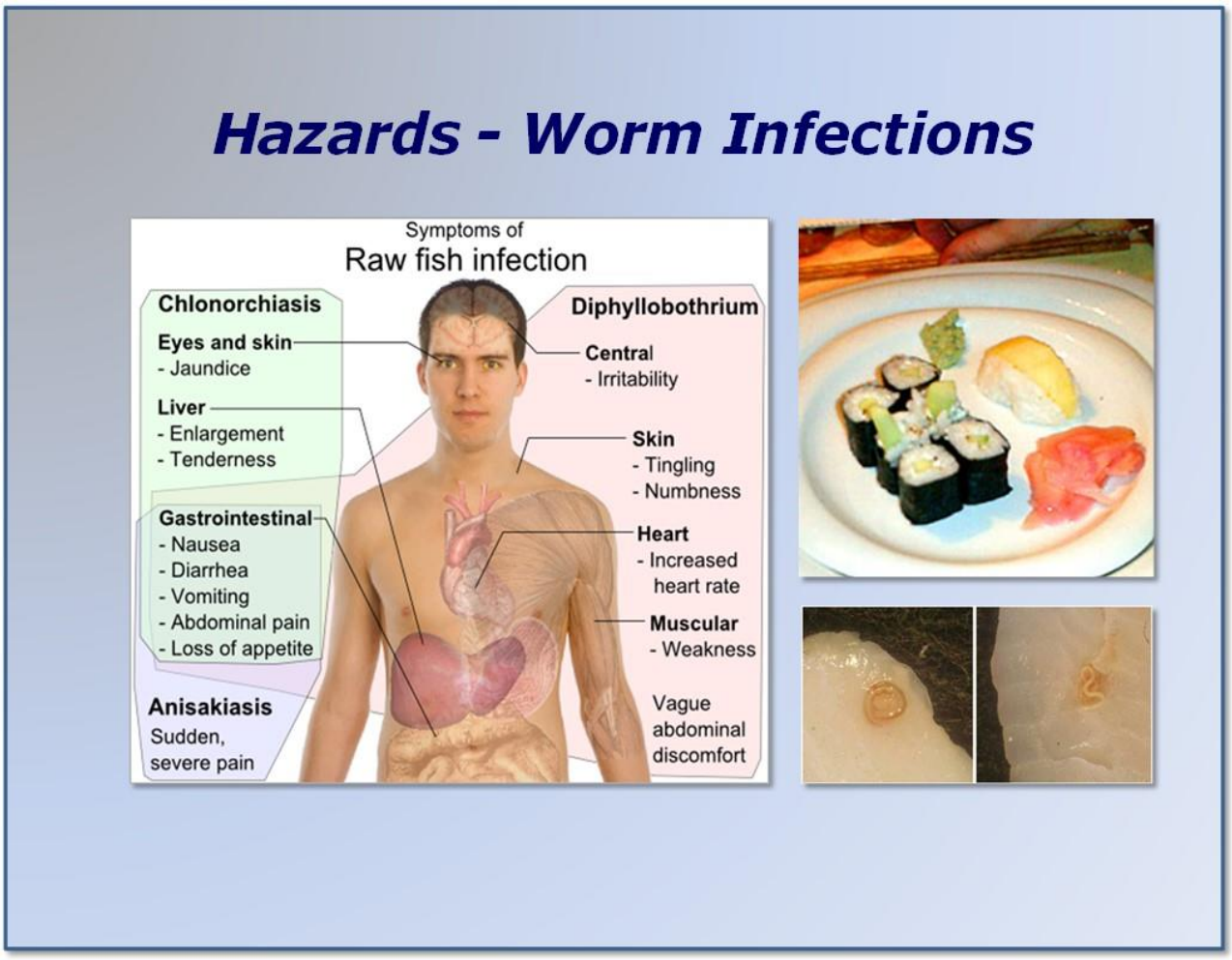


Fig. 6. Harmful parasitic worms in seafood, such as sushi and raw or under-cooked fish, and symptoms of infection. Adapted from BugBitten - Does your sushi contain parasites? (biomedcentral.com).

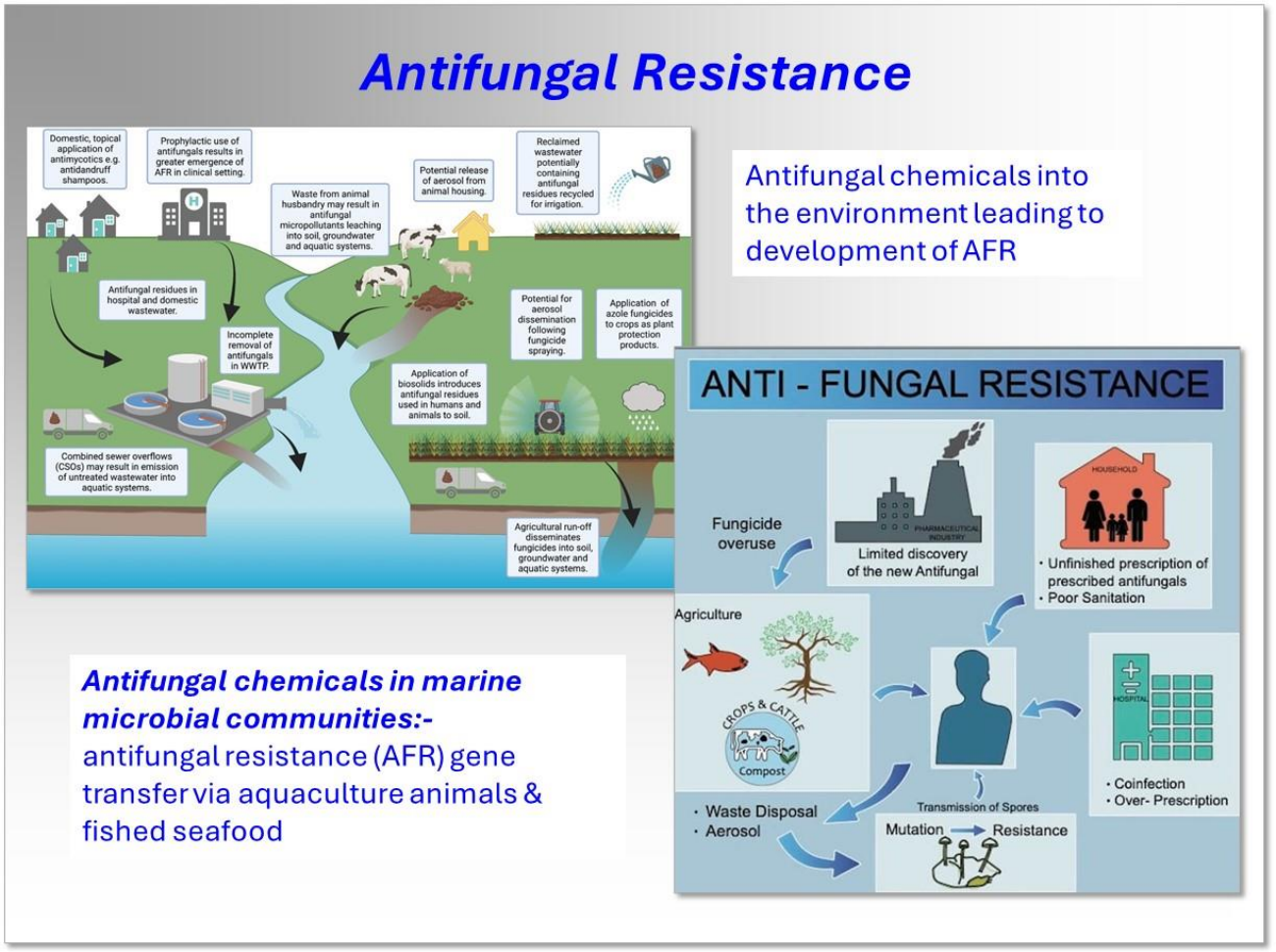


Fig. 7. Pathways for anti-fungal chemicals entering the marine environment and anti-fungal resistance. Adapted from Stevenson et al. (2022) and the American Society for Microbiology (Combating Antifungal Resistance (asm.org)).

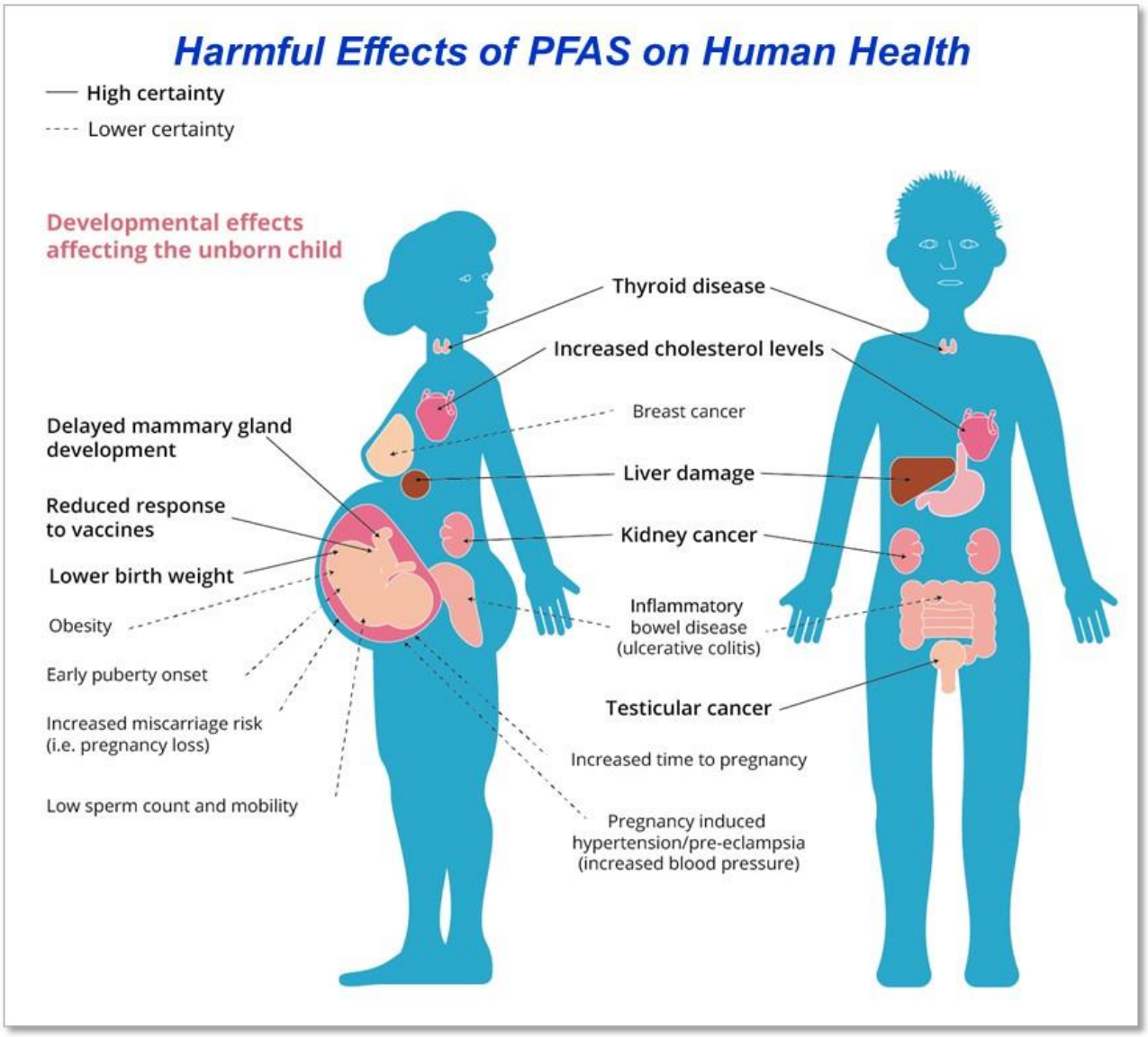


Fig. 8. Effects of PFAS on human health (European Environment Agency, 2023 - Emerging chemical risks in Europe - 'PFAS' (Effects of PFAS on human health | European Environment Agency's home page (europa.eu)).

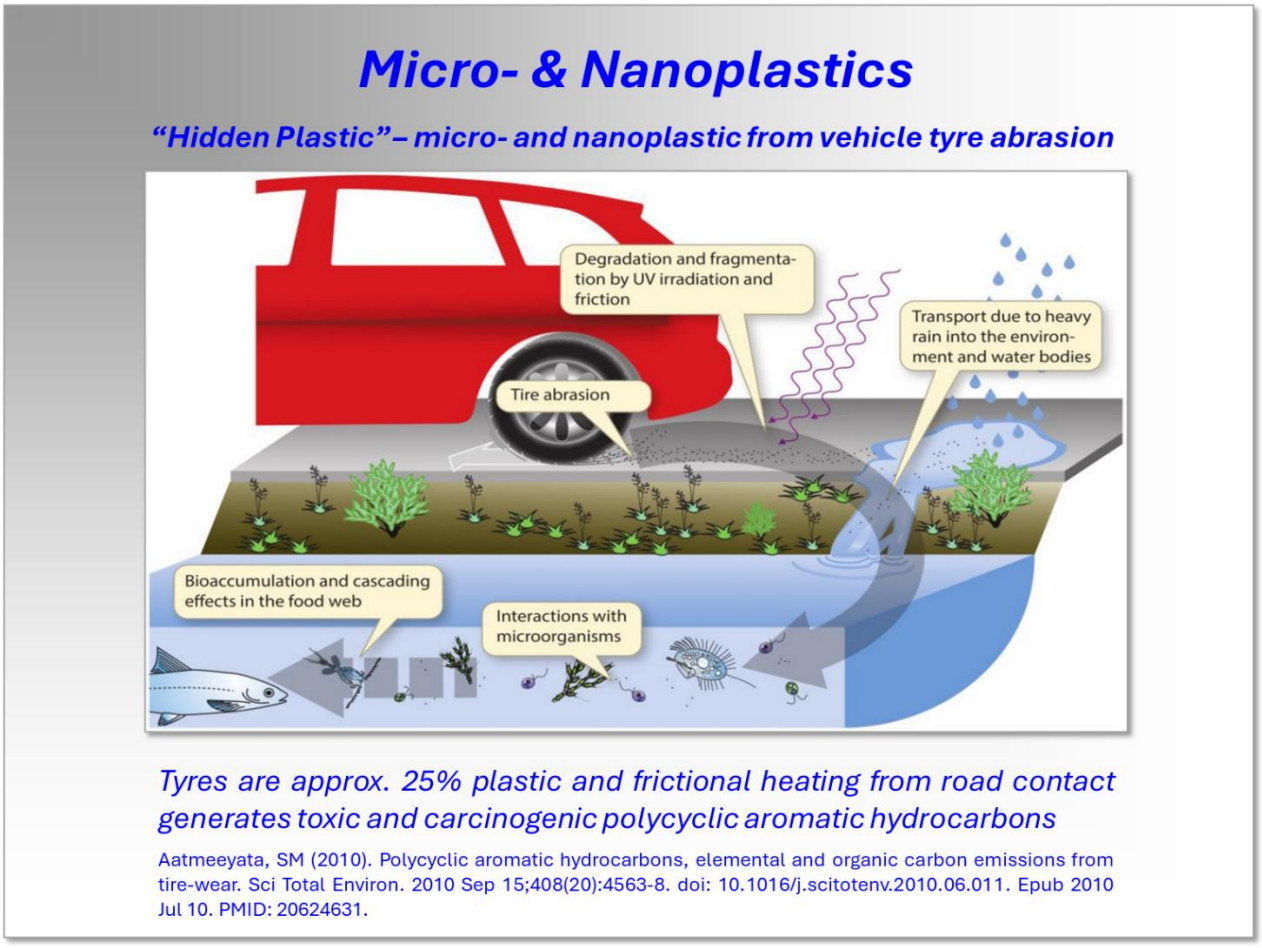


Fig. 9. Tyres contain approximately 25% plastic, and frictional heating and breakdown into tyre (tire) dust from road contact generates toxic and carcinogenic polycyclic aromatic hydrocarbons and nanoplastic particles (Adapted from Sieber at al., 2022; Aatmeeyata, 2010; Mayer et al., 2024).

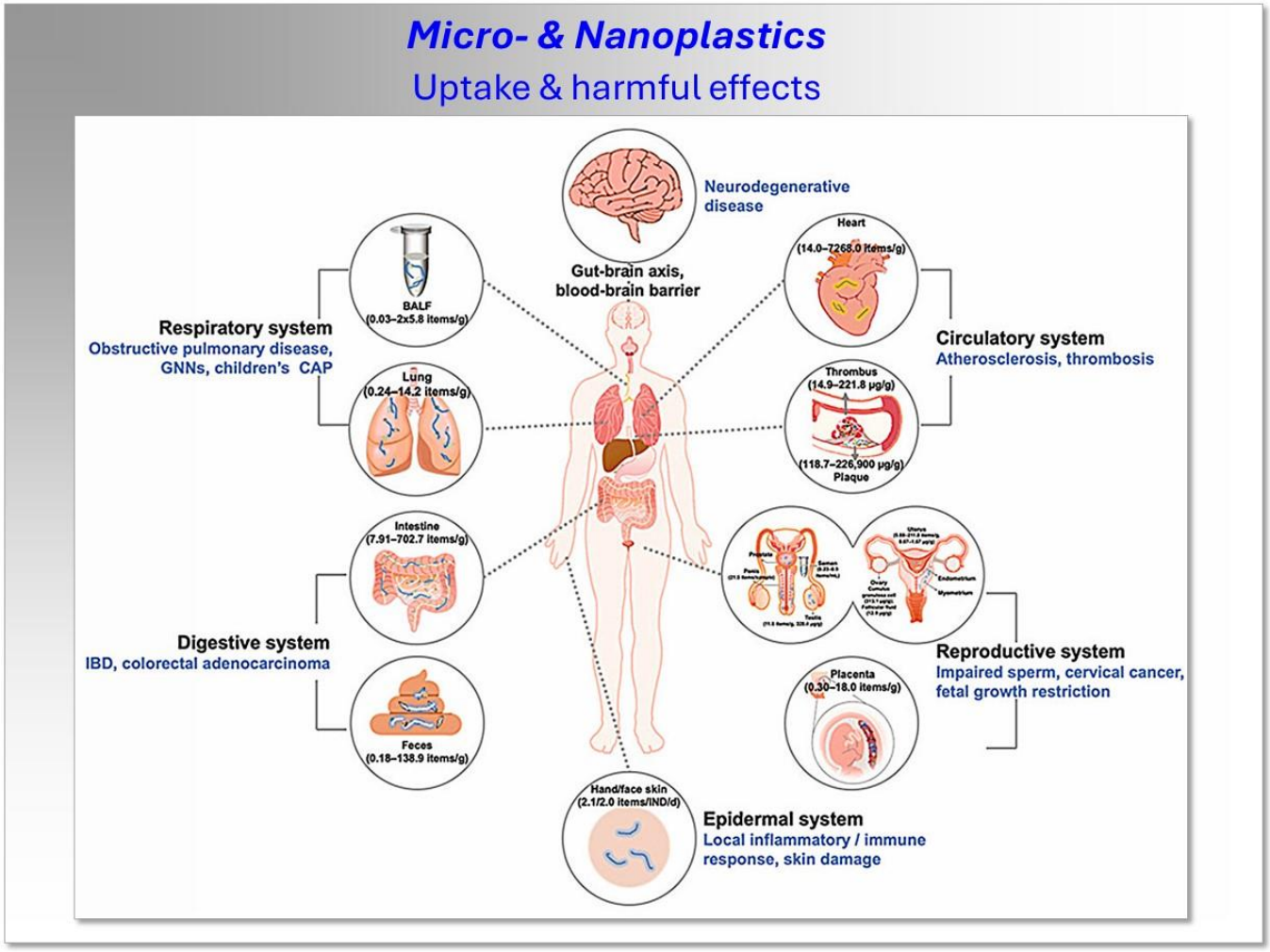


Fig. 10. Potential harmful effects of ingested and inhaled micro- and nanoplastics. Adapted from Patil et al. (2022).

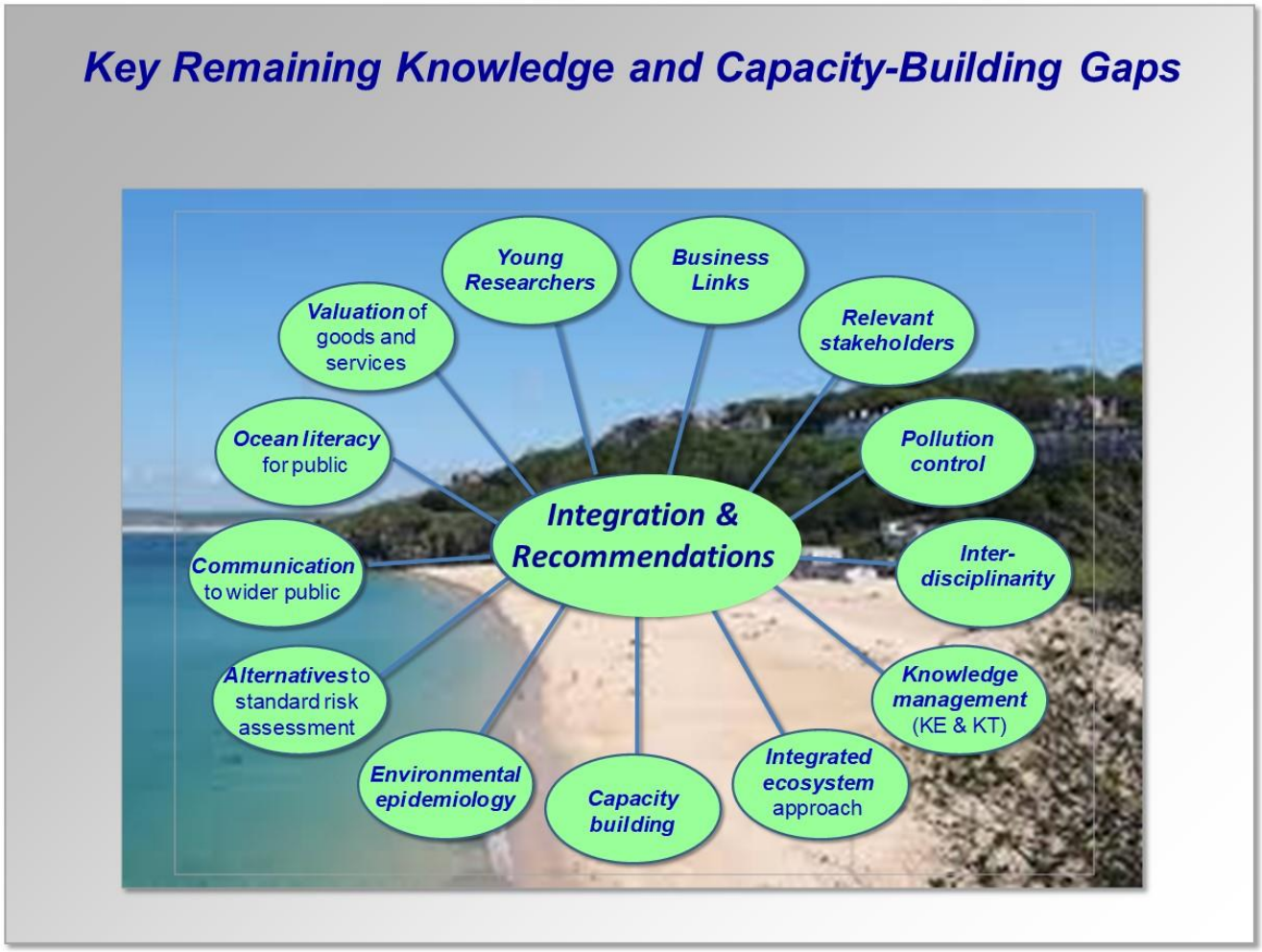


Fig.11. Key remaining knowledge and capacity gaps that are essential to addressfor effective Ocean regulation and management. Adapted from Moore et al. (2014).

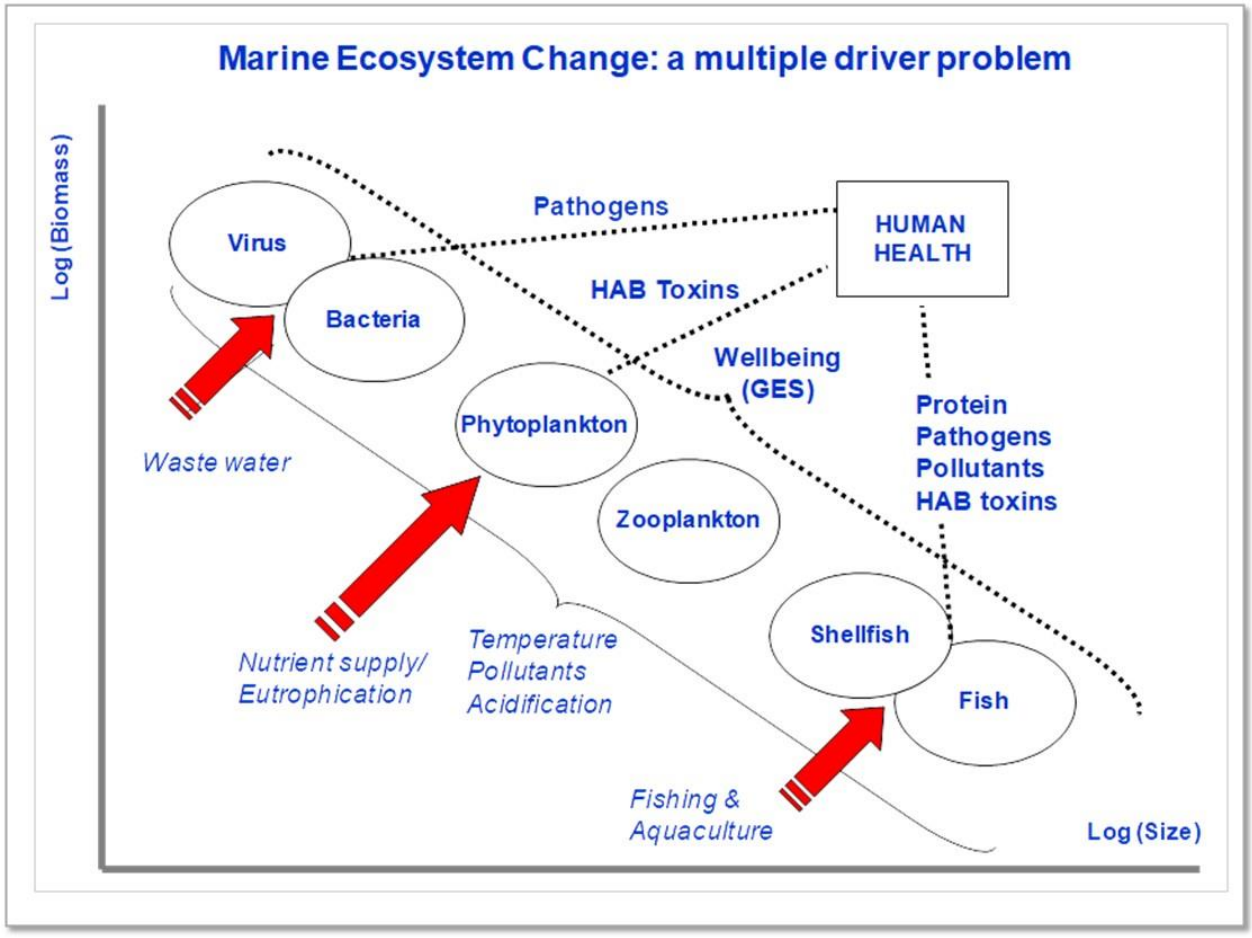


Fig. 12. Schematic diagram illustrating the multiple drivers underlying the various processes contributing to the interactions between marine ecosystems and human health (Courtesy of Prof. J. I. Allen; Allen, 2011; Moore et al., 2014).

Writing Team Members:

Professor Michael Moore (UK) - Co-ordinating Author - POE member

1. **Dr Lorraine Backer (USA) - POE member**
2. **Dr Elisa Berdalet (Spain) - POE member**
3. **Dr Timothy Bouley (USA) - POE member**
4. **Professor Alistair Boxall (UK) - POE member**
5. **Professor Lora Fleming (US) - POE member**
6. **Professor Will Gaze (UK) - POE member**
7. **Professor William Gerwick (USA) - POE member**

8. **Professor Awadhesh Jha (UK) - POE member**
9. **Dr Hanna Joerss (Germany) - POE member**
10. **Dr Jae Ryoung Oh (Republic of Korea) - POE member**
11. **Professor Francesco Regoli (Italy) - POE member**
12. **Professor Aldo Viarengo (Italy) - POE member**
13. **Dr Zhiyong Xie (China) - POE member**

Scientific Advisors who are not direct members of the Writing Team to be noted in Acknowledgements:

Professor Ralf Ebinghaus (Germany) - POE member

Professor Michael Depledge (UK)

Table 1. Selected direct and indirect risks, benefits and opportunities for human health and wellbeing from interactions with the ocean (Fleming et al in press).

Benefit/Opportunity	Healthy Ocean Benefit	Potential Human Health and Wellbeing Benefit	Citations
Climate and weather	The ocean is a key player in the regulation of the planet climate; it is critical to the mitigation of climate change.	Prevention of injury, death and mental health impacts from extreme weather.	Villasante et al 2023; Falkenberg et al 2023
Heat and CO_2 sink	The ocean absorbs 25% of all CO_2 emissions and more than 90% of excess atmospheric heat.	Prevention of extreme heat, drought, crop loss, starvation.	Hoegh-Guldberg et al 2023.
Oxygen	The ocean sustains all life on earth by providing 50% of the oxygen produced on Earth each year and 80% of all the oxygen ever created.	Prevention of crop and other biodiversity loss.	Grégoire et al 2023
Biodiversity (including marine protected areas [MPAs])	Biodiversity sustains food webs and ecosystems richness and productivity. Emerging research with communities living in/around MPAs and other areas designated as 'protected': diverse human health and wellbeing benefits; collaborative and effective management with ongoing involvement of local communities essential towards creating and sustaining these ocean and human health benefits.	Livelihoods, improved nutrition, decreased overall national mortality, and improved child health as well as positive ecosystem impacts.	Madarcos et al 2021; Haque et al 2023; Nowakowski et al 2023; Ban et al 2019; Gollan and Barclay 2020; Rasheed 2020; Winther et al 2020.
Livelihoods and Economics	The ocean is a source of wealth. The ocean economy is estimated to generate US $1.5-2.5 trillion annually and to	Seafood as nutrition and prevention of Non communicable diseases (NCDs)	Dodd et al., 2020; Ocean Panel 2020

	provide jobs for more than 30 million people.	and mental health impacts.	
Marine Biotechnology (including marine drugs)	Ca. 30,000 unique molecules, 10% currently known natural products discovered in marine life; 23 approved pharmaceutical agents have been developed from marine molecules, and an additional 33 are in clinical trials. The ocean is a source of new medicines and biotechnologies, from essential pain medicines to plastic alternatives to essential DNA libraries.	Development of treatments for inflammation, immune system disorders, skin pathologies, infectious diseases, NCDs, and cancers. Alternatives to plastics and creation of sustainable other biomaterials.	Antunes et al 2023; CHEMnetBASE 2023; Pascual Alonso et al 2024; Bouley et al 2023
Seafood and Food Security	For more than 3 billion people, nearly 40% of the world's population, the ocean is an essential source of food, and livelihood.	Prevention of: starvation, childhood stunting, NCDs.	Golden, Koehn, et al 2021; FAO Duke University & WorldFish 2022; Tigchelaar et al 2022; Golden et al 2016
Blue Spaces (including culture)	Interactions with the ocean and with other blue spaces enhance the physical health and mental wellbeing of humans from infancy to old age.	Supports culture, physical health and mental wellbeing.	White et al 2020; Fleming et al 2019
Threat	**Unhealthy Ocean Risks**	**Potential Human Health and Wellbeing RIsks**	**Citations**
Heat	The ocean absorbs more heat, sea surface temperature rises: changes in global and local ocean circulation patterns causing increased frequency of extreme weather, polar ice melting, sea level rise, and coastal flooding; migration of fish stocks from dependent communities; increased harmful	Death Injury Infectious diseases Starvation HAB illnesses Mental health	Nash et al 2017; Falkenberg et al 2023

	algal blooms (HABs); and pathogen spread.	Non communicable diseases (NCDs) Disrupt cultural integrity	
Acid	Increased atmospheric CO_2 absorbed by ocean resulting in low pH causing weakness of calcium skeletons in coral, shellfish, and calcium-containing microorganisms sustaining entire marine web; impacts on fisheries.	Starvation Obesity Mental health NCDs Disrupt cultural integrity	Nash et al 2017; Falkenberg et al 2020
Deoxygenation	Dissolved ocean oxygen decreases as water becomes warmer, creating 'Oceanic dead zones'; impacts on fisheries.	Starvation Obesity Mental health NCDs Disrupt cultural integrity	Grégoire et al 2023; Falkenberg et al 2020
Overfishing	Destructive industrial fishing practices with rising temperatures and pollution damage on ocean ecosystems, biodiversity, and fisheries exhaustion.	Starvation Obesity Mental health NCDs Disrupt cultural integrity Jobs loss in small fishery communities forcing population migrations	FAO. 2022; Golden, Koehn, et al 2021; FAO Duke University & WorldFish 2022; Tigchelaar et al 2022; Golden et al 2016; Maycock 2023
Oil and gas extraction	Fossil fuel extraction and transport with toxic hydrocarbons release, increasing climate change; oil spills: injury, death of marine organisms; destroy biodiversity; impact fisheries.	Death Injury Mental health Increased NCDs Disrupt cultural integrity	Lelieveld et al 2019; Nash et al 2017; Landrigan et al 2020

Deep-sea mining	Deep-sea mining damages: seabed and vulnerable habitats, radiation releases, impacts on fisheries, biodiversity threats.	Obesity NCDs ?Cancer Starvation Disrupt cultural integrity	Hamley 2022; Miller et al 2021; Landrigan et al 2020
Pollution	80% arises on land from human activities includes plastics, heavy metals, oil wastes, manufactured chemicals, pesticides, radiation, and nutrients (including sewage): damages ecological health; biodiversity; impacts fisheries.	HABs illnesses Neurotoxicity Fetal/developmental toxicity Reproductive toxicity Mental health NCDs Cancer Disrupt cultural integrity	Landrigan et al 2023; Landrigan et al 2020; Short et al 2021
Economics	Profit-driven, ocean-based economic development with inequitable andshort-term economic gain; no concern for protecting and preserving ocean health or for health and wellbeing of marginalised coastal communities: biodiversity loss and marine ecosystems degradation.	Occupational injury and death Starvation Mental health Disrupt cultural integrity	Germond-Duret 2022; Das 2023

1 Table 2. Selected Adverse Human Health Impacts from Ocean Interactions

2

Health Threat/ Source of Toxin/Pollutant	Primary Exposure Route	Known Adverse Health Effects (with key references)	Potential Prevention/ Mediation Actions and/or Information to Support Policy-making
Effects of Exposure to Contaminated Seawater, Marine Aerosols & Seafood			
Harmful algal blooms, respiratory distress and toxicity			
Brevetoxins from *Karenia brevis* blooms	Sea breezes during the planktonic *Karenia brevis* blooms	Respiratory distress, asthma exacerbations: Fleming 2011 https://www.sciencedirect.com/science/article/abs/pii/S1568988310000934	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from sea breezes. Monitoring benthic substrates (mainly macroalgae) on shallow beaches to establish early warnings.
Non-identified aerosolized toxins (emerging threat), spreading in temperate coasts with global change	Sea breeze during the benthic *Ostreopsis* spp. blooms	Respiratory distress, general malaise: Berdalet, E., et al. 2022. https://doi.org/10.1016/j.hal.2022.102320 Lemée, R., 2023. https://anses.hal.science/anses-04169914 Funari, E. et al. 2015. https://doi.org/10.1016/j.hal.2015.10.008	

			Coordination of scientists and local authorities. Increasing awareness of the symptoms among general public and medical professionals.
Ciguatera Poisoning, endemic in the tropical latitudes, spreading with global change	Ingestion of fish and some molluscs	Complex array of neurologic, gastrointestinal, cardiovascular, respiratory and psychological symptoms: Chinain, M. et al. 2021. https://doi.org/10.1016/j.hal.2020.101873 Friedman, M. et al. 2017. https://doi.org/10.3390/md15030072	Early Warning Systems for alerting local populations, such as the one implemented in French Polynesia. It includes: - awareness campaigns to warn individuals against specific risk-taking behaviours (most notably with regard to the fish species and parts of the fish

			preferentially consumed), - systematic report of ciguatera poisoning; - prevention messages provided all year-round - public meetings conducted alongside field campaigns. - dissemination tools in local languages for general public, schools, healthcare professionals. Monitoring benthic species using artificial substrates and quantitative qPCR.
Paralytic Shellfish Poisoning (PSP)	Ingestion of shellfish (e.g. butter clams in	Symptoms include nausea, vomiting, diarrhea, numbness and tingling of the lips, mouth, face, and neck; severe cases: paralysis of chest and abdomen muscles possibly leading to death:	Monitoring toxic species in the water and paralytic toxin in

affecting diverse communities in the Pacific coast of America, and Asia (e.g. the Philippines)	Alaska) from subsistence harvesting.	Berdalet, E. et al. 2023, in Fleming L. et al. 2023. ISBN: 978-0-323-95227-9	shellfish guarantee food safety; the challenge is monitoring in remote Indigenous Peoples~~communities~~. This results on economic losses and difficulties for the locals. The problem affects poorer regions of the planet, especially in Asia and Latin America. No data from Africa.
Extreme HAB events, e.g. *Pseudo-nitzschia* blooms in response to the 2014-16 northeast Pacific marine heat	Massive fish kills, poisoning of marine fauna. To date, no known effects of humans because of strict monitoring,	Limited evidence of human poisoning due to *Alexandrium catenella* Trainer, V. et al., 2019, https://doi.org/10.1016/j.hal.2019.03.009	Monitoring of events with reporting of human cases Appropriately targeted messaging for coastal communities regarding ocean-

wave, and HABs in Chile.	but fauna affectation.		borne risks from seafood consumption.
Dinophysis (Diarrhetic) in Europe	Ingestion of shellfish	Nausea, vomiting, severe diarrhea, abdominal cramps, respiratory distress: Reguera et al. 2024, https://doi.org/10.3389/frpro.2023.1328026	Monitoring of events with reporting of human cases Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption.
Allergies, food sensitivities & poisonings from consumption of seafood			
Allergic reactions to seafood	Typically, crustaceans but may include mollusks.	Symptoms include hives, wheezing, trouble breathing, cramps, nausea, vomiting, and anaphylaxis: Wai et al. 2020, https://doi.org/10.3390%2Fijms21062234; Ruethers et al. 2018, https://doi.org/10.1016/j.molimm.2018.04.008 American Academy of Allergy Asthma and Immnology, 2024, Histamine Toxicity Symptoms, Diagnosis, Treatment & Management (aaaai.org), Updated 2024, Accessed 7-1-24.	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption.
Food sensitivities and intolerance	Seafood consumption	Symptoms include bloating, flatulence, constipation, and stomach pain: Muthukumar et al. 2020, https://doi.org/10.1016/j.foodres.2020.109780 González-Delgado et al. 2022, https://doi.org/10.1016/j.jaip.2022.05.006	

Seafood poisonings	Fresh and processed seafood consumption	Wide range of effects, mostly self-limiting, depending on the toxin involved: Ansdell 2019. https://doi.org/10.1016/B978-0-323-54696-6.00049-5 Backer et al. 2004. https://doi.org/10.1201/9780203502358 Takahashi et al. 2019. https://doi.org/10.3390/ijms20102435 Landrigan et al. 2020. https://doi.org/10.5334/aogh.2831	Rapid methods to determine toxin concentrations in suspected seafood and clinical specimens. Global database for reporting human and animal allergies, food sensitivities, and poisonings from consuming seafood. [One Health Harmful Algal Bloom System; One Health Harmful Algal Bloom System (OHHABS) | Harmful Algal Blooms | CDC; National Outbreak Reporting System (NORS); National Outbreak Reporting

			System (NORS) | CDC]. Required reporting for specific foodborne and waterborne diseases [National Notifiable Diseases Surveillance System | CDC] Enhanced seafood monitoring programs. Modeling to connect environmental data with illness data (e.g., electronic health records [Centers for Medicaid and Medicare Services. https://www.cms.gov/]) to allow prediction of increased risks

			[Environmental Public Health Tracking Network https://ephtracking.cdc.gov/].
Asthma induction/exacerbation	Fish processing activities, skin contact, aerosols	Occupational asthma: Anibarro et al. 2023. Occupational asthma induced by fish exposure - PubMed (nih.gov)	Targeting messaging and enhanced personal protective equipment for those working in fish processing activities.
Microbial infections and parasitic infestations from consumption of seafood and seawater exposure (mainly from human sewage & agricultural runoff)			
Seawater infections		Infections (skin/wound, gastrointestinal, ENT, eye, respiratory, blood) associated with ocean exposure, including plastics: Bowley et al. 2022 https://doi.org/10.1016/j.tim.2020.06.011	
Seafood contamination with bacteria	Seafood, ocean plastics exposure	Bacterial infections (skin/wound, gastrointestinal, ENT, eye, respiratory, blood) associated with ocean exposure, including plastics: Iwamoto et al 2010 https://doi.org/10.1128/CMR.00059-09 With plastics Bowley et al 2021 https://doi.org/10.1016/j.tim.2020.06.011	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption.
Vibrio cholera	Seafood	Cholera (severe bacterial gastrointestinal illness): Kanungo et al. 2022 https://doi.org/10.1016/S0140-6736(22)00330-0	

Vibrio vulnificus	Seafood	Gastrointestinal disease, gangrene, death: Archer et al 2023, https://doi.org/10.1038/s41598-023-28247-2	Global database for reporting human and animal allergies, food sensitivities, and poisonings from consuming seafood. [One Health Harmful Algal Bloom System; One Health Harmful Algal Bloom System (OHHABS) | Harmful Algal Blooms | CDC; National Outbreak Reporting System (NORS); National Outbreak Reporting System (NORS) | CDC]. Required reporting for specific foodborne and waterborne diseases [National Notifiable
Norwalk virus	Seafood	Gastrointestinal disease: Campos and Lees 2014, https://doi.org/10.1128/AEM.04188-13	
Parasitic illnesses	Seafood	Gastrointestinal disease : Overstreet 2013, https://doi.org/10.1007/978-1-4419-0851-3_877	

			Diseases Surveillance System | CDC]. Enhanced seafood monitoring programmes.
Anti-microbial resistance (AMR)			
AMR associated with ocean exposure Anti-fungal resistance (AFR) associated with ocean exposure	Water skin and aerosol exposure, ingestion of seafood, beach sand exposure, ocean plastics exposure. Water skin and aerosol exposure,	Resistant or untreatable bacterial infections (skin/wound, gastrointestinal, ENT (ears, nose, throat), eye, respiratory, blood) associated with ocean exposure, including plastics: Krupesha Sharma & Sumithra, 2023, https://doi.org/10.1007/978-981-16-9723-4_6-1 Stevenson et al. 2023, https://doi.org/10.1016/j.scitotenv.2023.168234 Resistant or untreatable fungal infections (skin/wound, ENT (ears, nose, throat), eye, respiratory, blood) associated with ocean exposure: Babic et al. 2022 https://doi.org/10.3390/jof8080860 Stevenson et al. 2022 https://doi.org/10.3389/ffunb.2022.918717	Decreased use antibiotics veterinary and human. Increased environmental and human AMR monitoring. Decrease use of antifungals in veterinary and

	ingestion of seafood, beach sand exposure, ocean plastics exposure.		human medicine. Increased environmental and human antifungal monitoring.
Harmful non-biological pollutants (Chemical, Particle & Radiological Pollution)			
General exposure to pollutants			
Chemical exposure to pollutants in seawater, seafood and sediment/sand	Water skin and aerosol exposure, ingestion of seafood, sediment/ sand exposure.	Dermatologic, Cancer, reproductive, neurologic: Landrigan et al. 2020, https://doi.org/10.5334/aogh.2831 **Multiple toxicological targets:** **Mezzelani & Regoli, 2022, https://doi.org/10.1146/annurev-marine-040821-075606** **Tacon et al., 2023; https://doi.org/10.1080/ 23308249.2023.2238821** **Micro-/nanoplastics can cause alterations of immune system, inflammation, decreased growth rate, and energy unbalance** **Nardi et al. 2024, https://doi.org/10.1016/j.envpol.2024.123327** **Radiological injury** **Smith et al. 2023, https://doi.org/10.1126/science.adi5446**	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption. Global database for reporting human and animal allergies, food sensitivities, and poisonings from consuming seafood. [National Outbreak Reporting System (NORS);

			National Outbreak Reporting System (NORS) | CDC]. Required reporting for specific foodborne and waterborne diseases [National Notifiable Diseases Surveillance System | CDC]. Enhanced seafood monitoring programmes Increased research for toxicological pathology related to consumption of contaminated seafood.

Metals			
Industrial and natural processes	Seafood consumption of pollutant metals and metalloids.	**Neurotoxicity, oxidative stress and cancers EC 2023 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32023R0915**	Appropriately targeted testing of seafood.
Petrochemicals, fires & combustion products			
Industrial and natural processes, incomplete combustion, transport and shipping	Ingestion of seafood, inhalation of aerosols & skin contact.	Polycyclic aromatic hydrocarbons (PAHs) are considered toxic primarily due to their carcinogenic potential, meaning they can cause cancer, particularly of the skin, lung, and bladder, when exposed to significant levels over long periods; other potential toxic effects include impacts on the reproductive system, immune system dysfunction, and developmental issues, especially when exposure occurs during pregnancy; short-term exposure may cause irritation to the eyes, skin, and respiratory tract depending on the level of exposure. International Energy Agency - IEA, 2018; El-Maradny et al., 2023; Rovira et al. 2021; Hassaan et al. 2024; Landrigan et al. 2020; Liu et al., 2023; Montuori et al. 2021; Shi et al., 2022; Speight, 2019	Appropriately targeted testing of seafood.
Persistent organic pollutants			
Industrial	Seafood consumption.	**Oxidative stress, increased cancer risk, reproductive disorders, alteration of the immune system, neurobehavioral impairment, endocrine disruption, genotoxicity and increased birth defects** **Ritter et al., 1995; Stockholm Convention – pops.int** **https://www.pops.int/Home/tabid/2121/Default.aspx**	Appropriately targeted testing of seafood.
Neurotoxic pesticides and agrochemicals			
Agricultural / industrial from wastewater and land runoff	Seafood consumption.	Neurotoxicity contributing to Parkinson's Disease and possibly to Alzheimer's Dementia: **Richardson et al., 2019**	Appropriately targeted testing of seafood.

Pharmaceuticals and endocrine disruptors			
Industrial production, use by the patient or in veterinary use, and ultimate disposal including hospital waste	Bathing and seafood consumption.	**Toxicological risks of exposure have not yet been established although human health assessment for APIs contaminating freshwater environments would suggest that the level of risk from this route is likely to be low (WHO, 2012):** **WHO (2012) Pharmaceuticals in drinking water** **https://iris.who.int/bitstream/handle/10665/44630/9789241502085_eng.Pdf;jsessionid=A04913BAAEDED316C54839D2D9A8404F?sequence=1** UBA - Umweltbundesamt (2024) Database- pharmaceuticals in the environment https://www.umweltbundesamt.de/en/database-pharmaceuticals-in-the-environment-0#undefined **Madikezela and Ncube, 2022**	Precautionary ~~Principle~~ approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood and bathing water.
Contaminants of emergent concern			
Industrial waste, domestic wastewater	Seafood consumption.	**Endocrine disruption including reproductive and gender abnormalities in marine life and may contribute to human gender dysphoria Combi et al. 2022; Guo et al. 2023; Cocchetti et al., 2022; Liu et al. 2023; Xie et al. 2022**	Precautionary ~~Principle~~ approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood.
Micro-/nanoparticles (including plastics) and from road runoff			
Industrial waste, atmospheric pollution,	Seafood consumption & inhalation/i	May contribute to endocrine disruption, oxidative stress, dementias & cancers **Amelia et al. 2021; Andrade et al. 2021; Megha et al. 2024; Ciocan et al. 2024**	Precautionary ~~Principle~~ approach and further

runoff from highways & degradation of fibreglass boat hulls	ngestion of marine aerosols.		toxicological assessment focused on human health. Appropriately targeted testing of seafood.
Environmental radiation			
Nuclear industry & historical weapons testing	Seafood consumption, exposure to bathing water & inhalation /ingestion of marine aerosols.	Radiation injury, oxidative stress & cancers **Matsumoto et al., 2021; Smith et al., 2023**	Appropriately targeted testing of seafood and bathing water.
Pollutant interactions			
Multiple sources: seafood consumption & inhalation/ingestion of marine aerosols	Seafood consumption, exposure to bathing water & inhalation/ingestion of marine aerosols.	Synergistic and antagonistic toxicities in animal investigations Forest, 2021; Moore et al., 2021; Albani et al., 2023; Gauthier et al., 2014; Martin, 2023; Moore et al., 2018	Precautionary ~~Principle~~ approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood.

1

2

3

Section 5B
Chapter 3: Human well-being

Coordinating Author – Phoebe Koundouri

Team Lead – Donovan Campbell

Co Lead – Slimane Maliki

Contributing Authors (as of 31/10/24)

Phoebe Koundouri[1], Anastasia Litina[2], Laura Onofri[3], Alana Lancaster[4], Conrad Landis[5], Jiang Nanqih6[2], Ali Mashayek[7]

[1] Prof. Dr. Phoebe Koundouri Professor of Economics at Athens University of Economics and Business and Technical University of Denmark~~, Professor in Economics at Athens University of Economics and Business & Technical University of Denmark~~, Chair World Council of Environmental and Resource Economists Associations, Chair SDSN Global Climate Hub, Director of AE4RIA

[2] Prof. Anastasia Litina, Professor in Economics at the University of Macedonia, Research Fellow at the University of Luxembourg, Associated Researcher at AE4RIA

[3] Laura Onofri, Adjunct Professor at IUAV University of Venice and U.N. consultant~~Adjunct Professor at IUAV University of Venice, U.N. consultant~~

[4] Alana Malinde S.N. Lancaster, Lecturer in Law at the University of the West Indies, Head of the Environmental Law, Ocean Governance & Climate Justice Unit, Regional Director for GNHRE Caribbean, Researcher with the One Ocean Hub

[5] Dr. Conrad Felix Michel Landis. Senior Researcher, AE4RIA, Adjunct Professor, Athens University of Economics and Business

[6] Dr. Nanqing Jiang, Executive Director, Institute of Carbon Neutrality and Circular Economy, Research fellow of College of Plastic Circular and Innovation of North East Normal University, Secretary General of Circular Industry Committee of World Green Design Organization

[7] Prof. Ali Mashayeк, Associate Professor at the Department of Earth Sciences. University of Cambridge

Key Findings

- We discuss the intrinsic value of oceans beyond economic benefits, enriching human life through cultural, recreational, and ecological contributions.
- We emphasize non-economic benefits of oceans, like cultural and ecological value.
- To quantify intangible benefit of oceans (e.g., clean air, biodiversity, and recreational spaces) we use non-market valuation methods.
- Marine environments can boost subjective well-being and provide mental health benefits such as stress relief and emotional resilience—aspects that are central to the "blue health" concept.
- Concerning spiritual and cultural life, oceans support cultural practices, spiritual connections, and knowledge sharing across generations. This can strengthen identities and resilience within communities.
- Ocean-based recreational activities benefit physical and mental health, foster social bonds, community cohesion, and an appreciation for the environment.
- Potential risks to marine ecosystems and human well-being are climate change, pollution, and resource depletion.
- Sustaining fisheries preserves livelihoods, cultural heritage, social cohesion, and intergenerational well-being.

1. Introduction

This chapter provides an overview of the various ways oceans contribute to human well-being, exploring the interplay between the ocean ecosystems health and aspects of human prosperity. While the economic advantages that oceans offer to global and local communities are substantial, this chapter focuses on the non-economic benefits that contribute to well-being beyond measurable financial value (Koundouri et al, 2015; 2019). An assessment of economic benefits is covered elsewhere in the Third World Ocean Assessment (see e.g, Sections 5A, Chapters 4, 5A, 6, 7 and 9), enabling this chapter to center on the intrinsic value of oceans—such as cultural, mental health, recreational, and community-supporting roles.[112]

[112] Details and information on methods that can be usefull to reflect values to subjecitve well-being can also be found in Termansen et al. (2022).

Through welfare economics and non-market valuation, such as contingent valuation and travel cost methods, this chapter illustrates how quantifying these benefits informs sustainable policy-making. It explores various aspects such as the concept of "blue health," underscoring the mental and physical health advantages that arise from proximity to marine environments (see also Section 5A, Chapter 2). Community-focused case studies show the essential role oceans play in supporting cultural identity, heritage, and social cohesion, underscoring the need for inclusive, sustainable ocean management (see also Anderson et al. 2022; Brondizio ~~Bronditio~~ et al., 2019). Confronting threats like climate change and pollution is crucial to maintaining these benefits, and a wide-ranging governance approach will help sustain the critical connections between ocean health and human well-being for future generations.

2. Welfare Economics of Non-market Valuation

When aiming to examine the value that oceans provide beyond monetary metrics, we resort to welfare economics as it reveals a critical aspect of non-market valuation. Several examples of non-market goods and services, such as clean air, biodiversity, and recreational spaces, contribute non-trivially to human well-being (Millennium Ecosystem Assessment, 2005). Crucially though they are difficult to measure in traditional economic terms, as there are no consolidated markets. We thus need to find ways to capture this wide range of these non-market benefits, contributing not only to global ecological balance but also to quality of life, cultural heritage, and community cohesion.

Several methods can capture various environmental aspects such as the Contingent Valuation Method *(survey-based WTP approach, see e.g.,* Carson, 2012), the Travel Cost Method *(value from travel expenses, see e.g.,* Ward & Beal, 2000), Choice Experiments *(hypothetical choice modeling, see e.g.,* Louviere et al., 2000), Hedonic Pricing *(property price analysis, see e.g.,* Rosen, 1974), and the Replacement/Restoration Cost Method *(cost to restore ecosystems, see e.g.,* Freeman, 2003).

Among these methods, we will focus and discuss the *Contingent Valuation* and the *Travel Cost Method* as they are well-suited for capturing the intangible benefits of ocean ecosystems.

Valuation Methods

i) *Contingent Valuation Method (CVM):* Contingent valuation is a survey-based technique, that assesses people's willingness to pay (WTP) for preserving or restoring environmental goods. This approach is instrumental in gauging public support for conservation frameworks, particularly for intangible goods like ocean habitats or biodiversity, where direct market prices are absent. As Carson (2012) and Hanemann (1994) outline, contingent valuation is valuable when assessing non-market assets like ocean ecosystems. Examples include respondents indicating their WTP in order to protect marine biodiversity and evaluate the value of experience of ocean education (Lee and Kim, 2023). This approach provides a monetary estimate of the perceived worth of ecosystems. ~~.~~

ii) Travel Cost Method (TCM): A second method is the travel cost method. It estimates economic values associated with recreational sites by analyzing the expenses visitors incur to access these sites (see e.g., Padilla and Diswandi (2024), Parsons (2003) and Ward & Beal (2000)). When applying this method to marine parks or coastal areas, we use travel costs as a proxy to the value that visitors define on the recreational usage of ocean spaces. Visitor costs represent the recreational value of these sites (e.g., access fees for marine reserves), helping us understand how recreational goods contribute to the overall valuation of ocean ecosystems (Ward & Beal, 2000).

The overall contribution of market valuation in environmental cost-benefit analysis (CBA) is that it measures the benefits of ecological services against its potential costs (see e.g. Boardman et al.). Elsdon et al (2017) and Pearce & Turner (1990)) integrate non-market values in CBA to inform decision making regarding marine protection or pollution control.

~~Using these methods, policy makers assess non-market values and thus recognize ocean benefits such as climate regulation, biodiversity preservation, and public health, which might otherwise be underestimated or overlooked.~~ An important dimension that further relates to these approaches is the valuation of sustainable fisheries and ocean-based livelihoods. For many coastal communities, oceans are not only ecosystems to be protected but also vital sources of income, nutrition, and cultural identity. It is thus important to acknowledge the role of fisheries in supporting well-being. The latter is particularly true in low-income or food-insecure regions as it ensures that valuation frameworks reflect the full spectrum of ocean-related benefits. Moreover, in terms of policy, this is particularly relevant for designing inclusive policies that aim

to balance conservation goals and couple them with the needs of those who directly depend on marine resources for their living.

Using these methods, policy makers assess non-market values and thus recognize ocean benefits such as climate regulation, biodiversity preservation, and public health, which might otherwise be underestimated or overlooked.

Case studies further demonstrate how non-market valuation impacts marine policy (Koundouri et al, 2022;2023b) and discuss how valuations influenced the establishment of marine protected areas and guided decisions on resource allocation and conservation (see e.g., Spash (2000) and Costanza et al. (1997)). Through quantification of benefits derived from oceans, valuation methods hint to policies that can sustain marine ecosystems, ensuring oceans continue to support human welfare.

Another element, when considering the intrinsic nature of ocean resources is their public good characteristics. As every public good, oceans are non-excludable and non-rivalrous, meaning that first, access cannot easily be restricted, and second, one person's enjoyment does not diminish another's. At the same time, it is also essential to highlight that oceans often exhibit traits of common-pool resources rather than purely public goods, making them vulnerable to overuse or congestion if not carefully managed. All these complexities are explored in Ostrom (1990) and Samuelson (1954). The argue that such goods complicate valuation efforts, especially when trying to establish boundaries for WTP or equitable resource allocation. To complicate things further, another aspect policymakers need to consider is intergenerational equity (on equity see also Section 5BA, Chapter 5). This implies that one needs to ensure that ocean resources benefit present and future generations and this intergenerational nature needs to be accounted for when using this resource. It is important to preserve oceans to allow future generations to enjoy their substantial non-use values. Especially the latter, are challenging to measure because they reflect primarily intangible and non-measurable benefits like cultural heritage and intergenerational welfare. To be able to estimate how much individual value the existence or preservation of ocean ecosystems one can resort to survey techniques (Krutilla (1967) and Loomis (2000) and Halkos et al. (2024)). Via the process of developing methods to capture the intangible worth of oceans,

from recreational and health benefits to climate regulation and cultural significance, we allow for policies that honor the oceans' essential, enduring role in a world facing challenges.

3. Subjective Well-Being

Based on the knowledge obtained from welfare economics and non-market valuation, the next chapter focuses on subjective well-being so as to explain additionally how ocean environments can be a source of well-being to an individual and a means of community sustainability.

Welfare economics as a field focuses on two aspects, i.e., efficiency (maximizing total benefits) and equity (ensuring distributional fairness) (see e.g., Pigou, 1920). A core key here is that of subjective well-being (SWB), which measures self-reported life quality. As such it can capture factors like life satisfaction, happiness, and mental health. Studies by Kahneman and Krueger (2006) underscore how important are environmental conditions in shaping SWB, thereby illustrating how positive physical spaces can foster happiness and alleviate negative emotions.

When we focus specifically on marine environments, we see that their natural characteristics create unique psychological and emotional experiences that contribute to people's well-being. Moreover, oceans often carry important spiritual and cultural values, adding another layer to how they enhance SWB. Taken together, these considerations highlight the critical role oceanic environments play in improving mental health and overall happiness, positioning them as key contributors to both individual welfare and broader community resilience.

A concept that reflects all these distinctive health benefits of spending time near or in water bodies, and especially marine environments is that of "Blue health". Various strands of research underscore that proximity to blue spaces can significantly impacts mental and physical health and thus offer opportunities for both active and passive engagement with nature. For example, Gascon et al. (2017) argue that time spent near blue spaces is associated with stress reduction, enhanced mood, and increased opportunities for physical activity. All of these benefits are most noticeable in coastal communities where enjoying activities such as swimming, walking on the beach and being near water which can reduce anxiety, is good for heart health and helps boost emotional resilience (Kronsted et al, 2023).

Marine environments are especially restorative because their sensory perceptual qualities are, and so this helps them become some of the most important places where attention can be

directed. At least partly due to their natural sound, vastness of open water, and the impression of a relaxing atmosphere associated with these bodies of water (see e.g., Völker and Kistemann (2011)), researchers highlight that blue spaces such as oceans and rivers may offer health benefits beyond those provided by green spaces. All of which can be activated via nurturing physiological responses, like decreased blood pressure and cortisol levels, to aid in the reduction of stress (see e.g., Gascon et al, 2017). For this reason, the oceans can serve as natural refuges for people and communities alike, providing some respite from the pressures of modernity and urban living.

Long-term wellness is also enhanced by the physical advantages of blue health (see, for example, White et al., 2020). Living close to the sea can also encourage people to work harder because people who live along the coast are more likely to walk, swim, or play sports outside. People will primarily benefit automatically from this, and it may result in improved physical health outcomes. It is possible to view the disparity between water availability and physical activity as a catalyst for blue health, which is vital to communities. Additionally, it educates everyone on the value of walking near the sea, which can infuse one with a sense of physical and mental vitality. Beyond that, we could argue that ocean-related activities for the family could establish a real relationship among members, create interconnectedness among generation members and build mutual respect for coastal-culture.

The influence of marine environments on mental health is a significant factor in addition to the physical advantages of being close to the ocean. Being close to water and other natural settings is consistently linked to lower stress levels, happier moods, and better cognitive performance. Living near green and blue spaces is associated with lower psychological distress and higher life satisfaction, according to a number of researchers (e.g., White et al., 2013). It is frequently the case that oceans provide a peaceful setting in which people frequently express feelings of calm, which can lessen anxiety and depression. A respite from the noise and cognitive demands of the city is also offered by ocean environments, which promote mental renewal.

Additional research by Pearson and Craig (2014) highlights the specific mental health benefits derived from outdoor environments, including oceans. They argue that natural spaces encourage mindfulness which can in turn help individuals to focus on the present moment and temporarily

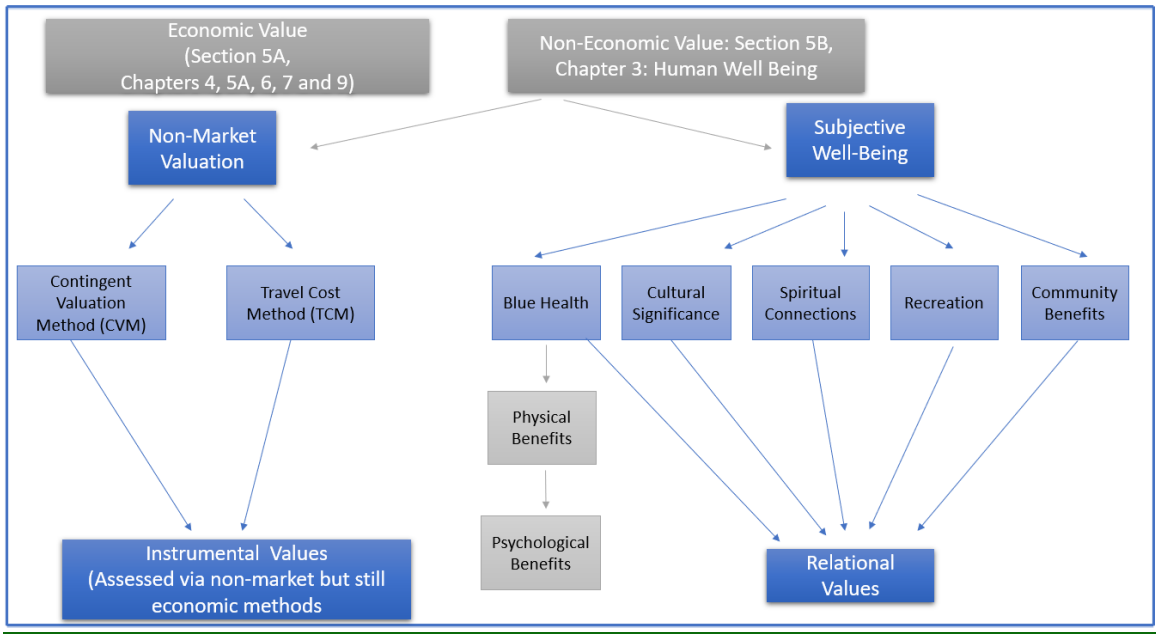
distance themselves from stressors. As a result, this shift of attention in crucial for mood regulation and helps in building resilience to mental fatigue.

In the light of the substantial benefits oceans provide for SWB and blue health, there are strong policy arguments for ensuring equitable access to coastal areas. Some measures that local governments and urban planners can prioritize are the development of accessible blue spaces, especially in areas where communities face socioeconomic barriers to such environments.

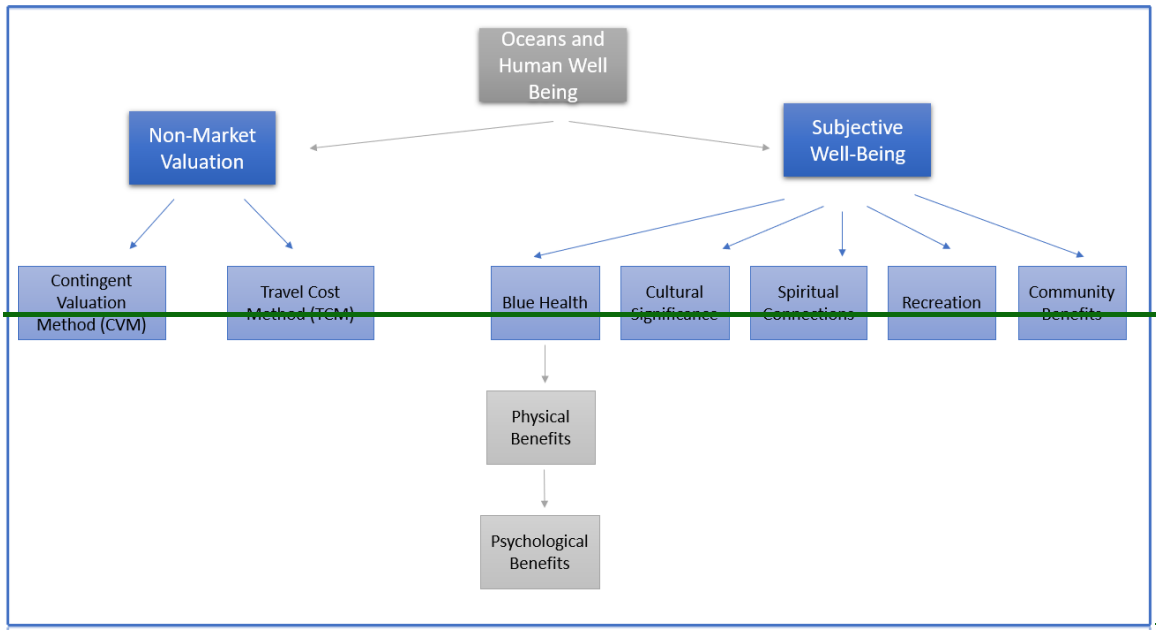
At the same time, it is important to acknowledge that expanding access to blue spaces for recreational purposes, such as tourism and leisure, may create tensions with the livelihood activities of local coastal communities. One example is the fact that increased beach access or tourism infrastructure can disrupt traditional fishing zones or compromise ecosystem health. This in turn can affect the well-being of those who rely on the ocean for their income and cultural practices. This is a critical issue that policymakers have to factor in their decision-making process. They must carefully balance the recreational and economic uses of marine spaces and ultimately ensure that on the one hand blue health benefits are equitably distributed, whereas on the other hand that local fishing communities are not marginalized in the pursuit of tourism-driven well-being.

Co-management approaches and stakeholder engagement can help mitigate such conflicts by integrating both local needs and environmental sustainability into planning. Additionally, actions that facilitate access to coastal areas or maintain affordable public beach access can contribute to building up mental and physical health across populations, while at the same time protecting local production.

In conclusion, we must preserve the health of ocean ecosystems to sustain their therapeutic benefits. Finally, enhancing the protection of coastal and marine ecosystems against pollution, habitat degradation and climate impacts will also be crucial to maintaining their natural contributions for mental health and well-being. To achieve this, it may necessitate the need to highlight the importance of limits on coastal development, the financial support of marine protected areas, as well as solutions that can synthesize climate change with ocean landscapes in the long-run.



1



2

3 *Fig1. Conceptual Framework Linking Oceans and Human Well-Being. This diagram illustrates the relationship*
4 *between* ***oceans and human well-being****, highlighting two main pathways:* ***Non-Market Valuation*** *and* ***Subjective***
5 ***Well-Being****. In the graph we align with the* ***IPBES Values Assessment (Anderson et al., 2022)****.*[113]

113

While economic valuation methods—market-based or non-market—play a key role in capturing instrumental values, especially for decision-making in environmental policy, this chapter does not expand on the full range of economic valuation techniques (see instead Sections 5A, 6, and 9). Our focus lies in emphasizing subjective well-being and non-economic dimensions that complement conventional valuation approaches.

4. Applications

4.1 Cultural Significance

For millennia, oceans have been a source of cultural meaning — an important part of the stories, identities and traditions that shaped countless societies throughout human history. Their role is multifaceted. They are not only intertwined with livelihoods in coastal communities but also contribute to cultural expressions and help maintain intangible heritage. There are several aspects to consider that are linked to maritime heritage such various practices, beliefs, and customs that have evolved around the sea, from fishing traditions to artistic expressions (see also Section 5A, Chapters 1A and 1B). All these are living proof as to how oceans shape the lives and identities of those who live near them. In this section we underline the vital role oceans play in supporting cultural practices, the preservation of intangible heritage, and intergenerational knowledge transfer.

When considering maritime heritage, it includes a vast array of cultural expressions, such as traditional fishing techniques, navigational knowledge, storytelling, and festivals that celebrate the connection between communities and the sea. For several coastal societies, oceans have been central to cultural identity, offering material and symbolic resources. Prominent examples include traditional maritime songs, dances, and rituals that are expressions of local identity and reinforce the importance of ocean conservation. It is frequently the case that coastal communities incorporate these expressions into local festivals and ceremonies, celebrating the ocean as a life-giving force (Berkes, 2012).

Instrumental values refer to the usefulness of nature as a means to achieve human ends. This is typically expressed through benefits such as provisioning, regulating, and cultural services. In this figure, they are assessed via non-market valuation tools like CVM and TCM, yet remain rooted in economic frameworks. This aligns with the IPBES Values Assessment, which frames instrumental values as those that view nature in terms of its capacity to satisfy human preferences, whether directly (e.g., food, water, recreation) or indirectly (e.g., ecosystem regulation).

Relational values, by contrast, describe the meaningful relationships individuals and communities have with nature, such as cultural identity, place attachment, or responsibilities to protect ecosystems. These values are especially relevant to concepts like community well-being, spiritual connections, and cultural significance. IPBES highlights relational values as essential for understanding how people define a good life in connection with nature, extending beyond utility or market proxies.

Another aspect is that of food culture, where oceans also provide culturally significant food sources integral to culinary traditions (see also Section 5A, Chapter 1). We can consider several types of food that are culturally relevant, such as traditional seafood dishes which can eventually reinforce community bonds and strengthen the connection between people and the ocean. As such access to culturally relevant food resources sustains dietary customs and maintains the cultural heritage of coastal societies. Besides its cultural significance we can also consider its nutritional value, essential for the overall health and well-being of those communities see also Section 5B, Chapter 2).

Additionally small-scale fisheries are a principal vehicle for nutrition, livelihood, and cultural identity for coastal people, thereby underscoring their deep social and economic connection with the Ocean. Aside from their economic contribution, these fisheries preserve biodiversity, remain a stronghold for community identity, and sustain intangible cultural practices that have been passed on for centuries (additional discussion can be found in the Third World Ocean Assessment, Section 5 A, sub-chapters 1a-1d).

In the process of preserving cultural practices associated with the ocean, the transfer of traditional knowledge is essential. Cultural knowledge is a concept that includes ecological wisdom and spiritual beliefs tied to the sea and critically it is often passed down through generations. As such, a vital aspect to this transfer is intergenerational equity. To achieve this each generation inherits both the responsibility and privilege of caring for the ocean (see e.g.Poe et al, 2014). A typical example is knowledge about marine ecosystems, seasonal fish patterns, and sustainable harvesting techniques which forms a knowledge base that supports both ecological health and cultural continuity (Berkes, 2012).

All these underline that the concept of intergenerational equity is central nowadays as ocean ecosystems face increasing environmental threats. We need to find the ways to ensure that future generations have access to healthy oceans with that being not only an ecological responsibility but also a cultural one. Whenever we observe that knowledge transfer is disrupted—whether by environmental degradation, restricted access to coastal areas, or loss of language and practices—cultural connections to the ocean risk are in the threat of being lost. Therefore, policies that support traditional knowledge transmission and promote sustainable ocean management are crucial for preserving cultural heritage (Koundouri et al, 2023).

4.2 Spiritual Connections

An ~~increasing~~ increasingly essential aspect for human well-being ~~are~~ is the concept of Ecosystem services (ES). This concept conveys the idea that natural systems may generate and provide a broad ~~has evolved to encompass a r~~range of benefits. ~~provided by natural systems~~ (M~~E~~EA, 2005). Cooper et al. (2016) report that the MEA contains 335 entries ~~occurrences~~ of 'spiritual'. "*Spiritual ecosystem services (SES) can be defined as a "subset" of cultural ecosystem services that provide intangible benefits to human well-being, such as inspiration, connection to nature, and a sense of place*" (Kondouri et al., 2025, pag 1)

Cultural, religious, and individual beliefs are frequently entwined with the services provided by the spiritual ecosystem. From the individual experiences and feelings connected to nature to the subjective beliefs and sense of sacredness, the spiritual ES offers numerous advantages, from the beauty and wonder of natural landscapes to the symbolic and religious significance of ecosystems.

~~The spiritual ecosystem services are often intertwined with cultural, religious, and personal beliefs. The spiritual ES provide many benefits, spanning from the sense of connection to nature and a larger universe; from the beauty and wonder of natural landscapes to the symbolic and religious significance of ecosystems, form the personal experiences and emotions associated with nature to subjective beliefs and sense of sacred.~~

Associated Literature

The reviewed literature on the economics of spiritual values of ecosystem services emphasizes that to fully realize the variety of advantages that ecosystems offer, conventional economic frameworks must be revised.

~~The surveyed literature on the economics of spiritual values of ecosystem services highlights the need to go beyond traditional economic frameworks to capture the full range of benefits provided by ecosystems.~~ While challenges remain, advancements in methodologies and a growing

recognition of the importance of spiritual values offer opportunities for more comprehensive and inclusive assessments of ecosystem services. By understanding and valuing spiritual values, we can better protect and manage. These services are often difficult to quantify and measure, making their assessment challenging. The measurement in economic terms of spiritual ES is still an open debate. While traditional economic valuations often focus on tangible, market-based benefits (e.g., food, water, timber), the intangible, non-market benefits, including spiritual and cultural aspects, are becoming more widely recognized. These values, which are frequently ingrained in cultural, religious, and personal beliefs as well as human-nature ties, are essential for comprehending the complete societal welfare and value of ecosystems but are frequently disregarded during decision-making processes. ~~there is growing acknowledgment of the intangible, non-market benefits, including spiritual and cultural values. These values, often deeply rooted in human-nature connections, cultural, religious, and personal beliefs are crucial for understanding the full social welfare and worth of ecosystems and are often overlooked in decision-making processes~~ (see e.g., Brander et al, 2024; Duha et al, 2023).

~~However, as the importance of nature-based solutions for addressing societal challenges becomes increasingly recognized, the need for a comprehensive understanding of SES has grown. Governments and organizations are increasingly recognizing the importance of incorporating spiritual values into decision-making processes Incorporating spiritual values into conservation planning can help ensure that ecosystems are protected and managed in a way that respects cultural and spiritual needs. Economic assessments can assist in making informed decisions about land use, development, and resource allocation. Recognizing the importance of spiritual values can foster greater public engagement in environmental issues. Incorporating spiritual values into policies can provide a more comprehensive assessment of the costs and benefits of development projects. Spiritual values can play a crucial role in fostering community involvement in conservation efforts.~~ owever, the necessity for a thorough grasp of SES has increased as the requirement of using nature-based solutions to address social issues is becoming more widely acknowledged. The significance of integrating spiritual values into decision-making processes is becoming more widely acknowledged by governments and enterprises. Ecosystems can be safeguarded and managed in a way that valorizes cultural and spiritual requirements by

including spiritual values into conservation planning. Making well-informed judgments about resource allocation, development, and land use can be aided by economic assessments. Increased public involvement in environmental concerns can result from acknowledging the significance of spiritual values. A more thorough evaluation of the advantages and disadvantages of development projects can be obtained by including spiritual values into policy. Promoting community participation in conservation initiatives can be greatly aided by spiritual principles.

Most studies contain qualitative valuation methods. In fact, while traditional economic valuation methods (e.g., contingent valuation, hedonic pricing) are often used to assess tangible benefits, they may not fully capture the spiritual values of ecosystem services. Monetary valuation of these services is a complex and often controversial task. E~~While e~~conomic valuation is fundamental to ~~crucial for~~ decision-making and policies related to ~~and~~ resource allocation, however, ~~,~~ the process of attaching a value expressed in monetary terms to ~~it can be challenging to as~~benefits with an ~~sign a monetary value to i~~intangible, subjective content can be very complex~~benefits. Quantifying spiritual values is complex due to their subjective and often intangible nature~~. Spiritual ES are inherently subjective and often difficult to express in quantitative terms. This makes it challenging to develop standardized assessment methods. The value and significance of spiritual ES vary across different cultures, religions, and individual experiences. This implies ~~means~~ that valuation ~~assessment~~ methods have to be ~~must~~ be flexible and adaptable to diverse contexts[114].

[114] Nonetheless, scholars have explored various methods:

- Qualitative methods: Interviews, focus groups, experts' elicitation and assessment, local communities involvement, and participatory mapping can provide insights into the subjective experiences, perceptions and beliefs associated with ecosystems.
- Integrated Multidisciplinary Assessment Methods: This framework integrates cultural, ecological, and economic perspectives to assess the full range of ecosystem services, such as provisioning, regulating, and cultural services. Those include ethnographic studies (that can provide insights into the cultural significance of spiritual ES within specific communities); spatial analysis techniques to identify areas that are important for spiritual ES provision; studies combining qualitative and quantitative methods; benefit transfer; remote sensing and GIS, are enabling new approaches to assessing spiritual ES.

~~It is worth highlighting that most ES associated to spirituality are forests and marine/coastal areas, that is, areas linked to water (Nevzati et al., 2023). Spiritual ecosystems, in any case, are surely considered (and measured) as values because the spiritual ecosystem services always conveys well-being, welfare, benefits, even if declined and defined in many different dimensions and facets: inspiration, freedom, sense of transcendence, interconnection with the natural element (i.e. ocean, forest), sense of sacred conveyed by the site located in the nature, or in the urban context, implementation of the concept of "creation", symbolic ancestral origin of humanity, synthesized by the myth. Personal or social assessments of benefits, wherever geographically or ecologically applied, are values.~~ It is important to note that the majority of ES linked to spirituality are located in coastal and marine sites, or places that are connected to water (Nevzati et al., 2023). In any case, spiritual ecosystems are unquestionably regarded (and quantified) as valuable because they consistently convey well-being, welfare, and benefits, even when they are declining and defined in a variety of ways. These benefits include inspiration, freedom, a sense of transcendence, a connection to nature (such as the ocean or forest), a sense of sacredness conveyed by the location in nature, or in an urban setting, the application of the concept of "creation," symbolic ancestral origin of humanity, synthesized by myth. Values are individual or societal evaluations of benefits, whether they be applied spatially or environmentally.

Recent studies in the field are beginning to integrate both quantitative and qualitative data-gathering techniques, such as interview surveys and case-study analyses, to identify and measure the spiritual importance ascribed to attributes of a specific ecosystem. The evidence-based approaches employed complement the chapter's reflective views while offering certain metrics or narratives that clearly depict how the spiritual value converges with ecosystem services. One example is the work by Cooper et al. (2016), who combined both survey data and in-depth interviews to explore how individuals perceive and value the spiritual and aesthetic qualities of ecosystems. This mixed-methods approach provided quantitative indicators, such as the frequency and degree of spiritual significance reported, and qualitative insights into participants' personal and cultural connections with natural landscapes.

Quantifying spiritual values, however, presents unique challenges. Spiritual values are highly subjective and vary across individuals and cultures. Spiritual values are not traded in markets, making it difficult to assign monetary values. Moreover, methods that are survey-based may be subject to biases, such as hypothetical bias or anchoring effects. Last, the act of monetizing spiritual values can raise ethical concerns about commodifying intangible aspects of human experience. On the other hand, understanding the economic value of spiritual values can inform policy decisions and resource management: by understanding the challenges and opportunities associated with assessing SES, researchers can develop more effective methods for valuing and protecting these important ecosystem benefits (Cheng et al, 2019).

Methodological Approaches to Assess SES

In order to assess SES we often rely on qualitative and participatory approaches, reflecting the intangible nature of spiritual values. One example is Sangha et al. (2018) that utilized a value transfer approach in Northern Australia, where Indigenous Peoples~~communities~~ derive spiritual and well-being benefits from coastal and marine resources. The finding of their study shows how SES can be captured by understanding the cultural narratives and symbolic meanings attached to natural resources, a perspective especially relevant for Indigenous People~~communities~~s. Likewise, are Klain et al. In British Columbia, (2014) interviewed marine resource users and found that the spiritual link to the ocean is important to interrelationships associated with personal identity as well as collective meanings of oneself.

A feature of those studies is their participatory orientation consistent with the methods in the work of Bryce et al. Johnston et al. (2016) who assessed SES at broad scales using hedonic measures of subjective well-being. They measured values — including sense of place, belonging and intergenerational continuity — through surveys and interviews. Such approaches shed light on how SES contribute to subjective well-being because participants also emphasize their relationships with particular natural places, which elicit reverence and respect for nature (Keniger et al. 2013).

Challenges in Quantifying Spiritual ES

The quantification of spiritual values poses a unique set of challenges due to their subjective and culturally dependent nature. A crucial element is that unlike market-based ES, spiritual values are often not traded in markets, making them difficult to measure through traditional economic methods (Cooper et al., 2016). Studies including those by Sangha et al. (2019) and Brown & Hausner (2017), rely on qualitative data to gauge the importance of SES, using participatory mapping and interviews to capture these non-material benefits. Whenever monetary valuation is applied, it can lead to ethical concerns around commodifying spiritual experiences. One example is attempts to apply contingent valuation for willingness-to-pay assessments may not fully capture the intrinsic value of spiritual landscapes, as motivations for conservation can be driven by cultural, existence, or bequest values rather than economic incentives (Klain & Chan, 2012).

Another important challenge lies in the lack of a unified definition of SES, as there are diverse cultural interpretations of spirituality in the context of nature. There are various studies that highlight the variance in SES definitions and the corresponding methodologies, further complicating a standardized assessment approach (Bryce et al., 2016; Jobstvogt et al., 2014). Importantly, spiritual values also extend beyond individual experiences to reflect shared, collective values, suggesting that SES assessments may need to incorporate more community-oriented perspectives to fully capture their importance (Irvine et al., 2016).

4.3 Recreation

Exercising in the ocean, swimming (or surfing) and diving are hugely beneficial to our physical and mental wellbeing. Such activities of local importance serve the twin purposes of individual enhancement and reflecting sea-based cultures where the ocean is a way of life. Ocean-based recreation is also recognized as supporting the right to play, which is vital for natural development during childhood, facilitates learning, and additionally strengthens a sense of connection with the marine environment (Keniger et al., 2013). See also Section 5A, Chapter 2.

Additionally, recreation plays a cultural role, serving as a community bond and source of identity. In this sense, ocean activities extend beyond enjoyment to include the right to culture and education, fostering an appreciation for marine ecosystems that lasts into adulthood.

Sustaining a healthy ocean is also integral to sustaining livelihoods that rely on recreational tourism (see also Section 5A, Chapter 4), a major economic driver for several coastal areas.

Whenever marine environments are sufficiently preserved, they attract tourists seeking unique ocean experiences, thereby generating income for local communities. It should be noted that this relationship is mutual; for recreation to thrive, the health of marine ecosystems must be prioritized. One example is the case of the Mosquito Divers where traditional fishers also engage in diving tourism. This example exemplifies this mutual dependency. In the case of pollution or degradation of marine habitats, such a case would directly affect their livelihoods, emphasizing the need for sustainable practices that balance human activity with ecosystem conservation (Sangha et al., 2019).

While public attention has generally turned to the physical wellness benefits of oceans, equivalent acknowledgment must be given to mental health. There are studies that show time with water is associated with reduced stress and anxiety, and enhanced mental clarity (Gascon et al., 2017). The ocean serves as a place of mindfulness and restoration for many, helping with stress-related ailments. Public health policies that encourage recreation on or near the ocean can contribute to mental health in addition to physical fitness.

Healthy ecosystems, created by environmentally-friendly leisure activities and policies that safeguard the oceans, support communities and provide opportunities for generations to come to use the ocean sustainably for health, recreation and economic opportunity without harming local production and leading to unsustainable growth.

4.4 Community Benefits

An important aspect of ocean ecosystems is that they are essential in promoting cooperation at the community level, shaping social identities, supporting community welfare, and fostering sustainable development.

There are a variety of social events to participate in, such as beach clean-ups, fishing, and celebrations, as well as in the sea, indicative of social involvement. By doing so, we make conscious individuals about the importance of caring for the ocean while also practising sustainability. It goes a step further in adding more than just recreational, social good as these events also educate the participants on ocean conservation and in promoting behaviours and habits that ensure these ecosystems continue to thrive for future generations (Irvine et al., 2016).

Via the means of hands-on engagement, community members feel shared responsibility for the ocean, thus leading to lasting support for conservation efforts.

Plus, we must acknowledge how much the sea values us even in immeasurable ways. It provides us with countless opportunities for recreation and cultural experiences but also contributes in no small way to our communities' well-being — and all of this has economic dimensions as well. As many people in coastal regions depend on the sea for their sustenance, be it fishing or tourism based on oceans. Such activities generate large economic benefits and contribute to the betterment of the welfare of these communities.

Eco-friendly sustainable tourism practices can help communities to find this balance of financial growth and marine habitat protection. It is critical that the right balance be struck between economic growth and conservation. These builds hope resilience and offers communities an anchor to develop sustainable life ways that support our global need to care for the health of ocean ecosystems (Sangha et al, 2019).

The importance of the ocean becomes particularly prevalent in a majority of coastal regions and plays quite strongly into cultural identity, heritage. The ocean is a resource and cultural icon for many of the Iindigenous Ppeoples around the world, acting as not only an essential service but also partaking in traditions that are passed down from generation to generation. Incorporating ocean literacy activities with local community youth helps not only reinforce their sense of cultural identity but is also an added benefit for instilling the values associated with environmental stewardship, illustrating the dependency on a healthy ocean to support overall well-being and maintain cultural continuity (Gould et al., 2015).

Social capital can also be viewed as one of the vital aspects contributing to coastal communities' resilience and sustainability through trust, cooperation, and shared responsibility toward ocean conservation. Strong community bonds stimulate cooperation in marine resource management so that traditional knowledge and collective action ensure long-term sustainability (Pretty & Smith, 2004). Areas that are cosmopolitan and developed in terms of social capital usually have stronger local governance systems and active community participation in environmental programs that promote the stewardship of marine ecosystems (Aldrich & Meyer, 2015). In addition, thanks to social networks, communities can mobilize resources, share information, and adjust to environmental changes, especially climate-related threats to fisheries and coastal livelihoods

(Adger, 2003). The strengthening of social capital through an inclusive decision-making process and participatory conservation frameworks can promote environmental conservation and community livelihood enhancement for a more integrated approach to ocean sustainability.

To fully harness these social, economic, and cultural advantages, developing sustainable policies is crucial. Actions that promote sustainable fishing, responsible tourism, and community-based conservation frameworks can help preserve marine ecosystems while supporting local economies. Further integrating community perspectives into conservation and resource management policies ensures that the needs of local populations are addressed, fostering a stronger connection between community welfare and ecosystem health (Chan et al., 2016).

5. Challenges and Threats

In recent times, a large number of risks is to be faced by most of the natural ecosystems such as water bodies including the sea that compromise the health of human beings and the sea itself. The IOC-UNESCO State of the Ocean Reports (2022, 2024) provided a detailed discussion of all these challenges. Similarly, problems and suggestions can be found in the second World Ocean Assessment (Chapter 27) as well as in the Third World Ocean Assessment (Chapter 6). The big problems with considerable influence on the existence, development and situation of certain populations along with their species, are driven by factors such as pollution, climate change and environmental degradation. It is essential to ensure that the increased exploitation of the environment and the pace of development are sustainable in tandem so as to better cope with and, in the long-term, eliminate these concerns.

Climate Change: Perhaps the most menacing peril facing oceanic systems is climate change. This happens as result of the increasing temperature which fastens and strengthens ocean acidification, damaging coral reefs and marine bio life which is often present on that substrate (see e.g., Hoegh-Guldberg et al. (2017)). As a consequence of wildlife moving to colder waters, the local ecosystems in turn are being debilitated rendering a danger to coastal societies particularly those that rely heavily on fishing.

Pollution: Another crucial threat is ocean pollution, particularly from plastic waste and chemicals. The latter severely impacts marine life and water quality. It is increasingly being recorded that microplastics have infiltrated the food chain, affecting fish and shellfish consumed

by humans, which poses health risks to people (Jambeck et al., 2015). Similarly, agricultural runoff, laden with nutrients, causes eutrophication in coastal areas, leading to algal blooms that deplete oxygen levels and create dead zones. In order to mitigate and even combat pollution, strategies like waste management reforms, stricter regulations on plastic production, and public awareness campaigns are essential.

Resources are depleted more than ever and it will be difficult to continue as a new threat comes forward (see also sub-chapters 3a and 3 b in the Third World Ocean Assessment). This has recurred during economic history. Recent instances such as unsustainable resource extraction have put more pressure on ocean ecosystems. Fish stocks are going down as a result of rising demand for seafood, and that in turn reduces marine biodiversity. This depletion not only affects marine life but also poses risks to food security and the economies that rely on fishing. This means that adopting sustainable fishing practices, investment in aquaculture, and cultivating international cooperation are necessary for a healthy fishery and sustainable stock control (Pauly & Zeller, 2016).

To address these challenges, we need comprehensive strategies that include conservation efforts, policy reforms, and community involvement. Global frameworks like the Paris Agreement, along with local efforts such as coastal restoration projects, underscore the significance of integrated approaches to protect ocean health. UN Decade of Ocean Science for Sustainable Development Vision 2030 white papers provide a series of paper discussing in depth several challenges and suggested solutions. By tackling climate change, minimizing pollution, and encouraging sustainable resource use, we can preserve ocean ecosystems and ensure the well-being of both current and future generations.

6. Case Studies

This section provides few case studies related to various topics of the chapter. In particular we discuss aspects such as marine resource management, fisheries management, recycling waste fishing nets, cultural ecosystem cases, community-based coral reef management and sacred sea rituals and marine conservation. Figures 2a and 2b present in a brief and consice way the *Context,* the *Challenges* and *Action* undertaken. In Section 5A, Chapter 8, a more detailed examination of ~~I~~indigenous Peoples', traditional and local community knowledges can be found.

Case Studies

Marine Resource Management

Sangha et al. (2019)

Context

The Torres Strait Islanders are an Indigenous group in northern Australia.

They have a deep cultural, economic, and survival-based connection to the ocean.

Marine resources are central to their traditions, livelihoods, and identity.

Challenges

Climate change and rising sea levels threaten local fish stocks and fishing areas.

These environmental changes put their food security and traditional way of life at risk.

Action

The community has adopted co-management strategies blending traditional ecological knowledge with modern science.

These efforts support sustainable resource management and adaptability to environmental changes.

The **Torres Strait Regional Authority (TSRA)** collaborates with community leaders to integrate Indigenous methods into marine policy

Fisheries Management

Carothers, 2015

Context

Many coastal towns in Alaska depend on fishing for both employment and cultural identity.

Fishing is vital for local economies and food security.

Challenges

Climate change has significantly reduced fish populations, impacting food supply and economic stability.

Action

Alaska has implemented community-based fisheries management, involving local participation in decision-making.

The **Alaska Community Development Quota (CDQ) program** allocates fisheries quotas to coastal towns.

This program promotes sustainable fishing, job creation, and marine conservation.

Recycling Waste Fishing Nets

UNDP GEF Small Grant Fund (2023)

Context

Ghost gear threatens marine ecosystems, entangling species and damaging habitats.

640,000 tons of fishing nets are abandoned yearly.

Challenges

In Hainan, China, fishing makes up 63% of aquatic production and sustains 80% of household incomes.

High labor costs and low financial incentives hinder net recovery efforts.

Action

A 2023 UNDP GEF survey in Sanya City examined fishing practices and recycling attitudes.

95% of fishermen support recycling but are price-sensitive.

The project introduced high-value recycled products and a carbon tracking system to enhance sustainability.

Case Studies ctd

Cultural Ecosystem Services (Vave et al. 2024)

Context

Cultural ecosystem services (CES) in Fiji's **Funerary Protected Areas (FPAs)** integrate spirituality with conservation.

Clan-specific water practices (CPWB), including funerals and rituals, reinforce cultural identity.

Challenges

External influences threaten **Indigenous knowledge** and **social cohesion**.

CPWB practices are often **overlooked in conservation planning**, risking cultural displacement.

Action

Vave et al. (2024) call for integrating FPAs into conservation strategies.

Vave (2022) identifies key CPWB practices, emphasizing their role in **ecological and cultural preservation**.

Community-Based Coral Reef Management Cinner and Canela (2007)

Context

Coral reefs provide critical ecosystem services, supporting marine biodiversity, fisheries, and coastal protection.

In Indonesia, many coastal communities rely on reefs for food security, livelihoods, and cultural practices.

Challenges

Climate change, coral bleaching, overfishing, and destructive fishing practices threaten reef ecosystems.

Loss of coral reefs reduces fish stocks, affecting food security and local economies.

Action

Community-based coral reef management (CBCRM) initiatives empower local fishers to monitor, protect, and sustainably manage reef ecosystems.

Programs like the Locally Managed Marine Areas (LMMAs) integrate Indigenous knowledge with scientific conservation to establish no-take zones, reef restoration projects, and sustainable fishing practices.

These efforts restore marine biodiversity, enhance fisheries, and strengthen cultural and social resilience among coastal communities.

Sacred Sea Rituals and Marine Conservation Foale and Macintrye (2000)

Context

In Papua New Guinea (PNG), coastal communities maintain deep spiritual and cultural ties to the ocean.

Traditional sea rituals play a central role in community identity, governance, and ecological stewardship.

Challenges

Modernization and external influences have led to declining adherence to customary marine management practices.

Overfishing and habitat degradation threaten marine biodiversity and cultural continuity.

Action

Communities integrate sacred sea rituals with marine conservation efforts, reinforcing traditional taboos (Tambu areas) where fishing is restricted.

Customary marine tenure (CMT) practices combine Indigenous ecological knowledge with modern conservation strategies to protect marine species and sustain fisheries.

Partnerships with NGOs and local governments support revitalization of rituals,

1 *Fig2: Community-Led Ocean Conservation: Case Studies in Sustainable Marine Management*

2

7. Conclusion

This chapter underscores the extensive contributions of ocean ecosystems to human well-being, which range from economic value to non-market benefits, such as spiritual, cultural, and recreational services. Non-market valuation, despite its challenges, remains crucial to understanding and quantifying the non-monetary value of oceans, which can enable educated policy decisions that support both human and environmental health. Subjective well-being is further linked to the therapeutic and restorative qualities of marine environments, reinforcing the significance of accessible blue spaces for mental and physical health. Ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge, and intergenerational heritage. Last, keeping marine resources for small-scale fisheries and coastal communities is very important for their livelihood, preservation of cultural heritage, and social unity. Many of those communities actually do participate in conservation efforts because they protect their fisheries to get economic stability while continuing their traditions, identities, and well-being across generations through community-based management and stewardship.

Case studies illustrate how different communities interact with and depend on ocean resources, often employing innovative strategies to balance conservation with socio-economic needs. However, growing environmental challenges—such as climate change, pollution, and resource depletion—pose severe risks to these benefits, underscoring the necessity for robust policy frameworks and community-driven conservation. The integration of cultural, economic, and ecological perspectives into ocean management policy ensures that oceans continue to support human well-being, cultural heritage, and sustainable development for future generations.

7. References

1. Adger, W. N. (2003). Social capital, collective action, and adaptation to climate change. *Economic Geography, 79*(4), 387-404.
2. Aldrich, D. P., & Meyer, M. A. (2015). Social capital and community resilience. *American Behavioral Scientist, 59* (2), 254-269.

3. Anderson, C.B., Athayde, S., Raymond, C.M., Vatn, A., Arias, P., Gould, R.K., Kenter, J., Muraca, B., Sachdeva, S., Samakov, A., Zent, E., Lenzi, D., Murali, R., Amin, A., and Cantú-Fernández, M. (2022). Chapter 2: Conceptualizing the diverse values of nature and their contributions to people. In: Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6493134
4. Apostolaki, S., Akinsete, E., Koundouri, P., & Samartzis, P. (2018). *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/B978-0-12-409548-9.12117-7
5. Bateman, I. J., et al. (2011). Economic Analysis for Ecosystem Service Assessments. *Environmental and Resource Economics, 48*(2), 177-218.
6. Berkes, F. (2012). *Sacred Ecology* (3rd ed.). Routledge.
7. Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). *Cost-Benefit Analysis: Concepts and Practice* (4th ed.). Cambridge University Press.
8. Brander, L.M. R. de Groot, J.P. Schägner, V. Guisado-Goñi, V. van 't Hoff, S. Solomonides, A. McVittie, F. Eppink, M. Sposato, L. Do, A. Ghermandi, M. Sinclair, R. Thomas, (2024) *Economic values for ecosystem services: A global synthesis and way forward, Ecosystem Services*, Volume 66.
9. Britton, E., Kindermann, G., Domegan, C., & Carlin, C. (2020). Blue care: A systematic review of blue space interventions for health and wellbeing. *Health Promotion International, 35*(1), 50-69.
10. Brown, G., & Hausner, V. H. (2017). An empirical analysis of cultural ecosystem values in coastal landscapes. *Ocean & Coastal Management, 142*, 49-60.
11. Brondizio, E., Diaz, S., Settele, J., Ngo, H. T., Gueze, M., Aumeeruddy-Thomas, Y., Bai, X., Geschke, A., Molnár, Z., Niamir, A., Pascual, U., Simcock, A., & Jaureguiberry, P. (2019). Chapter 1 Assessing a planet in transformation: Rationale and approach of the IPBES Global Assessment on Biodiversity and Ecosystem Services. Zenodo.

12. Bryce, R., Irvine, K. N., Church, A., Fish, R., Ranger, S., & Kenter, J. O. (2016). Subjective well-being indicators for large-scale assessment of cultural ecosystem services. *Ecosystem Services, 21*, 258-269.
13. Carothers, C. (2015). Fisheries privatization, social transitions, and well-being in Kodiak, Alaska. *Marine Policy, 61*, 313-322.
14. Carson, R. T. (2012). Contingent Valuation: A Practical Alternative When Prices Aren't Available. *Journal of Economic Perspectives, 26*(4), 27-42.
15. Chan KM, Balvanera P, Benessaiah K, Chapman M, Díaz S, Gómez-Baggethun E, Gould R, Hannahs N, Jax K, Klain S, Luck GW, Martín-López B, Muraca B, Norton B, Ott K, Pascual U, Satterfield T, Tadaki M, Taggart J, Turner N. (2016). Why protect nature? Rethinking values and the environment. *Proceedings of the National Academy of Sciences, 113*(6), 1462-1465.
16. Cheng, X., Van Damme, S., Li, L., & Uyttenhove, P. (2019). Evaluation of cultural ecosystem services: A review of methods. Ecosystem services, 37, 100925
17. Cinner, J. E., & Aswani, S. (2007). Integrating customary management into marine conservation. *Biological Conservation, 140*(3-4), 201-216.
18. Cooper, N., Brady, E., Steen, H., & Bryce, R. (2016). Aesthetic and spiritual values of ecosystems: Recognising the ontological and axiological plurality of cultural ecosystem 'services'. *Ecosystem Services, 21*, 218-229.
19. Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., & van den Belt, M. (1997). The Value of the World's Ecosystem Services and Natural Capital. *Nature, 387*(6630), 253-260.
20. Duha, S. P. I., Harefa, O. O., Lombok, J. L., & Marpaung, N. B. (2023). Tanggung Jawab Orang Percaya Atas Pengrusakan Alam: Perspektif Pendidikan Agama Kristen. REAL DIDACHE: Journal of Christian Education, 3(2), 90-105.
21. Foale, S., & Macintyre, M. (2000). Dynamic and flexible aspects of customary marine tenure in Papua New Guinea. *Asia Pacific Viewpoint, 41*(3), 281-294.
22. Freeman, A. M. (2003). *The Measurement of Environmental and Resource Values: Theory and Methods.* RFF Press.
23. Gascon, M., Zijlema, W., Vert, C., White, M. P., & Nieuwenhuijsen, M. J. (2017). Outdoor blue spaces, human health, and well-being: A systematic review of quantitative

studies. *International Journal of Hygiene and Environmental Health, 220*(8), 1207-1221.

24. Gould, R.K, Klain, S.C, Ardoin, N.M, Satterfield, T, Woodside, U, Hannahs, N, Daily, G.C, Chan, K.M (2015). A protocol for eliciting nonmaterial values through a cultural ecosystem services frame. *Conservation Biology, 29*(2), 575-586.
25. Halkos, G., Aslanidis, P.-S., Plataniotis, A., & Koundouri, P. (2024). *Global insights on Sustainable Development Goal 14: Reviewing willingness-to-pay levels for marine ecosystem protection and conservation* (No. 2416). DEOS Working Papers, Athens University of Economics and Business.
26. Hanemann, W. M. (1994). Valuing the Environment Through Contingent Valuation. *Journal of Economic Perspectives, 8*(4), 19-43.
27. Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W., & Dove, S. (2017). Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science, 6*, 14.
28. Intergovernmental Oceanographic Commission. (2024). *State of the ocean report, 2024* (H. Enevoldsen, K. Isensee, & Y. J. Lee, Eds.). IOC Technical Series, No. 190. UNESCO.
29. Intergovernmental Oceanographic Commission. (2022). *State of the ocean report 2022: Pilot edition* (H. Enevoldsen, K. Isensee, & I. Yoon, Eds.). IOC Technical Series, No. 173. UNESCO.
30. Irvine, K. N., O'Brien, L., Ravenscroft, N., Cooper, N., Everard, M., Fazey, I., Reed, S.M, & Kenter, J. O. (2016). Ecosystem services and the idea of shared values. *Ecosystem Services, 21*, 184-193.
31. Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Ramani, N., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768-771.
32. Johannes, R. E. (2002). The renaissance of community-based marine resource management in Oceania. *Annual Review of Ecology and Systematics, 33*, 317-340.
33. Kahneman, D., & Krueger, A. B. (2006). Developments in the measurement of subjective well-being. *Journal of Economic Perspectives, 20*(1), 3-24.

34. Keniger, L. E., Gaston, K. J., Irvine, K. N., & Fuller, R. A. (2013). What are the benefits of interacting with nature? *International Journal of Environmental Research and Public Health, 10*(3), 913-935.
35. Klain, S. C., & Chan, K. M. (2012). Navigating coastal values: participatory mapping of ecosystem services for spatial planning. *Ecological Economics, 82*, 104-113.
36. Koundouri, P., and Giannouli, A. (2015). Blue growth and economics. *Front. Mar. Sci*. 2, 94. doi: 10.3389/fmars.2015.00094
37. Koundouri, P., Anquetil-Deck, C., Becchetti, L., Berthet, E., Borghesi, S., Cavalli, L., Chioatto, E., Cruickshank, E., Devves, S., Dibattista, I., Fusacchia, I., Giovannini, E., Halkos, G., Hansmeyer, C., Landis, C., Mazzarano, M., Papa, C., Patel, K., Plataniotis, A., Salustri, F., Tiwari, M.M., (2023b) Transforming Our World: Interdisciplinary Insights on the Sustainable Development Goals, SDSN European Green Deal Senior Working Group
38. Koundouri P, Halkos G, Landis C, Dellis K, Stratopoulou A, Plataniotis A and Chioatto E (2023) Valuation of marine ecosystems and Sustainable Development Goals. Front. Environ. Econ. 2.
~~*38.*~~*39. Koundouri P, Landis C, and Onofri L. (2025) Exploring the Economic Nature of Spiritual Values: Results from a Qualitative Meta-analysis. Munich Personal Repec Archives Online at https://mpra.ub.uni-muenchen.de/124399/ MPRA Paper No. 124399,*
~~*39.*~~*40. Kronsted Lund, L., Gurholt, K. P., & Kaae, B. C. (2023). Whose blue healthy spaces? A scoping study on blue health promotion and recreation, planning and management. Sport, Education and Society, 28(6), 714–726*
~~40.~~41. Krutilla, J. V. (1967). Conservation Reconsidered. *American Economic Review, 57*(4), 777-786.
~~41.~~42. Seulgi Lee and Tae-Goun Kim (2024). "Economic Value of Ocean Education in Korea Using the Contingent Valuation Method (CVM)," *Journal of Coastal Research* 116(sp1), 304-308
~~42.~~43. Loomis, J. B. (2000). Environmental Valuation Techniques in Water Resource Decision Making. *Journal of Water Resources Planning and Management, 126* (6), 339-344.

~~43.~~44. Louviere, J. J., Hensher, D. A., & Swait, J. D. (2000). *Stated Choice Methods: Analysis and Applications*. Cambridge University Press.

~~44.~~45. Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis*. Island Press. Link: https://www.millenniumassessment.org/documents/document.356.aspx.pdf, last accessed on 13/03/2025.

~~45.~~46. Nevzati, Fiona, Mart Külvik, Joanna Storie, Liisa-Maria Tiidu, and Simon Bell. (2023). "Assessment of Cultural Ecosystem Services and Well-Being: Testing a Method for Evaluating Natural Environment and Contact Types in the Harku Municipality, Estonia" Sustainability 15, no. 13: 10214.

~~46.~~47. Ocean Conservancy (2020). *The impact of fishing gear as a source of marine plastic pollution: A global ghost gear initiative (GGGI) information paper to support negotiations in preparation for UNEA 5.2.*

~~47.~~48. Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action.* Cambridge University Press.

~~48.~~49. Padilla Arya, M., & Diswandi. (2024). A Bibliometric Analysis of the Travel Cost Method. *International Journal of Tourism Business Research*, 3(1), 136–142.

~~49.~~50. Parsons, G. R. (2003). The Travel Cost Model. In *Handbook of Environmental Economics* (Vol. 2, pp. 269-329). North-Holland.

~~50.~~51. Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Communications, 7*, 10244.

~~*51.*~~*52.* Pearson, D. G., & Craig, T. (2014). The great outdoors? Exploring the mental health benefits of natural environments. *Frontiers in Psychology, 5*, 1178.

~~*52.*~~*53.* *Poe, M. R., Norman, K. C., & Levin, P. S. (2014). Cultural dimensions of socio-ecological systems: Key connections and guiding principles for conservation in coastal environments. Conservation Letters, 7(3), 166-175.*

~~*53.*~~*54.* *Pigou, A. C. (1920). The Economics of Welfare. Macmillan*

~~54.~~55. Pretty, J., & Smith, D. (2004). Social capital in biodiversity conservation and management. *Conservation Biology, 18*(3), 631-638.

~~55.~~56. *Rosen, S. (1974). Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. Journal of Political Economy, 82(1), 34-55*

~~56.~~57. *Sachs, J., Koundouri, P., Becchetti, L., Brunnhuber, S., Chioatto, E., Cordella, M., et al. (2022). Financing the Joint Implementation of Agenda 2030 and the European Green Deal. Report of the UN Sustainable Development Solutions Network. Available online at:* https://resources.unsdsn.org/financing-the-joint-implementationof-agenda-2030-and-the-european-green-deal

~~57.~~58. Sala, A. & Richardson, K. (2023). *Fishing gear recycling technologies and practices.* Rome, FAO and IMO.

~~58.~~59. Samuelson, P. A. (1954). The Pure Theory of Public Expenditure. *The Review of Economics and Statistics, 36*(4), 387-389.

~~59.~~60. Sangha, K. K., Preece, L., Villarreal-Rosas, J., Kegamba, J. J., Paudyal, K., Warmenhoven, T., & Krishnan, P. S. (2018). An ecosystem services framework to evaluate indigenous and local peoples' connections with nature. *Ecosystem Services, 31*, 111-125.

~~60.~~61. Sangha, K. K., Stoeckl, N., Crossman, N., & Costanza, R. (2019). A state-wide economic assessment of coastal and marine ecosystem services to inform sustainable development policies in the Northern Territory, Australia. *Marine Policy, 107*, 103595.

62. Spash, C. L. (2000). Ecosystems, Contingent Valuation and Ethics: The Case of Wetland Re-Creation. *Ecological Economics, 34*(2), 195-215.

~~61.~~63. Termansen, M., Jacobs, S., Mwampamba, T.H., Ahn, S., Castro, A., Dendoncker, N., Ghazi, H., Gundimeda, H., Huambachano, M., Lee, H., Mukherjee, N., Nemogá, G.R., Palomo, I., Pandit, R., Schaafsma, M., Ngouhouo, J., Choi, A., Filyushkina, A., Hernández-Blanco, M., Contreras, V., and González-Jiménez, D. (2022). Chapter 3: The potential of valuation. In: Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. P. Balvanera, U. Pascual, M. Christie, B. Baptiste, and D. González-Jiménez (eds). a secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6521298.

62.64. Turner, N. J., Gregory, R., Brooks, C., Failing, L., & Satterfield, T. (2008). From invisibility to transparency: Identifying the implications. *Ecology and Society, 13*(2), 1-17.

63.65. United Nations Environment Programme (2021). *Drowning in Plastics: marine litter and plastic waste vital graphics.*

64.66. UN Decade of Ocean Science for Sustainable Development Vision 2030 white papers, Link: https://oceandecade.org/publications/ocean-decade-vision-2030-white-papers/ last accessed 15/12/2023

65.67. Vave, R., Friedlander, A. M., Kittinger, J. N., & Ticktin, T. (2024). Cultural ecosystem services and the conservation challenges for an Indigenous people's aquatic protected area practice. *Conservation Biology*, *38*(6).

66.68. Vave, R. (2021). Five culturally protected water body practices in Fiji: Current status and contemporary displacement challenges. *Ambio*, 51(4), 1001-1013.

67.69. Völker, S., & Kistemann, T. (2011). The impact of blue space on human health and well-being – Salutogenetic health effects of inland surface waters: A review. *International Journal of Hygiene and Environmental Health, 214*(6), 449-460.

68.70. Ward, F. A., & Beal, D. (2000). *Valuing Nature with Travel Cost Models: A Manual.* Edward Elgar Publishing.

69.71. White, M. P., Alcock, I., Wheeler, B. W., & Depledge, M. H. (2013). Would you be happier living in a greener urban area? A fixed-effects analysis of panel data. *Psychological Science, 24*(6), 920-928.

70.72. White, M. P., Elliott, L. R., Gascon, M., Roberts, B., & Fleming, L. E. (2020). Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environmental Research*, 191, 110169.

Key-findings

- ~~Proposal of a~~A methodological approach ~~that integrates~~integrating Ocean Hazards of Natural Origin (OHNO) into the "One Health" concept (Figure 5B.4.1).
- ~~Identification of pathways is key in order~~Identifying pathways is essential to a) assessing OHNO's ~~the~~ impact ~~of OHNO~~ on ~~the~~ natural~~/~~ and human environments across oceanic scales and ~~around the world's ocean and across scales,~~ b) ~~build towards~~enhancing ocean~~/~~ and coastal resilience.
- Pathways ~~connecting~~ linking "Pressures", "Ocean Hazards", and "Impacts-Disasters" ~~highlight the differences between~~illustrate the distinctions within OHNO (Figure 5B.4.17).
- Pathways connecting "Impacts-Disasters" and "Mitigation-Management-Adaptation" highlight available strategies in a multi-hazard context (Figure 5B.4.18).

Introduction

Ocean Hazards of Natural Origin (OHNO) can be classified into four categories: a) Geophysical/Geological, b) Ocean Weather, Hydrology, and Climate, c) Ecological and d) Biological (Pinardi and others; 2024). S5B.4 focuses on categories a), b) and partly c (for acidification and deoxygenation) ~~b~~) since those hazards largely impact/affect the ones of categories c) and d), while also aspects regarding c) and d) are addressed by other WOA III Chapters (S4.4-5-6, S5B.1-2; see 0~~5B.4.6~~).

S5B.4 is a new addition to WOA. WOA I and II address elements that are relevant to ocean hazards and/or integrate them within broader environmental and ecological frameworks; however, WOA III elevates the topic to a focused chapter. Accordingly, the approach presented in the following essentially proposes the blueprint on which future versions of WOA should build upon.

This approach is graphically represented by the flowchart of Figure 5B.4.1. Its essence is to highlight "pathways" connecting the four core-components in order to facilitate a structured overall assessment of OHNO within the framework of WOA III. This approach aligns to UNFCCC National Determined Contributions (NDCs) and Dialogues, both

regarding the role of OHNO in the above context, as well as regarding the roadmap towards Ocean/Coastal Resilience (UNFCCC, 2023, 2024a, b).

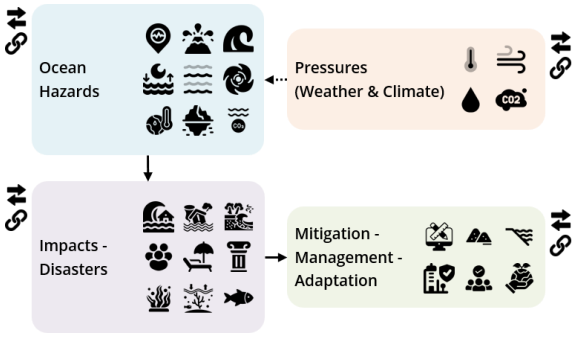


Figure 5B.4.1 Flowchart of the approach of S5B.C4 with its four core-components (leaders/arrows denote the pathways between core-components; "Pressures" make part of the pathways only for Hazards affected by the Weather/Climate, thus the dotted line; double arrows that denote information exchanges and link icons refer to other WOA III Chapters as presented in 05B.4.5).

Ocean Hazards Analysis

~~1.~~

~~2.~~

~~3.~~

This Section analyses OHNO within the context of identifying pathways connecting components "Pressures", "Ocean Hazards" and "Impacts-Disasters" (Figure 5B.4.1). It is divided into 17 sub-sections, each describing a distinct hazard. The final product of this effort is presented in 05B.4.3.18 / Figure 5B.4.17. Information in Figure 5B.4.17 reflects the assimilation of available knowledge regarding the examined hazards in relevant literature (see also 05B.4.5). Figure 5B.4.17 should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale assessments when studying phenomena with significant local/regional variations. Given the above, this Section is fundamentally linked to S4.C1-3 of WOA III, with detailed links identified in 05B.4.6.

~~1.~~

~~2.~~

~~3.~~

Tsunamis

Geohazards (05B.4.3.1 to 05B.4.3.4), are associated to major impacts on the human and natural environment, ranging from direct ones (loss of life; infrastructure/property damage), to indirect ones (economic loss, social disruption, environmental degradation). Tsunamis are long sea waves with periods typically within the minutes to hour range. Their wavelengths are in the order of tenths to hundreds of km depending on the the dimensions of the causative sources (Levin and Nosov, 2016). Tsunamis can be produced by several mechanisms (Bryant, 2008); however, submarine geological processes produce the majority of tsunamis. Shallow submarine earthquakes with moment magnitude M_W>6.5 produce 79 percent of the global number of tsunamis, while submarine volcanic eruptions/landslides produce 18 percent of tsunamis. Most tsunamis and the largest of them are generated along subduction zones (Figure 5B.4.2). Tsunamis have caused an estimated 250,000 deaths and $280 billion in economic losses between 1998 and 2017 (UNDRR, 2018).

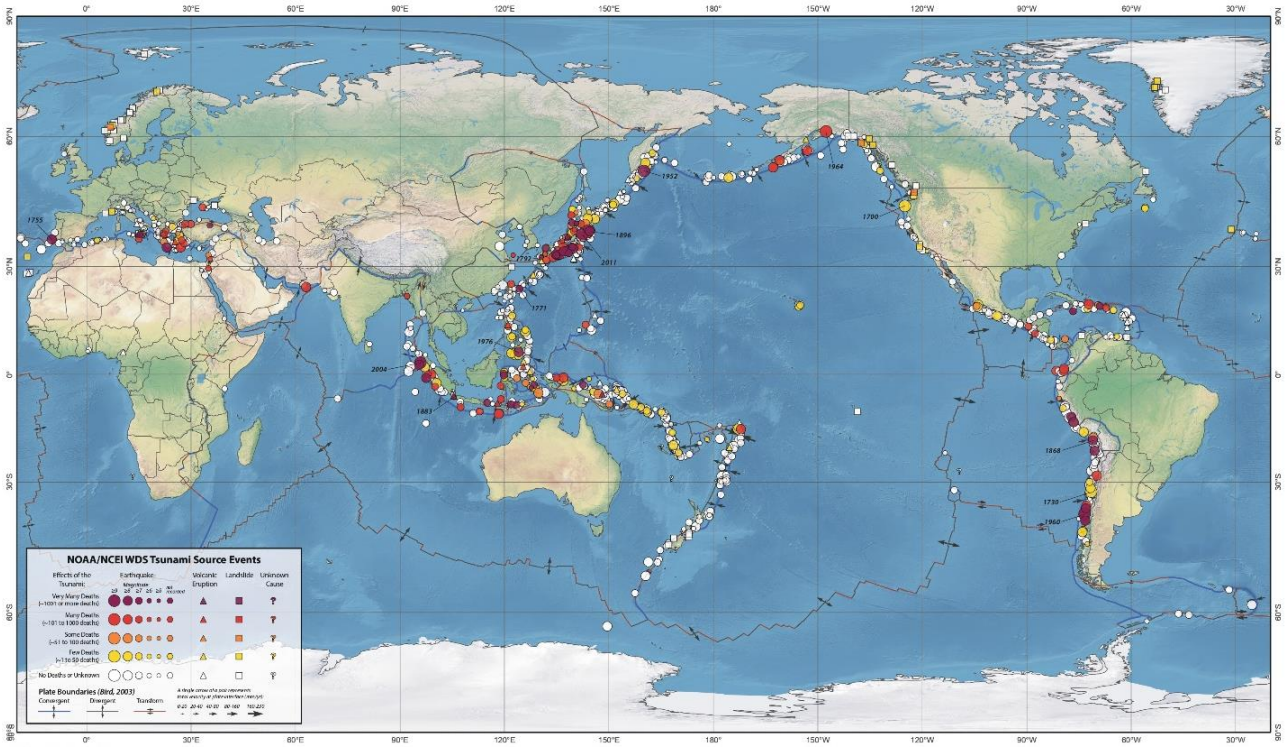


Figure 5B.4.2 Known tsunami sources from 1610 B.C. to A.D. 2023 (IOC, 2019).

Earthquakes

The global seismic activity is concentrated mainly along the boundaries of moving lithospheric plates (Lay and Wallace, 1995; Figure 5B.4.3). The sudden rupture of rocks releases the stored dynamic energy in the form of seismic waves. Every year about

15-18 earthquakes of magnitude 7 or larger take place as an average globally, while hundreds are the earthquakes of exceeding magnitude 6 (USGS, 2024). The majority of tectonic earthquakes takes place at shallow depths (focal depth<80km) but seismic activity has been observed at depths up to about 720km within the earth (maximum depth of lithospheric subduction). The seismic waves travel from the seismic source to all directions in the Earth's interior and reach the earth surface causing the shaking of ground. Earthquakes occurring in association with volcanic activity represent less than 10 percent of the total number of earthquakes. Earthquakes have caused an estimated 500,000 deaths and $380 billion in economic losses between 1998 and 2017 (UNDRR, 2018; Wallemacq and Rowena, 2018).

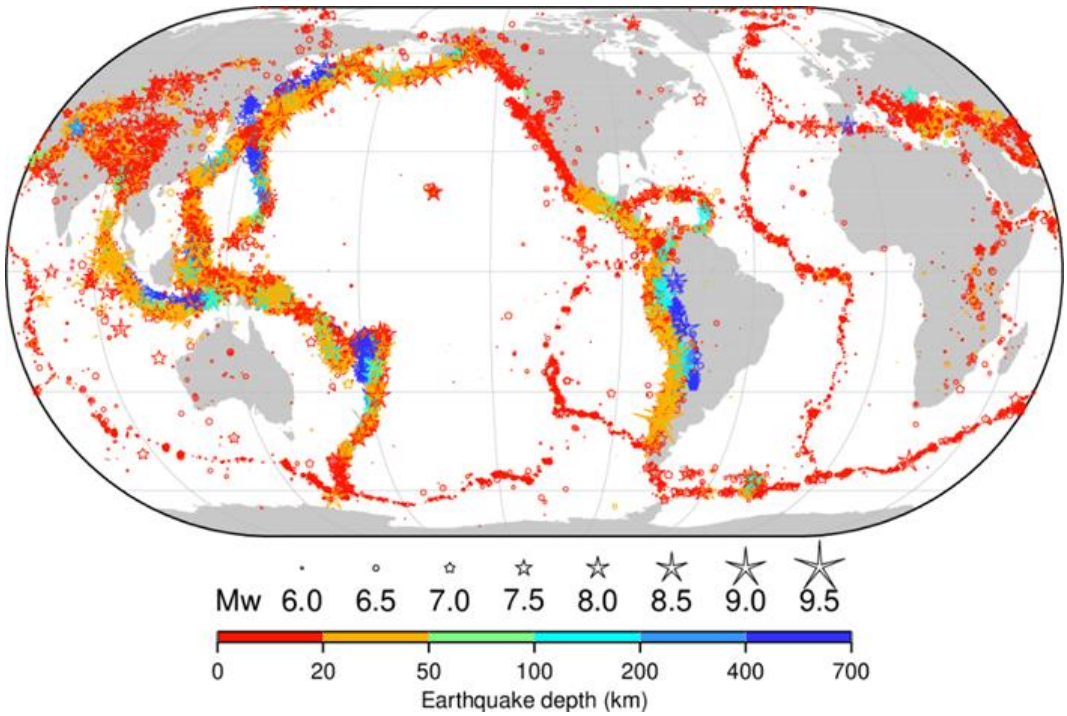


Figure 5B.4.3 Epicenters of earthquakes (ISC, 2024).

Volcanic eruptions

The geographical distribution of the active volcanoes on a global scale is similar to that of earthquake sources (Loughlin and others, 2017; Figure 5B.4.4). More than 75 percent of all active volcanoes are located along submarine and coastal volcanic belts, e.g. the Ring of Fire in the Pacific Ocean. Strong volcanic eruptions that occur near populated areas become dangerous or even quite destructive. Over the past 500 years, volcanic eruptions have caused an estimated >200,000 deaths (Muzeau and others, 2010),

with the 1900-2009 events amounting to about 100,000 of those (Doocy and others, 2013).

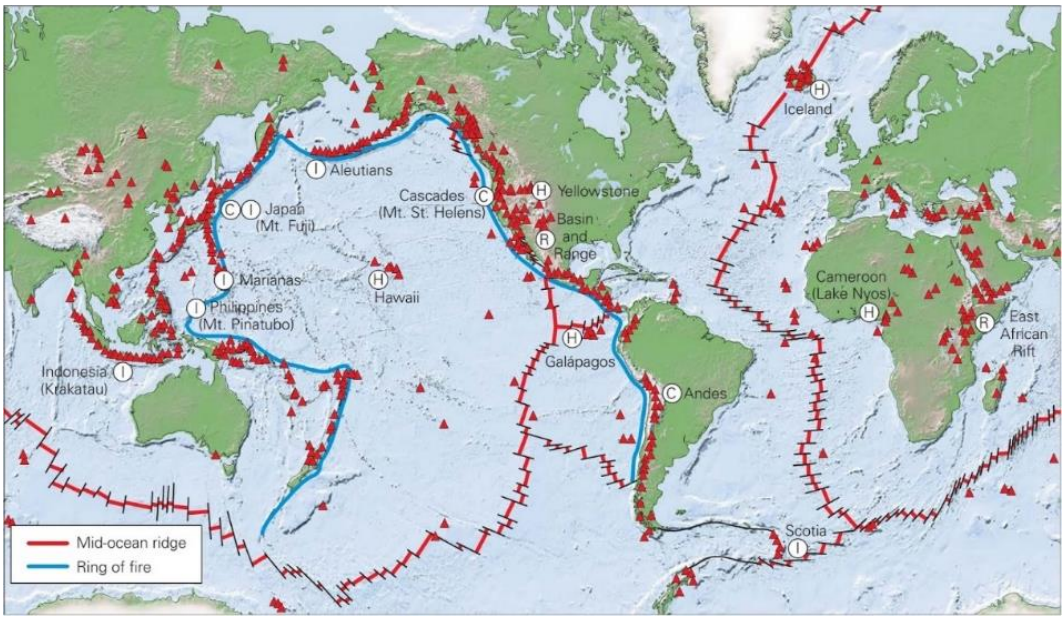


Figure 5B.4.4 Main lithospheric plates and distribution of volcanoes (Learning Geology, 2024).

Tectonic subsidence

In regions characterized by subduction zones, the overriding lithospheric plate may experience subsidence. As the subducting plate pulls down the Earth's crust, large areas can gradually sink. This is a large-scale geodynamic process, driven by the plate tectonics mechanisms (Turcotte and Schubert, 2002). Tectonic subsidence may also occur suddenly at the overriding plate with the occurrence of a large subduction zone earthquake (Figure 5B.4.5). Therefore, during large earthquakes, fault rupture can cause abrupt subsidence, creating tsunamis or permanently lowering parts of the coastline. Furthermore, in regions near convergent boundaries, heavy sediment deposition from rivers/glaciers can cause the crust to bend and subside due to weight (often seen in coastal/delta regions). Tectonic subsidence in coastal regions lowers the land relative to sea level, making these areas more vulnerable to flooding, storm surges, and sea-level rise. Gradual subsidence over time can cause damage to infrastructure, especially in areas where the land is subsiding unevenly. It is noted that the opposite process, tectonic uplift, can also cause similar damage to infrastructure and lead to changes or disruptions in navigable waterways.

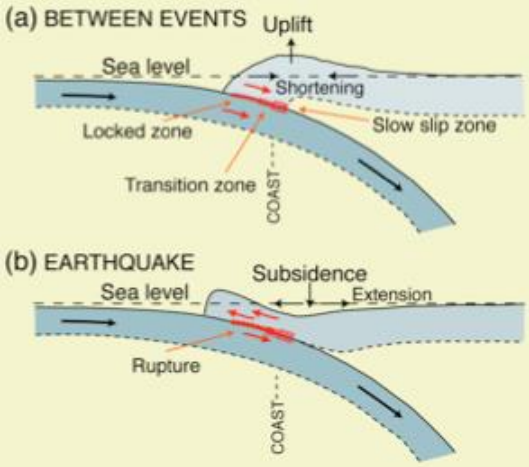


Figure 5B.4.5 Cross section of subduction zone (a) before and (b) during an earthquake (LDEO, 2024).

Coastal erosion

A global assessment of shoreline typology using satellite imagery (Hulskamp and others, 2023) classified 26 percent, 12 percent, 27 percent, and 33 percent of ice-free shorelines as sandy, muddy, rocky, and vegetated, respectively, using automated image detection validated at over 50 sites. Luijendijk and others (2018) provide the first historical sandy shoreline position change rates over 1984-2016, showing 24 percent of sandy coasts eroding, 28 percent accreting, and 48 percent stable.

IPCC (2021) states with high confidence that sandy shorelines will retreat in most regions of the world, in the absence of additional sediment sources or physical barriers to shoreline retreat (for erosion trends for high-latitude permafrost-built shorelines refer to Section S4.C5k). The total length of sandy shorelines around the world projected to retreat by more than 100m by the end of the century is about 35 percent greater under RCP8.5 (about 130,000km) compared to that under RCP4.5 (about 95,000km). Vousdoukas and others (2020) find that 13.6-15.2 percent (36,097-40,511km) of the world's sandy coastline could face shoreline retreat > 100m by 2050, increasing to 35.7-49.5 percent (95,061–131,745km) by the end of the century. Concentrating on the densely populated Low elevation coastal zone (LECZ) of the world, comprising 31 percent of the world's sandy coastline, Vousdoukas and others (2020) show that about one-third of the global LECZ will experience shoreline retreat >100m by 2050, an estimate that reaches 52 percent and 63 percent by the end of the century, under RCP4.5 and RCP8.5, respectively (Figure 5B.4.6).

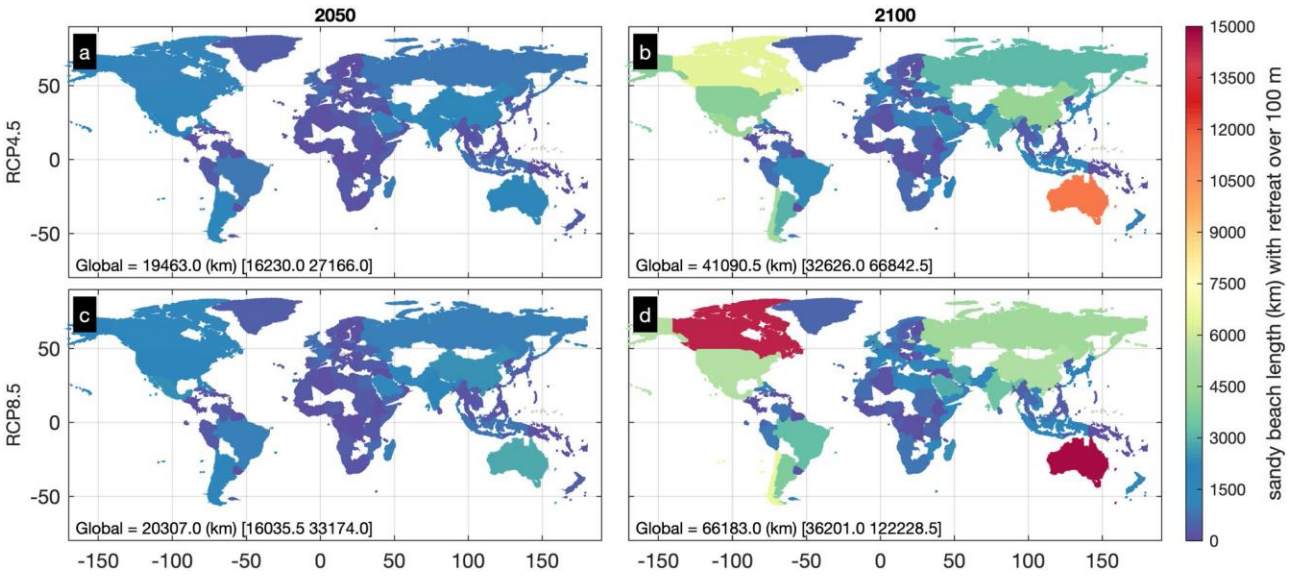


Figure 5B.4. 6 Per country length of sandy beach coastline projected to retreat by more than 100m by 2050 (a,c) and 2100 (b,d), under RCP4.5 (a,b) and RCP8.5 (c,d) (Vousdoukas and others, 2020).

Tropical and extra-tropical cyclones

Cyclogenesis occurs through different mechanisms at varying latitudes (Emanuel 1991) and plays a crucial role in global circulation by transporting heat and moisture. This process is a significant hazard for coastal areas and maritime activities, especially in the form of Tropical Cyclones (TCs), which are warm-core, axisymmetric vortices with radii between 100km and 1000km, fuelled by thermodynamic disequilibrium between the atmosphere and ocean surface. TCs are regionally known as hurricanes and typhoons. These terms also refer to specific classifications of TCs that exceed certain wind speed thresholds in different regions. Annually, around 90 tropical cyclones occur globally (Emanuel and others, 2023), causing severe impacts in coastal regions through strong winds, intense rainfall, and storm surge effects. Extreme events can lead to hundreds of thousands of casualties (Cerveny and others, 2017). Since the 1970s, increased coastal exposure and climate change have exacerbated damages and the number of affected individuals (Kunze and others, 2021). At higher latitudes, extratropical cyclones such as polar lows and Mediterranean hurricanes (Medicanes, or Tropical-Like Cyclones, see Miglietta and Rotunno, 2019), smaller and shorter-lived than TCs are influenced by sea-surface heat fluxes and baroclinic instability and significantly affect annual precipitation in coastal areas (Schultz and others, 2019).

Accurate tracking and property assessment of cyclones are vital for disaster management and long-term preparedness. However, challenges remain in identifying long-term trends

due to limited observational records and interannual variability. While studies indicate potential increases in TC and TLC intensity due to warming, projections regarding frequency changes and poleward migration of maximum intensity remain uncertain (Knutson and others, 2020). Additionally, sea level rise may heighten storm impacts even if storminess decreases (Lionello and others, 2017).

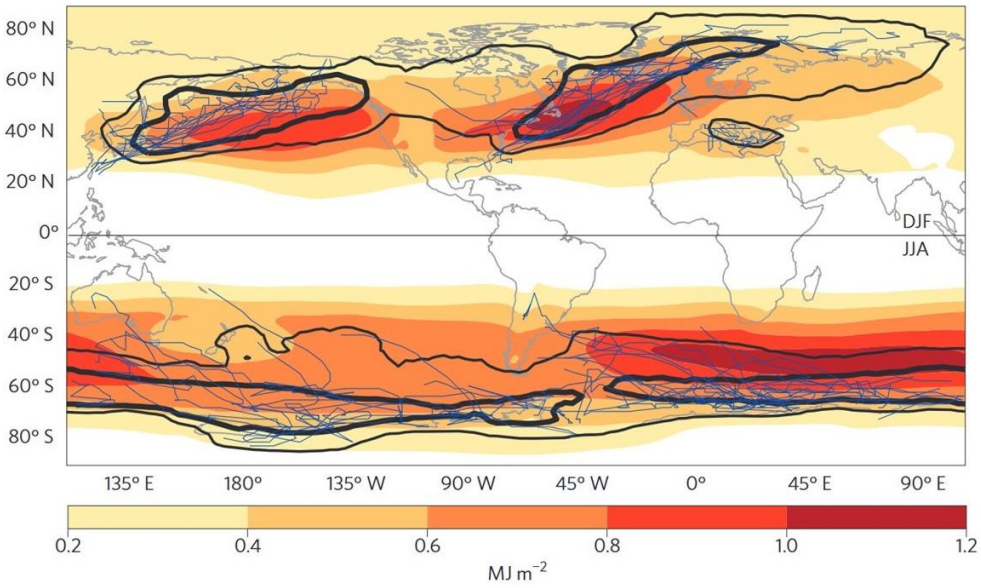


Figure 5B.4.7 Wintertime (adapted for N/S hemispheres) extratropical storm eddy kinetic energy (colour) and track density (contours). Thick/Thin contours: 20/10 tracks ($10^6 km^{-2}$) per season; blue lines: individual tracks for the top 0.5 percent most intense cyclones (Shaw and others, 2016).

Meteotsunamis

Meteotsunamis are long barotropic ocean waves generated by the resonance between atmospheric perturbations and sea surface oscillations. This resonance can occur when the propagation velocities of atmospheric and oceanic waves align (Proudman resonance) or along coastlines (Greenspan resonance), or through interactions between incoming waves and the oscillation characteristics of a harbour or bay. Nearshore processes, such as topographic amplification or focusing, can further enhance these waves (Ličer and others, 2017). Depending on the mechanisms involved, meteotsunamis may manifest as solitary waves impacting coastlines or as seiches ringing in bays, with amplification reaching up to 100 times the “inverse barometer” response to the atmospheric disturbance (Pattiaratchi and Wijeratne, 2015).

While the triggering conditions for meteotsunamis occur at large scales, significant events only arise when multiple conditions coincide (Monserrat and others, 2006). Consequently, meteotsunamis often exhibit local characteristics, with hotspots where

these events frequently occur (e.g. Mediterranean Sea, East China Sea, US East Coast, Great Lakes; Rabinovich, 2020). Severe meteotsunami events can cause considerable economic losses and impact local economies (e.g. Šepic and others, 2016), and possibly lead to fatalities.

Characterizing meteotsunami hazards is challenging for both short-term early warning and long-term climate-proof coastal planning. Early warning systems use approaches like synoptic indices correlating atmospheric patterns with meteotsunamis, high-resolution numerical modeling of relevant physical processes and probabilistic methods (Denamiel and others, 2023). Global adjustments in sea level monitoring protocols to 1-minute intervals, initiated after the 2004 Indian Ocean tsunami, have improved meteotsunami detection and long-term climatological trend reconstruction. Advances in technologies like high-frequency radars and GNSS satellite sensors also enhance tsunami monitoring in the ionosphere (Angove and others, 2021).

Figure 5B.4.8 Locations of meteotsunami occurrences (Pattiaratchi and Wijeratne, 2015).

Sea level rise

It is well established that the ice loss from the Greenland and Antarctic ice sheets, glacier mass loss and the expansion of ocean volume from ocean warming (Cazenave and Moreira, 2022) cause global sea level to raise, and human influence was very likely the main driver of these increases since at least 1971 (IPCC, 2021). It is well established that the rate of global sea level rise is increasing (von Schuckmann and others, 2024; WMO, 2024), with a very likely acceleration rate of 0.094mm/yr^2 [0.082-0.115] for 1993–2018 (IPCC, 2021). At the regional scale, sea level rise is not uniform. While

most areas show a positive trend, localized regions with negative trends can also be observed (Fasullo and Nerem, 2018). It is well established that in the past 30 years, nearly 50 percent of the ocean has experienced sea level rise at rates exceeding the global average, particularly in regions influenced by major western boundary currents, as well as parts of the western Pacific, Indian Ocean, and some areas of the Atlantic Ocean (von Schuckmann and others, 2024). While at regional scale, sea-level trends are still dominated by steric changes (Stammer and others, 2012), studies show that with accelerated land ice melt, associated fingerprints will become detectable (Tamisiea, 2011; Coulson and others, 2022; Oppenheimer and others, 2019). The rising of sea levels has increased the adverse effects of coastal floods (well established), storms and tropical cyclones (established but incomplete), and hence the consequent losses and damages, increasing inhabitants and infrastructure vulnerability and food security risk, in particular in low-lying areas and island states (~~well established;~~ IPCC, 2022). Adaptation and mitigation measures such as the restoration of mangroves and coastal wetlands reduce the risks from sea level rise (~~well established,~~ IPCC, 2022).

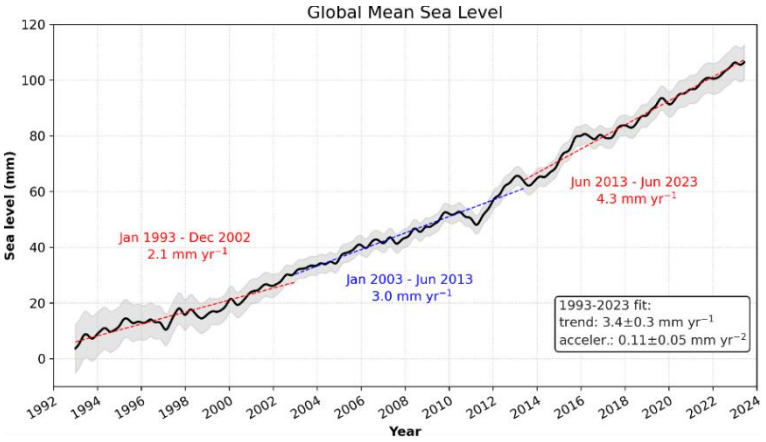


Figure 5B.4.9 Global mean sea level time series from January 1993 to June 2023 (curve) and its uncertainty envelope (shaded; von Schuckmann and others, 2024).

Waves / Wave runup

Wave runup combines wave setup with shoreline oscillation (swash) from each incoming wave (Figure 5B.4.10). It includes contributions from sea, swell, and infragravity waves, varying over seconds to minutes. On gently sloping beaches, infragravity wave runup can dominate. During storms, wave runup on open coast beaches may reach 3-6 m above other components (Hughes, 2016). Runup characteristics change with beach and offshore wave properties (Holman, 1986) and is the main driver of beach face hydro- and

morphodynamics (Elfrink and Baldock, 2002). Runup also plays a critical role in dune erosion during storm conditions (Ruggiero and others, 2001) and structure overtopping (van der Meer and Stam, 1992). Thus, runup is key to successful coastal planning and management and a critical parameter in assessing the effect of sea level rise on coastal inundation.

Wave runup is tightly related to many of the hazards presented in 05B.4.3 (05B.4.3.1, 05B.4.3.6, 05B.4.3.7, 05B.4.3.8, 05B.4.3.10). Accordingly, it is difficult to disengage its assessment from a multi-hazard approach when it comes to the flowchart of Figure 5B.4.1, especially considering that - apart from tsunamis - all other related hazards will be exacerbated by climate change. There are several studies highlighting regional variability in wave climate under present and future conditions. Regardless of regional variability, though, there appears to be a consensus that major impacts will derive from significant increase in wave heights, changes in the frequency of occurrence and magnitude of extremes, as well as from changes in wave directionality (Casa and others, 2024; Lobeto and others, 2021).

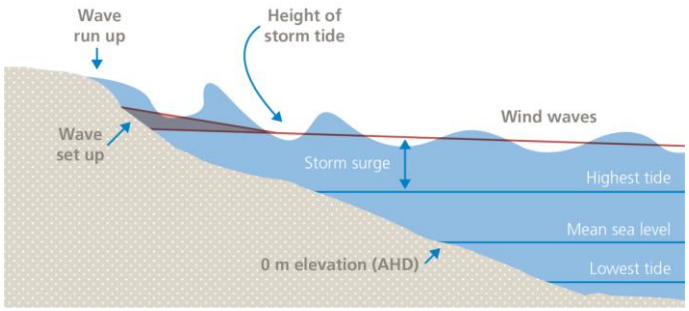


Figure 5B.4.10 Schematic of the surf zone (DSE, 2012).

Storm surge / Coastal flooding

Coastal flooding is the episodic or permanent flooding of the Low Elevation Coastal Zone (LECZ) due to extreme total water levels (ETWL). ETWL's are composed of relative sea level rise, which combines sea level rise and local subsidence (05B.4.3.8, 05B.4.3.4), storm (wind and pressure-driven) surge, tides, and wave setup (Rueda and others, 2017). In many cases, storm surge is the dominant contributor to ETWL. Hazards associated with coastal flooding will, with high confidence, increase in the coming decades for the majority of the world's coastlines (IPCC, 2021). Vousdoukas and others (2018) project a global increase by 2100 of 34-76cm of the 100-year return period ETWL under the RCP4.5 scenario, and an increase of 58-172cm under the RCP8.5 scenario.

Moreover, after 2050, the present-day high return period ETWL is expected to become a much more frequent event in the majority of the world's coastal areas, and especially in the tropics (Vitousek and others, 2017), even under the most optimistic 1.5°C warming scenarios (Tebaldi and others, 2021).

Looking at coastal flooding impacts on a global scale, without taking coastal protection and adaptation into account, an estimated area of $533*10^3 km^2$ (512-603), a total of $148*10^6$ ($128*10^6$-$171*10^6$) people and assets valued at $7761*10^9$$ (6466-9135) would be at risk under a present day 100 year return period ETWL event, increasing by 2100 with 33 percent, 36 percent and 32 percent under the RCP4.5 scenario, respectively, and with 48 percent, 52 percent and 46 percent under the RCP8.5 scenario, respectively (Kirezci and others, 2020). Within the above context, impacts on food systems (especially fisheries and aquaculture) should not be overlooked as well (Suhring and others, 2023). Looking at risk, Tiggeloven and others (2020) found a 150-fold increase in expected annual damage by 2100 under the RCP4.5-SSP2 scenario, if no adaptation to coastal flooding is taking place. When applying different adaptation scenarios, this increase reduces to 11-39-fold, depending on the adaptation pathway selected.

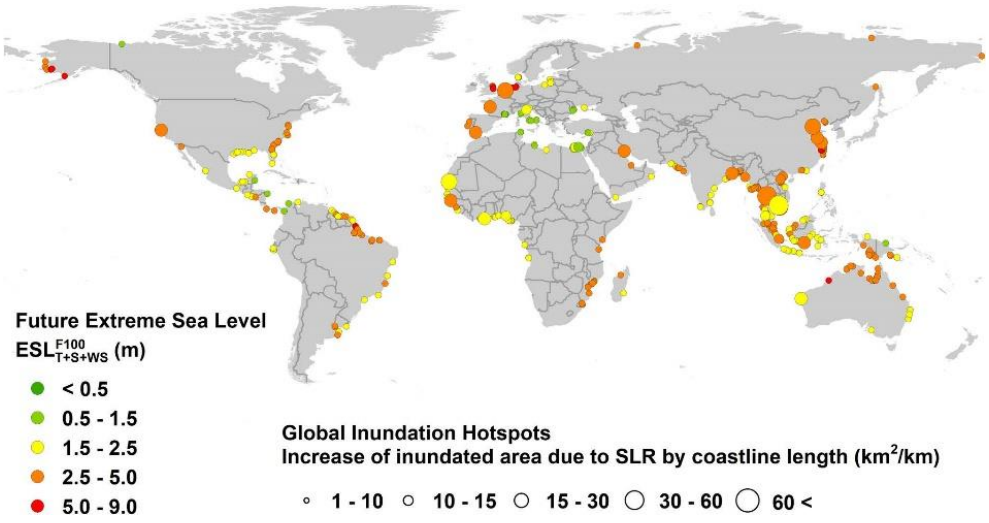
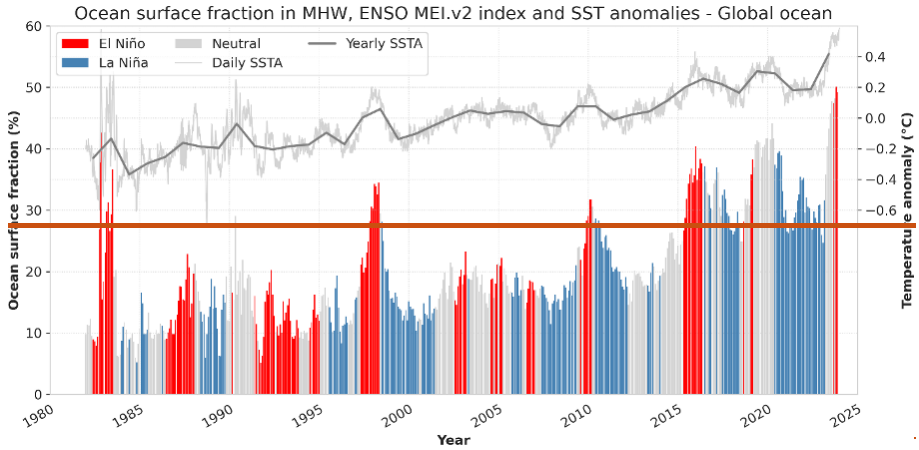


Figure 5B.4.11 Global hotspot regions of changes in episodic coastal flooding in 2100 for RCP8.5 (i.e. difference between projected episodic flooding in 2100 minus present day episodic flooding; Kirezci and others, 2020).

Marine heatwaves

A marine heatwave (MHW) is a period of at least five consecutive days of sea surface temperatures above the 90th climatological percentile (Hobday and others, 2016). MHWs result from air-sea interactions, shifts in ocean currents, and climate variability like El Niño (Bindoff and others, 2019). It is well established that since the 1980s, MHW

frequency has doubled, with further increases expected, especially in tropical and Arctic waters, and human influence has very likely contributed to most of them since at least 2006 (IPCC, 2019; 2021). With further increases in intensity and frequency observed, and projected for coming decades, MHWs are emerging as pervasive stressors to marine ecosystems globally (Smith and others, 2023; see Figure 5B.4.12 from IPCC, 2019), exposing species and ecosystems to environmental conditions beyond their tolerance and acclimation limits (IPCC, 2022). Adverse impacts already reported include reduction of primary production, migration or reduction of endemic species, emergence of species coming from other regions, and mass mortality of organisms (Smith and others, 2023; Oliver and others, 2019; Garrabou and others, 2022). These changes in turn can have adverse impacts on human systems like on fisheries and aquaculture (Cheung and Frölicher, 2020; IPCC, 2022; Wakelin and others, 2021).



~~Figure 5B.4.12 Upper: Globally averaged daily/annual SST anomalies from remote sensing (reference period 1993-2016). Bottom: Percentage of global ocean surface where MHW were detected (von Schuckmann and others, 2024).~~

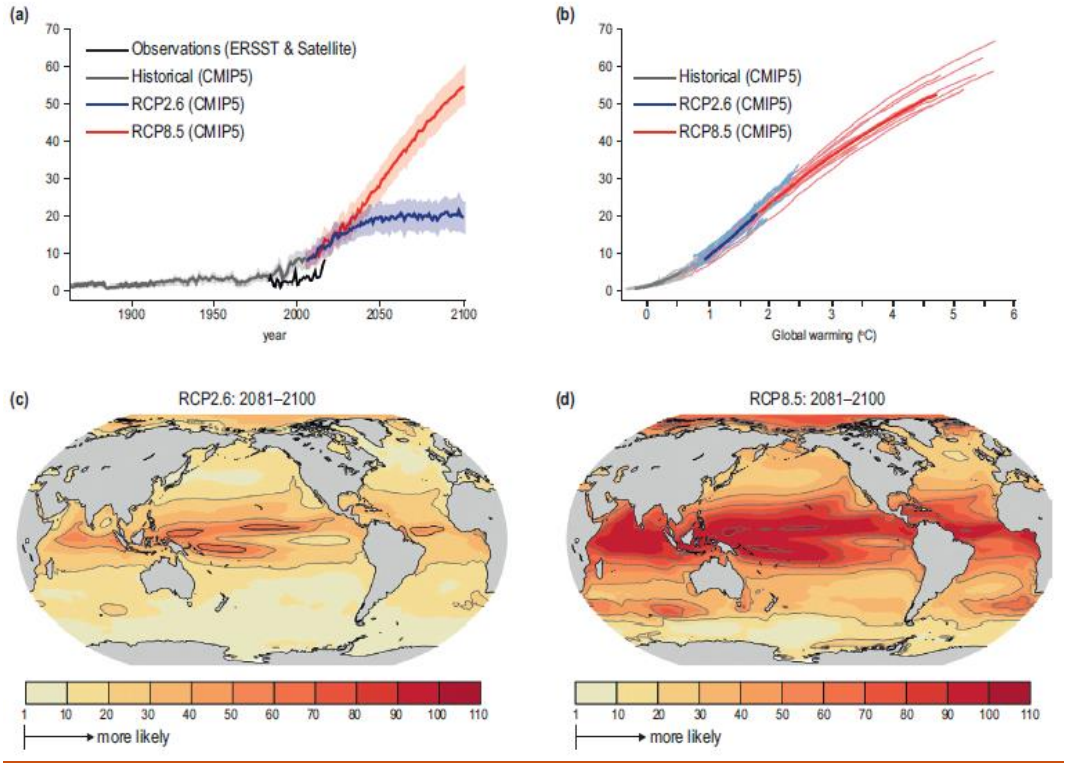


Figure 5B.4.12 Global and regional changes in the probability ratio of marine heatwaves (MHWs). The probability ratio is the fraction by which the number of MHW days per year has changed since 1850–1900. (a) Changes in the annual mean probability ratio of MHWs exceeding the 99th percentile of pre-industrial local daily sea surface temperature (SST) averaged over the ocean. (b) Same as (a), but the probability ratio is plotted for different levels of global surface atmospheric warming and for the individual models. The simulated time series in (b) are smoothed with a 10-year running mean. (c,d) Simulated regional changes in the multi-model mean probability ratio of MHWs exceeding the preindustrial 99th percentile in 2081–2100 for the (c) RCP2.6 scenario and the (d) RCP8.5 scenario (IPCC, 2019).

Glacial melt

Glacial melt refers to the large-scale melting of glaciers and ice sheets, which releases vast amounts of freshwater into the world's oceans. Glacial melt contributes to sea level rise (see 05B.4.3.8) while the influx of freshwater disrupts ocean salinity and density, also modifying habitat conditions, nutrient availability, and the biological productivity of affected regions (IPCC, 2019). Ice loss from glaciers and ice caps accounts for about 60 percent of the ice loss contributing to sea level rise, with the remaining attributed to the melting of the Antarctic (AIS) and Greenland (GIS) Ice Sheets (Meier and others, 2007; Figure 5B.4.13). This has resulted in a sea level rise of approximately 1.48±0.26mm/year from all ice-covered regions (Jacob and others, 2012). Projections suggest that glacier melt could contribute an additional 10-25mm to sea level rise by 2100 (Meier and others, 2007), while the GIS alone could contribute between 75-140mm to sea-level rise by the same time (Gillet-Chaulet and others, 2012).

Freshwater input from glacial melt affects regional dynamics and global overturning circulation (Cenedese and Straneo, 2023), while it also affects nutrient and carbon cycling, influencing primary and secondary productivity in marine ecosystems (Oliver and others, 2020). The previous also considering not only coastal areas, but also the freshwater discharged downstream through glacial-fed rivers (Hock, 2014).

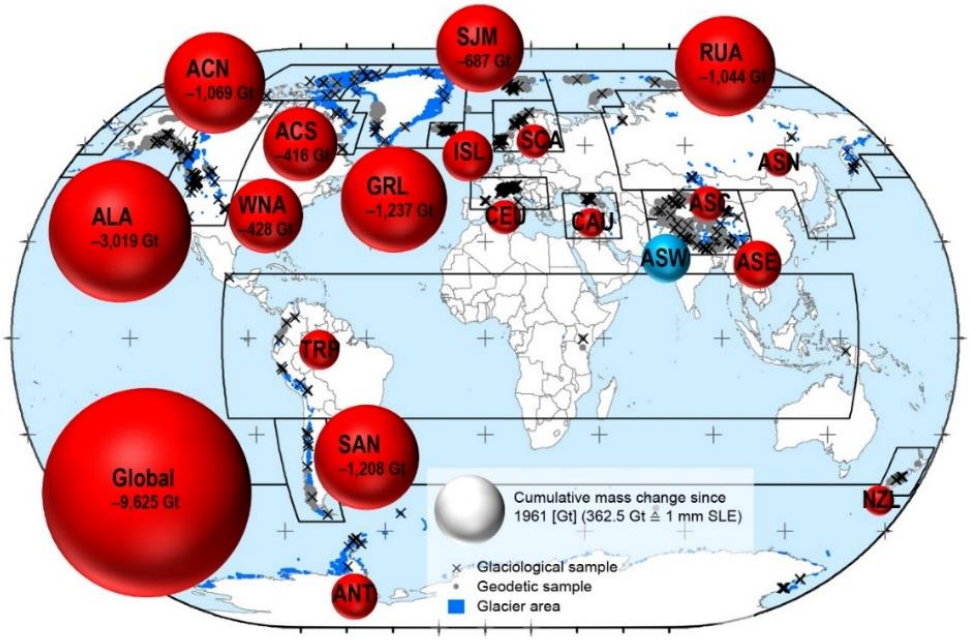


Figure 5B.4.13 Regional share of glaciers in sea-level rise from 1961/62 to 2015/16 (WGMS, 2024; adjusted from Zemp and others, 2019).

Heavy rainfall / River flooding

Heavy rainfall in watersheds and associated river flooding can pose significant threats for downstream coasts, through compound flooding, degraded water quality, saltwater intrusion, and threats to marine ecosystems. Compound flooding is the simultaneous occurrence of multiple flood drivers (storm surge, river overflow, torrential rain). This type of flooding is particularly severe and can exacerbate the impacts on coastal areas, by increasing flooding extents and flow depths (Wright and others 2019; Shen and others, 2019). Effects typically extend to saltwater intrusion, contaminating drinking water supplies and affecting water quality for years (Marques and others, 2020) and health risks for coastal communities, direct or indirect. River and compound flooding also affect coastal ecosystems and habitats, through nutrient/sediment transport, physical/biogeochemical changes and habitat disruption (Ge and others, 2021;

Furnas 2011). Climate change is expected to modify spatial and temporal modulation of rainfall regimes, leading to increased frequency of intense precipitation events and higher flood risks in many regions (IPCC, 2021). This is particularly evident in tropical and subtropical areas where more intense rainfall is projected to increase flood frequency and magnitude (Winarta and others, 2019). Assessing the impacts of climate change on compound flooding involves significant uncertainties due to the complex interplay of various factors. For example, in Europe, the Mediterranean coasts might currently experience the highest probability of compound flooding, but future projections indicate emerging high probabilities along parts of the northern European coast (Bevacqua and others, 2019).

Droughts

Drought, a hazard typically considered as terrestrial, has nonetheless significant impacts on coastal regions, affecting various aspects of the natural and human environment (Mishra and Singh, 2010). Its impacts range from water resources (reduced freshwater availability and salinization of coastal aquifers; Yihdego, 2017), to ecosystems and biodiversity (Mafi-Gholami and others, 2020), and to human activities (agriculture, industry, energy production, tourism, human health; Miyan, 2015; Mishra and others, 2010). Droughts occur in both developed and developing countries, with significant impacts on the global ecosystem, varying from region to region. South and Southeast Asian countries have been experiencing increasing droughts due to changing precipitation patterns (Miyan, 2015), while the Mediterranean, Amazon, southern Africa, and Central America are projected to be the most impacted regions by extreme multivariate drought in the future (Tabari and Willems, 2023; Dai, 2011, 2013). Climate change is expected to exacerbate drought conditions, leading to more frequent and severe droughts (IPCC, 2021), while combined effects of sea level rise / coastal flooding and drought will further stress coastal regions, leading to increased salinization and reduced groundwater quality (Shishaye, 2021).

Saltwater intrusion

Saltwater intrusion, i.e. the migration of salty water into freshwater coastal aquifers, has significant environmental impacts on coastal regions (Werner and others, 2013). The increase in water salinity has an immediate impact on drinking water quality and

supplies (Moore and Joye, 2021), while it also affects crop yields and soil health through biochemical changes in aquifers, leading to detriment to food security in vulnerable regions (Hu and others, 2024; Tully and others, 2019). Saltwater intrusion alters coastal ecosystems, affecting vegetation and wildlife dependent on freshwater (Visschers and others, 2022).

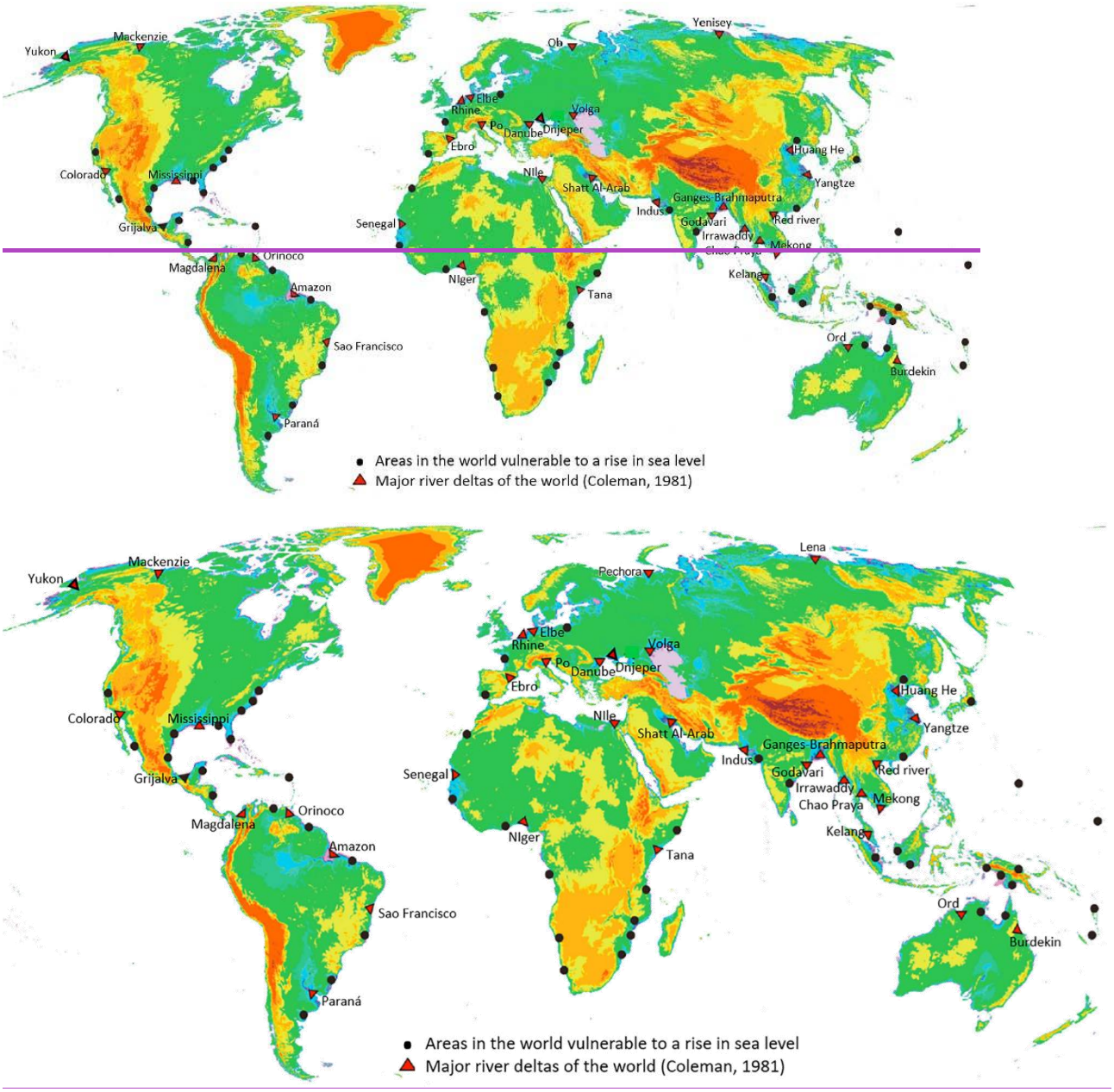


Figure 5B.4.14 Global hotspots of groundwater vulnerability to sea-water intrusion and sea-level rise (modified from van der Gun, 2021; Coleman, 1981).

The hazard is a global issue, evident to different extents to the majority of coastal aquifers. Areas in Vietnam, China and India are particularly vulnerable due to their low elevation and high population density, and thus among the most-studied in relevant research. Climate change is expected to enhance saltwater intrusion impacts, through increased sea levels, extremes in waves and coastal flooding (05B.4.3.8, 05B.4.3.9, 05B.4.3.10; Hingst and others, 2024; Werner and Simmons, 2009), while the interplay between multiple hazards primarily identified at the terrestrial field (05B.4.3.13, 05B.4.3.14) along with human activities (freshwater pumping) will probably result in unprecedented effects in already problematic coastal areas and elsewhere (Safi and others, 2018).

Ocean acidification

The ocean is a major player in the global carbon cycle and a key sink for anthropogenic CO_2, helping moderate climate change (Gruber and others, 2019). The ocean has taken up between 20 and 30 percent of total anthropogenic carbon dioxide emissions since the 1980s (very likely, IPCC, 2019). The decrease of ocean pH is referred to as ocean acidification (Canadell and others, 2021). Ocean acidification is among the targets of SDG 14 of the UN 2030 Agenda for Sustainable Development (UN, 2015).

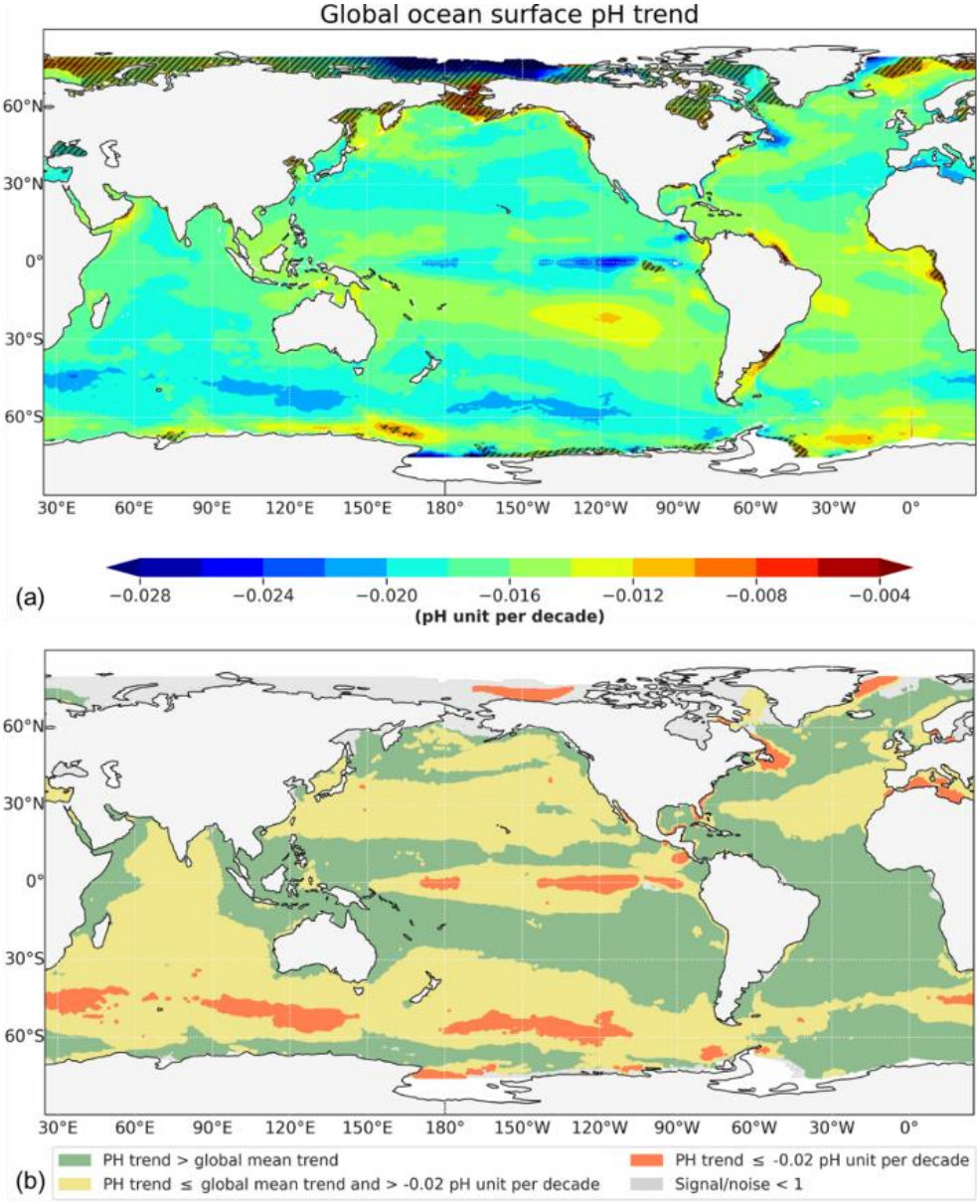


Figure 5B.4.15 (a) Global ocean surface pH trend computed over the period 1985-2022. (b) Magnitude of the pH decrease rates (von Schuckmann and others, 2024).

IPCC (2019) has assessed that open ocean surface pH has declined by a very likely range of 0.017-0.027 pH units per decade since the late 1980s, with the decline in surface ocean pH very likely to have already emerged from background natural variability for more than 95 percent of the ocean surface area. Ocean acidification has spread deeper in the ocean (Fassbender and others, 2023), surpassing 2000m depth in the northern North Atlantic and in the Southern Ocean (Canadell and others, 2021). Acidification, in conjunction with other climate change-related environmental stresses puts at risk many valuable ecosystem services like fisheries, aquaculture, and shoreline

protection (Doney and others, 2020; IPCC, 2022). In addition, together with ocean warming, ocean acidification threatens the future growth of coral reefs (Cornwall and others, 2021), and has diverse adverse impacts on marine biodiversity (Bindoff and others, 2019; Taixido and others, 2024).

Ocean deoxygenation

It is well established that oxygen loss in the ocean, known as deoxygenation, is a significant consequence of climate change, further intensified by other global changes. Over the past 50-100yrs, deoxygenation has already emerged over most of the global open ocean, which has experienced an average oxygen decline of 2 percent or more, with even more pronounced losses in intermediate waters (100-600m) of the North Pacific, East Pacific, tropical regions, and the Southern Ocean (Levin, 2018; Oschlies and others, 2018; Breitburg and others, 2018). Natural oxygen variability has made it difficult to detect the emergence of a climate-forced signal of oxygen loss; the observed open-ocean deoxygenation and expansion of oxygen minimum zones are attributed only in part to human influence (Arias and others, 2021).

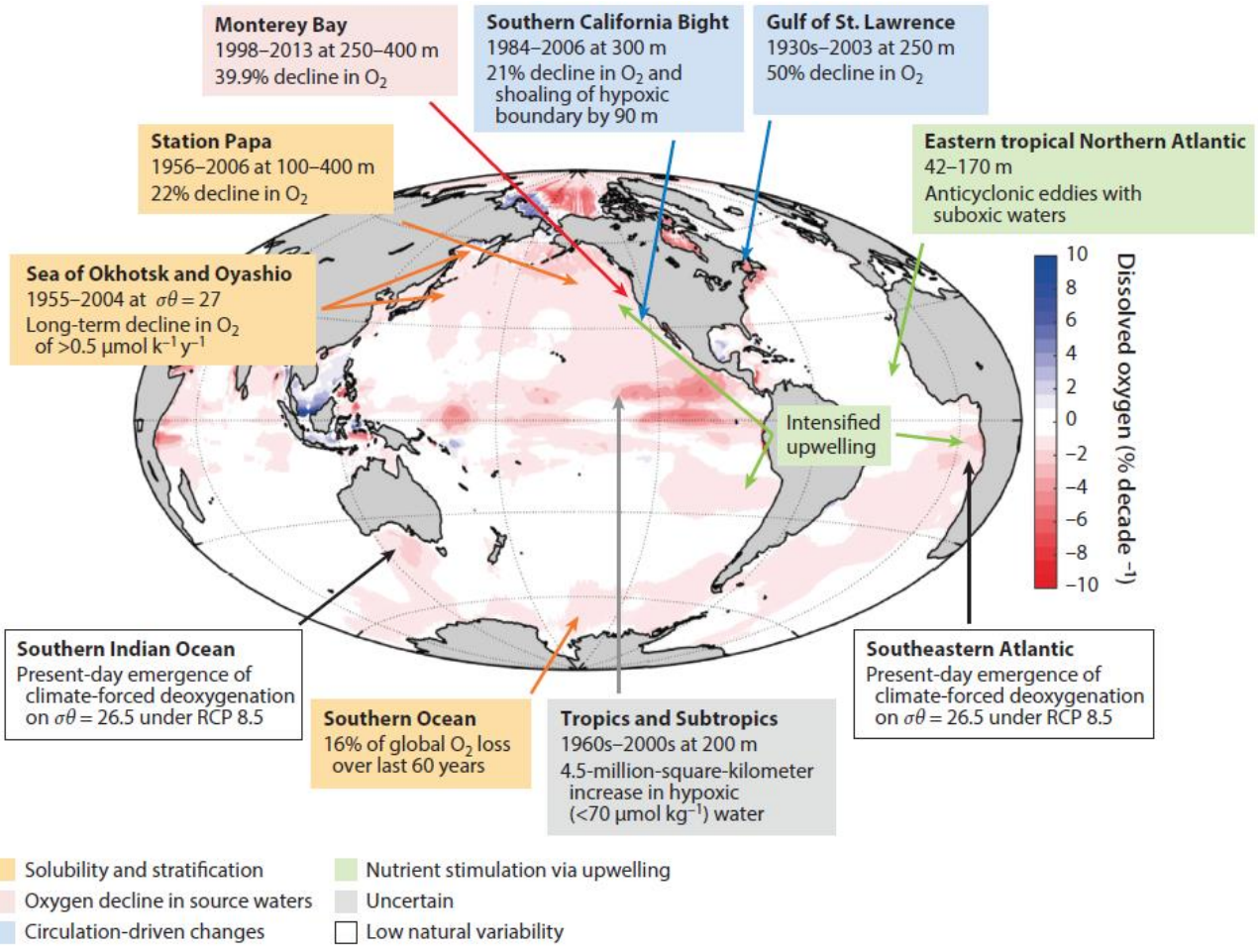
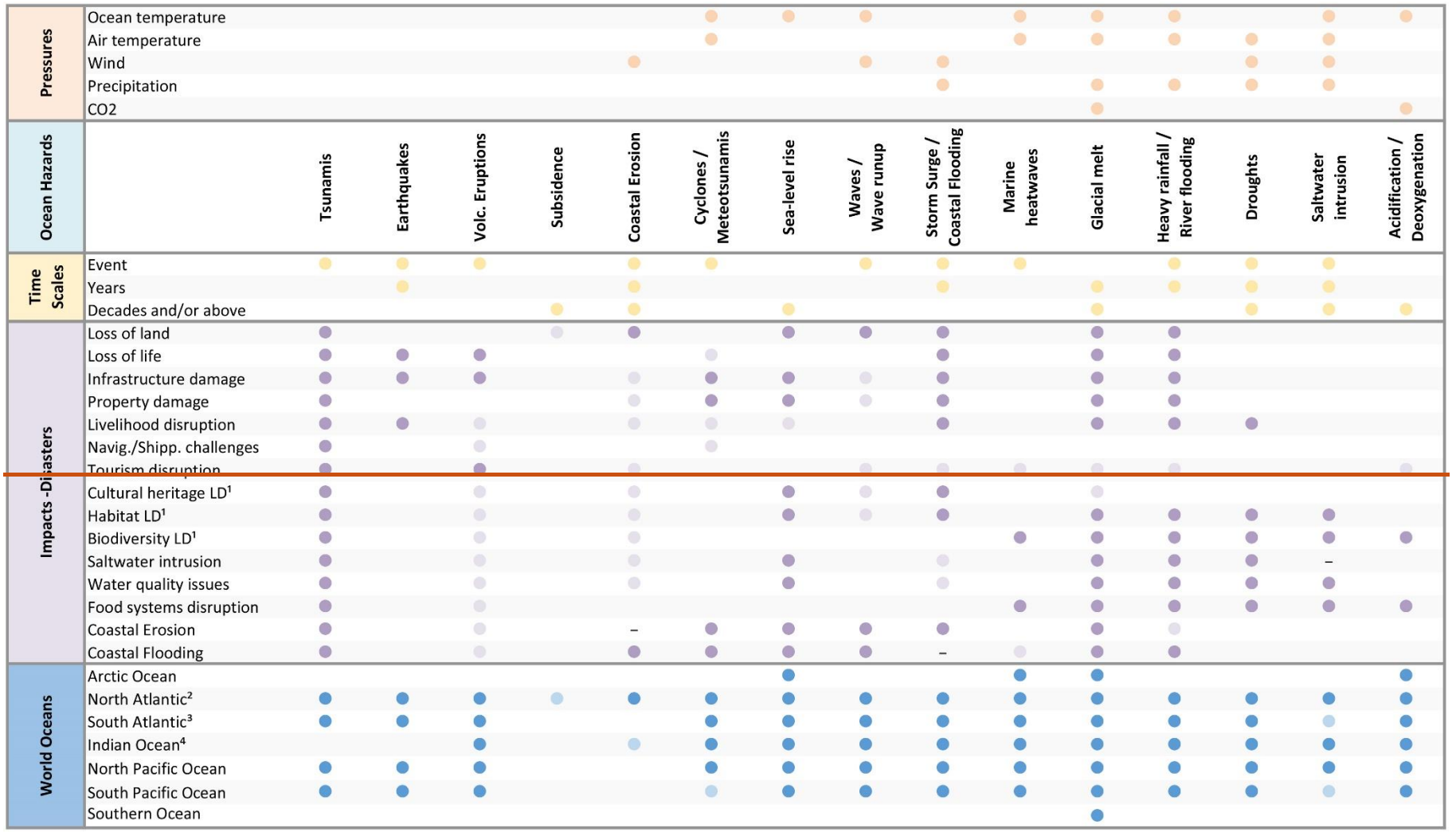


Figure 5B.4.16 Representative long-term records of open ocean deoxygenation in intermediate waters superimposed on full ocean percentage change in dissolved oxygen per decade since 1960 ($\sigma\vartheta$: density surface; Levin, 2018).

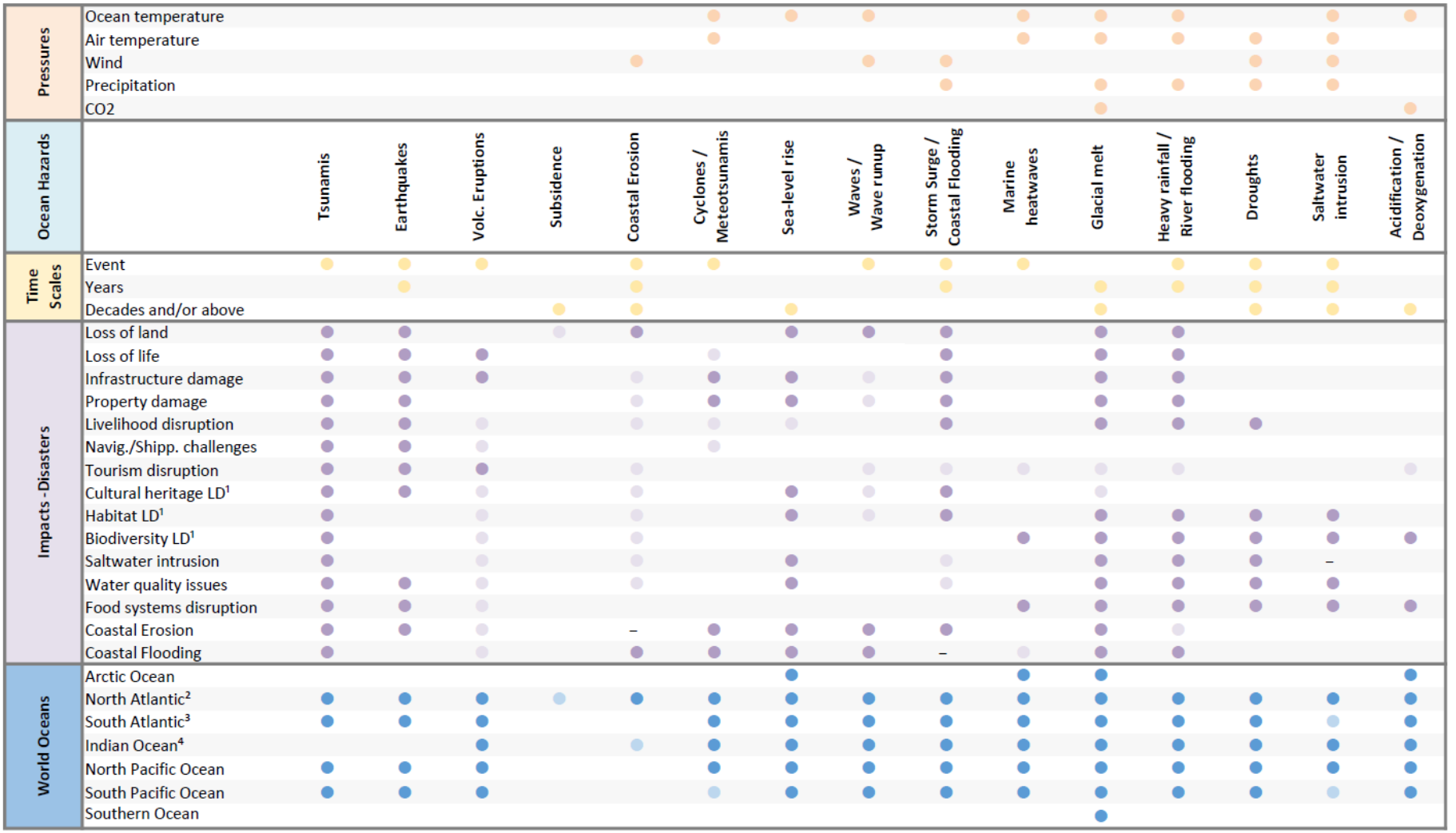
Continued global deoxygenation is projected to persist under most emissions scenarios, but with regional heterogeneity (Canadell and others, 2021). Notably, even small changes in oxygenation can have significant biological and biogeochemical effects, such as for ocean productivity, nutrient cycling, carbon cycling, and marine habitat (Bindoff and others, 2019). Together with warming and acidification, deoxygenation alters ecological communities by increasing the spread of physiologically suboptimal conditions for many marine fish and invertebrates. It is well established that these and other responses have subsequently driven habitat loss, population declines, increased risks of species extirpations and extinctions and rearrangement of marine food webs (Cooley, 2022).

Section assessment / pathways



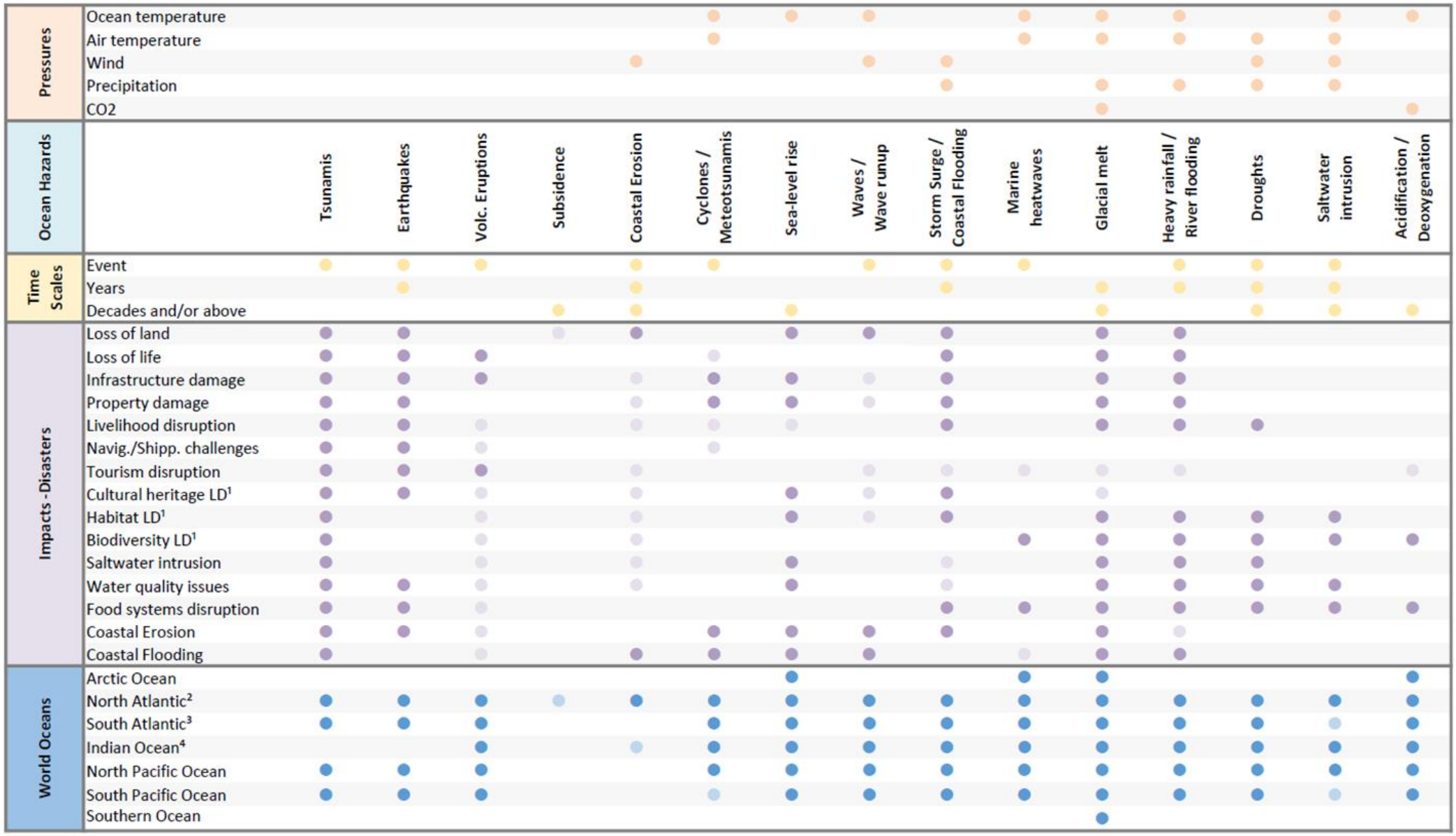
[1] Loss/Destruction or Loss/Disruption
[2] Incl. Baltic Sea, Black Sea, Medit. Sea, North Sea
[3] Incl. Wider Caribbean
[4] Incl. Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf

Light severity
Medium/Strong severity
Low importance
Medium/High importance



[1] Loss/Destruction or Loss/Disruption
[2] Incl. Baltic Sea, Black Sea, Medit. Sea, North Sea
[3] Incl. Wider Caribbean
[4] Incl. Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf

Light severity
Medium/Strong severity
Low importance
Medium/High importance



[1] Loss/Destruction or Loss/Disruption

[2] Incl. Baltic Sea, Black Sea, Medit. Sea, North Sea

[3] Incl. Wider Caribbean

[4] Incl. Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf

Light severity

Medium/Strong severity

Low importance

Medium/High importance

Figure 5B.4.17 Assessment regarding the pathways connecting components “Pressures”, “Ocean Hazards” and “Impacts – Disasters” of Figure 5B.4.1~~Figure 5B.4. 1~~, including connections to “Time Scales” and geographical distribution (“Word Oceans” are listed adopting the division of WOA III).

Towards Ocean/Coastal Resilience

This Section analyses strategies towards Ocean/Coastal resilience that serve this Chapter's context of identifying pathways connecting components "Impacts-Disasters" and "Mitigation-Management-Adaptation" (see 5B.4.2 and Figure 5B.4.1), referring to single-/multi- hazard assessment. It is divided into 9 sub-sections. Some of the hazards presented in 05B.4.3 are grouped, as relevant strategies typically address multiple hazards. Regarding hazards, per se, it is noted that, according to UNFCCC (2024c), in the 58 National Adaptation Plans (NAPs) submitted the most commonly identified climate hazard was sea level rise, along with ocean acidification, saltwater intrusion and increased sea surface temperatures. Furthermore, according to (2024a), of the Parties that included an ocean-based measure in their NAPs, 12 per cent included reference to human- and climate-induced ocean changes such as acidification, extreme weather events, sea level rise, storms and drought.

The "Mitigation-Management-Adaptation" strategies presented in this Section strongly align with evolving international climate policy frameworks on ocean resilience (UNFCCC, 2023, 2024a, b). Ecosystem-based adaptation, enhanced early warning systems and risk-informed planning are prioritized as integral parts of the developed/under-development NAPs (UNFCCC, 2024a, c). Likewise, focus on community engagement and robust governance relates to UNFCCC calls for inclusive, "whole-of-society" approaches to climate resilience.

The final product of this Section's effort is presented in 05B.4.4.9 / Figure 5B.4.18. Information in Figure 5B.4.18~~Figure 5B.4.18~~ reflects the assimilation of available knowledge regarding the examined strategies in relevant literature (see also 05B.4.5). It is noted that Figure 5B.4.18 does not focus on specific technical or managerial solutions, but rather adopts strategies' division to "Risk Reduction" and "Governance / Institutional / Social Transformation" according to Pinardi and others (2024). Figure 5B.4.18 should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale multi-hazard assessments when studying phenomena with significant local/regional variations, but also existing gaps of knowledge in relevance research. Given the above, this Section is fundamentally linked to S4.C2, S5A and S5B of WOA III, with detailed links identified in 05B.4.6.

~~The "Mitigation-Management-Adaptation" strategies presented in this Section strongly align with evolving international climate policy frameworks on ocean resilience (UNFCCC, 2023, 2024a, b). Ecosystem-based adaptation, enhanced early warning systems and risk-informed planning are prioritized as integral parts of the developed/under-development National Adaptation Plans (NAPs) by the Nationally Determined Contributions (NDCs).Likewise, focus on community engagement and robust governance relates to UNFCCC calls for inclusive, "whole-of-society" approaches to climate resilience.~~

Geophysical / Geological Hazards

Understanding the impacts of geohazards underlines the importance for effective mitigation and adaptation strategies including preparedness actions, improvement of building codes, development of Early Warning Systems, and land-use planning. For instance, after the 2011 Tohoku earthquake and

tsunami, NE Japan, the Government invested heavily in building higher sea walls along the coastline to protect communities as well as in developing high-tech early warning systems in the country (NIED, 2024https://www.bosai.go.jp/e/research/center/network.html). On a global scale, warning services are provided by regional systems operating in different ocean basins (see IOC, 2023). These systems focus on end-to-end tsunami warning and mitigation, and are coordinated by IOC-UNESCO as a global "system of systems". Just as important is that communities are aware and prepared to respond quickly to these extremely short notice and fast onset events (IOC, 2022; UNDRR, 2024). Earthquakes, on the other hand, can cause extensive damage on land but also liquefaction in coastal zones and partial collapse of structures (e.g. the 1989 Loma Prieta/California earthquake and impact on the San Francisco-Oakland Bay Bridge). Following that aforementioned earthquake, public and private sectors made substantial investments for redevelopment and seismic retrofitting programs to reduce the impact of future earthquakes and enhance earthquake resilience (Zoback, 2014).

Cyclones - Meteotsunamis

When meteotsunami risk is recognized and protection is economically justified (e.g. for strategic infrastructure), design criteria for coastal structures and flood protection systems can be adapted to account for these events (deJong and others, 2021). Nevertheless, in most cases early warning remains the backbone for meteotsunami risk reduction, although key obstacles to this end include observational challenges (limited spatial/temporal data) and modeling difficulties (accurate location/timing predictions, considering local geomorphology). Relevant benefits can derive from relative small investments integrating existing multi-hazard coastal warning systems and emerging technologies (Vilibic and others, 2016).

The mitigation of cyclone impacts is typically carried out by means of different management approaches dealing with risk reduction strategies and post-event response and recovery (Hoque and others, 2017). Risk reduction in particular has traditionally mostly been tackling vulnerability and exposure of coastal assets, infrastructures, and communities, by means of technological instruments such as early warning systems and changes in urban planning and building practices. As these approaches struggle to keep pace with the increasing pressures on the coastal areas, new techniques based on geo-engineering principles are emerging as potential lines of development for risk reduction addressing the characteristics of the cyclone as a hazard factor (Miller and others, 2023). In both cases, addressing education, training, involvement of coastal communities as well as issues related to social acceptance and trust is key to risk reduction.

Sea level rise - Glacial melt

Addressing current coastal impacts, managing future risks, and preventing accelerated sea level rise post-2050 all require immediate mitigation and adaptation (Nicholls and others, 2018). The most urgent adaptation challenge is chronic flooding at high tide (IPCC, 2022). Until 2050, adaptation planning and implementation needs are projected to increase significantly in most inhabited coastal regions (IPCC, 2019, 2021). Risks and adaptation can be anticipated, planned and

implemented over the coming decades considering that adaptation capacity and governance to manage risks from projected sea level rise typically require decades to implement (e.g., IPCC, 2022; Haasnoot and others, 2021). Without timely action, vulnerable communities will face a reduction in adaptation options and bear disproportionate impacts (IPCC, 2022). Effective responses include decision analysis, land-use planning, public participation, and conflict resolution to chart adaptive pathways and manage governance challenges posed by sea level rise (IPCC, 2019). Also, evidence-informed risk management, strengthened stakeholder dialogue and coordination, and enhanced action and support for finance, technology and capacity-building has been prioritized internationally (UNCC, 2025). It is well-established that available near-term adaptation options include engineered, sediment- or ecosystem-based protection; land-use planning to reduce vulnerability; and advance (land reclamation) or retreat strategies (relocation; IPCC, 2022; Oppenheimer and others, 2019). Only avoidance and relocation can remove coastal risks for the coming decades, while other measures only delay impacts temporarily, have increasing residual risk or perpetuate risk and create ongoing legacy effects and virtually certain property and ecosystem losses (Siders and others, 2019). Large-scale relocation has immense cultural, political, social and economic costs, and equity implications, which can be reduced by fast implementation of climate mitigation and adaptation policies (IPCC, 2021, 2022; Haasnoot and others, 2021). Ecosystem-based adaptation (e.g., planting and conserving vegetation; landward migration, sediment supply) can reduce impacts on human settlements and generate substantial co-benefits across various socioeconomic dimensions, but they require space for sediment and ecosystems and have site-specific physical limits (IPCC, 2022; Neijnens and others, 2021; UNFCC, 2023, 2024b).

Regarding glacial melt, since its main direct impact is the contribution to sea level rise, strategies are largely covered by the previous paragraph and 05~~B.4.4.4~~). Beyond that, hazard-specific measures include using geotextiles to cover glaciers (Senese and others, 2020) creating submerged barriers or dams in front of ice sheets and glaciers (Hunt and Byers, 2019), as well as a wide range of other geoengineering approaches (Lockley and others, 2020).

Coastal erosion - Waves / Wave runup - Storm Surge / Coastal flooding

Mitigating coastal erosion and flooding involves strategies aimed at protecting shorelines, preserving natural landscapes, minimizing the impacts of shoreline retreat on coastal infrastructure, and reducing the hazards posed by rising sea levels, storm surges, and high tides on coastal communities (IPCC, 2022). Risk mitigation and adaptation strategies should ideally operate across multiple timescales to be effective: in the short term, this includes implementing early warning systems, emergency response protocols, and maintaining existing protective infrastructure (Singhvi and others, 2022; Winter and others, 2020); in the medium term, focus could shift to upgrading infrastructure, consideration of Nature-Based Solutions like mangrove restoration, and developing comprehensive coastal zone management plans (Andersson and others, 2022); while long-term strategies may require transformative approaches such as relocation from high-risk areas (Revell and others, 2021),

major infrastructure redesign, and strategic rethinking of land-use planning that account for projected sea-level rise and increased storm intensity/frequency (IPCC, 2022). Successful implementation requires careful alignment of these temporal scales along adaptation pathways (Haasnoot and others, 2013), with an appropriate multi-level governance framework, responsible from emergency response to long-term socio-economic planning, while ensuring continuity across political cycles (Rocle and others, 2021; Bisaro and others, 2020). Successful risk reduction strategies depend heavily on community buy-in, local knowledge integration, and social justice considerations. Vulnerable coastal communities, particularly those with limited resources, often face disproportionate risks while being the least resilient to coastal flooding and erosion (IPCC, 2022).

Marine heatwaves

Well established impacts of MHWs have been reported for different types of ecosystems, particularly warm water coral reefs, rocky shores, kelp systems, estuaries, lagoons, mangroves, seagrasses, sandy beaches, semi-enclosed sea, shelf seas and the Arctic region (IPCC, 2022). Socioeconomic systems (including Indigenous Ppeoples and local communities) that rely on these ecosystems are threatened by MHW impacts on incomes, economy sectors such as fisheries and tourism and, in the case of coral reefs, shoreline protection from waves (IPCC, 2022). Management and adaptation strategies include the use of high-resolution data, forecasts and early-warning systems to better prepare for MHWs and collect data on their effects (Holbrook and others, 2020; McAdam and others, 2023). In addition, these data can guide economic sectors such as aquaculture when selecting new sites to reduce the likelihood of exposure to MHWs (Sandersen and others, 2021; Liu and others, 2014), and support active restoration efforts (Fox and others, 2021; Aoki and others, 2020). Early management intervention and shifts in management approaches (e.g. quotas or stock assessments, flexible harvesting strategies) can also help to limit the impacts of MHWs, (Le Bris and others, 2018; Pershing and others, 2018; Holbrook and others, 2020). Furthermore, Marine Protected Areas (MPAs) and no-take zones, in addition to terrestrial protection surrounding vulnerable coastal ecosystems, cannot prevent MHWs from occurring. Nevertheless, depending on the location and adherence by people to restrictions on certain activities, the cumulative effect of other stressors on vulnerable ecosystems can be reduced, potentially helping to enhance the rate of recovery of marine life (IPCC, 2022; Arafeh-Dalmau and others, 2023). Moreover, MPAs are more likely to buffer the impacts of MHWs if climate change responses are considered in their design (Smith and others, 2021).

Heavy rainfall / River flooding

Mitigation-Management-Adaptation strategies against heavy rainfall / river flooding extend beyond coastal zones. Regarding “traditional” defense infrastructure, reinforcing levees, dikes, and barriers, will protect low-lying coastal areas against coastal, riverine or compound flooding (Couasnon and others, 2020; Moftakhari and others, 2017), while retention basins and river regulation

works will contribute to reducing downstream flooding risks (Winarta and others, 2019). Nature-Based Solutions (wetlands, mangroves, salt marshes, coastal dunes), can also significantly improve flood resilience, while at the same time enhancing water quality and supporting estuarine biodiversity (Bevacqua and others, 2019; Maiolo and others, 2020). Furthermore, adopting integrated watershed management approaches can prove highly beneficial, by controlling erosion, runoff, and pollutant loads travelling downstream (Ge and others, 2021), while climate-adaptive infrastructure and planning in coastal cities can enhance the resilience of coastal communities (Wang and others, 2021). Finally, improvements in monitoring, forecasting and early warning systems development, along with the strategic investment on community preparedness and response, will always constitute integral parts towards coastal resilience (Figlus, 2022; Shen and others, 2019).

Droughts - Saltwater intrusion

Droughts and saltwater intrusion are correlated in several aspects regarding their impacts (see ~~05B.4.3.14~~, ~~05B.4.3.15~~) and, accordingly, the suitable strategies towards ocean/coastal resilience. In general, aligning water management, land use policies and coastal zone management should be a key requirement for effective water resources management from catchment to coast. Water conservation measures and efficient crop selection/irrigation practices can alleviate stress from water resources during drought periods (Cook and others, 2018; Tabari and Willems, 2023), while sustainable groundwater management and coastal infrastructure like barriers and subsurface dams can mitigate saltwater intrusion (Werner and others, 2013; Ferguson and Gleeson, 2012). Coastal land use zoning in vulnerable areas and managed aquifer recharge can also be reliable management strategies (Chong and others, 2014), along with the controlled release of freshwater from upstream reservoirs (Moore and Joye, 2021). Furthermore, Ecosystem-Based Adaptation (restoring/conserving coastal ecosystems), shifting towards drought-/salinity-tolerant crops in agriculture, and community engagement/education towards sustainable water use and irrigation practices, can all build towards resilient coastal ecosystems and communities (Visschers and others, 2022; Mafi-Gholami and others, 2020).

Ocean acidification - Ocean deoxygenation

Hazards from ocean acidification and ocean deoxygenation have wide reaching impacts on ocean sectors such as coastal population, small-scale and large-scale fisheries, mariculture and tourism and affect all elements of marine ecosystem services, from the regulating, provisioning to the supporting services (IPCC, 2022). Adapting to ocean acidification requires enhancing the resilience of marine ecosystems, supporting affected industries, and developing adaptive management practices (Pelletier and others, 2020; Trebilco and others, 2022; Woods and others, 2022). As for MHWs (~~05B.4.3.11~~), the protection and restoration of resilient ecosystems such as seagrass, beds, mangroves and kelp forests ecosystems can help buffer the effects of acidification by

absorbing CO_2 and creating more stable local conditions (Falkenberg and others 2021; Voolstra and others, 2023). Informed supporting of marine species adaptation also plays an increasing role, such as selective breeding and diversify of the major aquaculture species (e.g., Boudry and others, 2021, Tan and others, 2020). Ocean acidification also affects human health and well-being in the context of malnutrition and poisoning, respiratory issues, mental health impacts, and development of medical resources (Falkenberg and others, 2020). Adapting to ocean changes will necessarily include efforts to manage socio-ecological systems adaptively (Cinner and others, 2019), such as for fisheries and aquaculture by iteratively changing management practices via biodiversity conservation and local management (Doubleday and Connell, 2018; Arkhipkin and others, 2015; Bille and others, 2013; Arafeh-Dalmau and others, 2023).

Section assessment / pathways

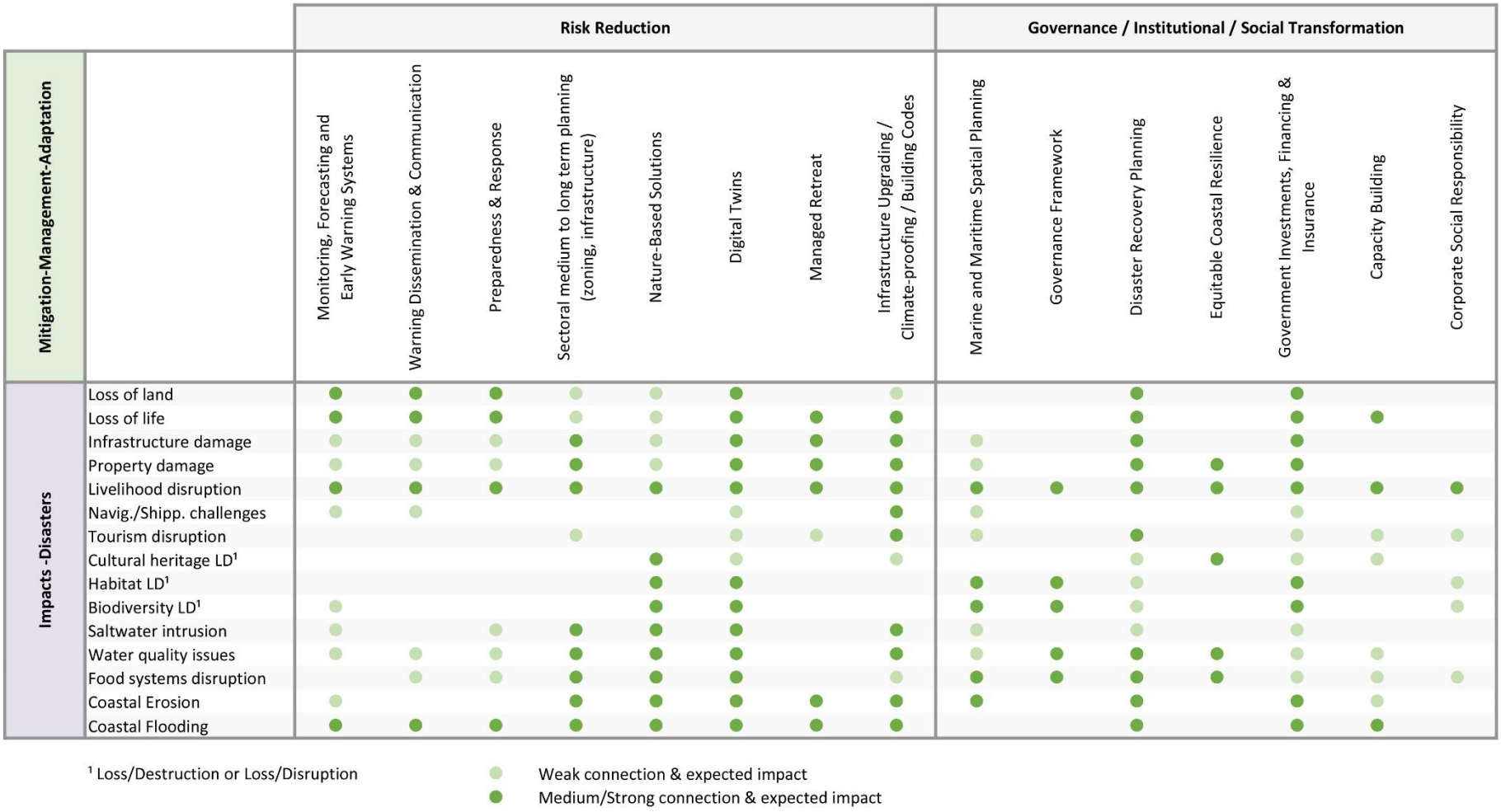


Figure 5B.4.18 Assessment regarding the pathways connecting components "Impacts – Disasters" and "Mitigation-Management-Adaptation" Figure 5B.4.1~~Figure 5B.4. 1~~ (division to Risk Reduction and GIS Transformation adopted from Pinardi and others, 2024).

1 Extended literature by Section

Sub-Section	Extended Literature
5B4.3.1	Doocy and others (2013), Espinosa and others (2017)
5B4.3.2	Daniel (2014), Jaiswal and Wald (2013), Skufina and others (2019)
5B4.3.3	-
5B4.3.4	-
5B4.3.5	Nawarat and others (2024)
5B4.3.6	Wang and Lin (2020), Earl-Spurr and others (2023), Lamers and others (2023), Heidarzadeh and Rabinovich (2021), Kim and Omira (2024), Raible and others (2021), Gaertner and others (2018), Hoque and others (2017), Catto (2016), Leroux and others (2018), Heming and others (2019), Wang and others (2016), Catto and others (2019), Knutson and others (2019), Hart (2003)
5B4.3.7	Dusek and others (2019), Vilibic and others (2016), Huang and others (2022), Angove and others (2021)
5B4.3.8	-
5B4.3.9	Xu and Perrie (2012), Wong and others (2019), Dissanayake and others (2021), Hemer and others (2010, 2013), Meucci and others (2023), Shimura and other (2015), Young and others (2011), Hsu and others (2023), Lee and others (2022)
5B4.3.10	-
5B4.3.11	Harris and others (2018)
5B4.3.12	Zemp and others (2020), Sraneo and Heimbach (2023), Khan and others (2022), Zhou and others (2021), Cape and others (2019), Sejr and others (2022)
5B4.3.13	Wood and others (2024), Yuan and others (2024), Couasnon and others (2020), Wang and others (2021), Howley and others (2018), Cardoso and others (2008), Shore and others (2021), Draut and others (2009), Milner and others (2018), Dankers and others (2014), Eccles and others (2019)
5B4.3.14	Fakhruddin and Eslamian (2017), Thomsen and Green (2019), Lake (2011), Ravindra and others (2010), Oh and others (2023), Dai (2011, 2013)
5B4.3.15	Chong and others (2014), Hu and others (2024), Bui and others (2024), Vu and others (2024), Datta and others (2009), Ferguson and Gleeson (2012)
5B4.3.16	-
5B4.3.17	Levin (2003), Sperling and others (2016), Orio and others (2021)
5B4.4.1	-
5B4.4.2	Lewis and others (2023), Angove and others (2021), Lamers and others (2023)
5B4.4.3	Huss and others (2021), Xie and others (2023)
5B4.4.4	Vousdoukas and others (2018, 2020), Dedekorkut-Howes and others (2020), Casella and others (2014), Polk and Eulie (2018)
5B4.4.5	
5B4.4.6	Dankers and others (2014), Barbier and others (2011), Howley and others (2018), Mansour Abdelkareem (2024), Ward and others (2018), Wahl and others (2015)
5B4.4.7	Hingst and others (2024), Bhattachan and others (2018), Chang and others (2019), Hu and others (2024), Murgulet and Tick (2008), Miyan (2015), Ravindra and others (2010), Osemwegie and Boko-Koiadia (2019)
5B4.4.8	-

Links to WOA III Sections/Chapters

		Links to WOA III Chapters/Sections					
Pressures	Ocean temperature	S4.C1	S4.C2	S4.C3			
	Air temperature	S4.C1	S4.C2	S4.C3			
	Wind	S4.C1	S4.C2	S4.C3			
	Precipitation	S4.C1	S4.C2	S4.C3			
	CO2	S4.C1	S4.C2	S4.C3			
Ocean Hazards	Tsunamis		S4.C3				
	Earthquakes		S4.C3				
	Volc. Eruptions		S4.C3				
	Subsidence		S4.C3				
	Coastal Erosion	S4.C1	S4.C3				
	Cyclones / Meteotsunamis	S4.C1	S4.C3				
	Sea-level rise	S4.C1	S4.C3				
	Waves /	S4.C1	S4.C3				
	Storm Surge /	S4.C1	S4.C3				
	Marine heatwaves	S4.C1	S4.C3				
	Glacial melt	S4.C1	S4.C3				
	Heavy rainfall /	S4.C1	S4.C3				
	Droughts	S4.C1	S4.C3				
	Saltwater intrusion	S4.C1	S4.C3				
	Acidification / Deoxygenation	S4.C1	S4.C3				
Impacts -Disasters	Loss of land	S4.C1	S4.C3	S5A.C9			
	Loss of life	S4.C1	S4.C3	S5B.C2			
	Infrastructure damage	S4.C1	S4.C3	S5A.C3	S5A.C9		
	Property damage	S4.C1	S4.C3	S5A.C9			
	Livelihood disruption	S4.C1	S4.C3	S5A.C3	S5B.C3		
	Navig./Shipp. challenges	S4.C1	S4.C3	S5A.C6	S5A.C9		
	Tourism disruption	S4.C1	S4.C3	S5A.C2	S5A.C4	S5A.C9	S5B.C3
	Cultural heritage Loss/Destruction	S4.C1	S4.C3	S5A.C7	S5A.C9		
	Habitat Loss/Destruction	S4.C1	S4.C3	S4.C5	S5A.C9	S5B.C1	S5B.C2
	Biodiversity Loss/Disruption	S4.C1	S4.C3	S4.C4	S5A.C5	S5B.C1	S5B.C2
	Saltwater intrusion	S4.C1	S4.C3				
	Water quality issues	S4.C1	S4.C3	S5A.C8	S5B.C2		
	Food systems disruption	S4.C1	S4.C3	S5A.C1	S5A.C5	S5B.C2	
	Coastal Erosion	S4.C1	S4.C3	S5A.C9			
	Coastal Flooding	S4.C1	S4.C3	S5A.C9			
Mitigation-Management-Adaptation	Monitoring, Forecasting and Early Warning Systems						
	Warning Dissemination & Communication						
	Preparedness & Response						
	Sectoral medium to long term planning						
	Nature-Based Solutions						
	Digital Twins						
	Managed Retreat						
	Infrastructure Upgrading / Climate-proofing / Building Codes	S4.C2	S5A.C*	S5B.C*			
	Marine and Maritime Spatial Planning						
	Governance Framework						
	Disaster Recovery Planning						
	Equitable Coastal Resilience						
	Government Investments, Financing & Insurance						
	Capacity Building						
	Corporate Social Responsibility						

* Potential link to all Chapters of this Section

References

Allan, Jonathan C. and Komar, Paul D. Wave Climate Change and Coastal Erosion in the US Pacific Northwest. In Proceedings of the Ocean Wave Measurement and Analysis, Reston, VA, pp. 680-689, 2002.

Alves, P. B. R., and others. An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas. Urban Water Journal, vol. 18, No. 7, pp. 530-543, 2021.

Andersson, Erik, and others. Urban climate resilience through hybrid infrastructure. Current Opinion in Environmental Sustainability, vol. 55, pp. 101158-101158, 2022.

Andreeva, N., and others. Identification of Coastal Flooding Hotspots in a Large Bay Using an Index-Based Risk Assessment Approach. In Proceedings of the Lecture Notes in Networks and Systems, pp. 51-65, 2023.

Andreeva, N., and others. Assessment of coastal receptors' exposure vulnerability to flood hazard along varna regional coast. In Proceedings of the Proceedings of the Coastal Engineering Conference, 2016.

Angove, Michael, and others. Addressing the meteotsunami risk in the United States. Natural Hazards, vol. 106, No. 2, pp. 1467-1487, 2021.

Aoki, Lillian R., and others. Depth Affects Seagrass Restoration Success and Resilience to Marine Heat Wave Disturbance. Estuaries and Coasts, vol. 43, No. 2, pp. 316-328, 2020.

Arafeh-Dalmau, Nur, and others. Integrating climate adaptation and transboundary management: Guidelines for designing climate-smart marine protected areas. One Earth, vol. 6, No. 11, pp. 1523-1541, 2023.

Arkhipkin, Alexander I., and others. World Squid Fisheries. Reviews in Fisheries Science & Aquaculture, vol. 23, No. 2, pp. 92-252, 2015.

Armstrong, S. B. and Lazarus, E. D. Reconstructing patterns of coastal risk in space and time along the US Atlantic coast, 1970-2016. Natural Hazards and Earth System Sciences, vol. 19, No. 11, pp. 2497-2511, 2019.

Baouham, A., and others. A Review of Structural Vulnerability Assessment Methods in the Advent of a Tsunami. In Proceedings of the E3S Web of Conferences, 2024.

Barbier, Edward B., and others. The value of estuarine and coastal ecosystem services. Ecological Monographs, vol. 81, No. 2, pp. 169-193, 2011.

Barría, P., and others. From multi-risk evaluation to resilience planning: The case of central Chilean coastal cities. Water (Switzerland), vol. 11, No. 3, 2019.

Benassai, G., and others. Coastal risk assessment of a micro-tidal littoral plain in response to sea level rise. Ocean and Coastal Management, vol. 104, pp. 22-35, 2015.

Bevacqua, E., and others. Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. Science Advances, vol. 5, No. 9, 2019.

Bhattachan, A., and others. Evaluating the effects of land-use change and future climate change on vulnerability of coastal landscapes to saltwater intrusion. Elementa, vol. 6, 2018.

Billé, Raphaël, and others. Taking Action against Ocean Acidification: A Review of Management and Policy Options. Environmental Management, vol. 52, No. 4, pp. 761-779, 2013.

Bin, L., and others. Urban flood risk assessment characterizing the relationship among hazard, exposure, and vulnerability. Environmental Science and Pollution Research, vol. 30, No. 36, pp. 86463-86477, 2023.

Bongarts Lebbe, T., and others. Designing Coastal Adaptation Strategies to Tackle Sea Level Rise. Frontiers in Marine Science, vol. 8, 2021.

Booij, N., and others. A third-generation wave model for coastal regions 1. Model description and validation. Journal of Geophysical Research: Oceans, vol. 104, No. C4, pp. 7649-7666, 1999.

Borges Monteiro, A. C., and others. A machine learning methodology to calculate the percentage of areas affected by drought in Brazil in map images. Modern Cartography Series, vol. 12, pp. 701-718, 2024.

Bosom, E. and Jiménez, J. A. Storm-induced coastal hazard assessment at regional scale: Application to Catalonia (NW Mediterranean). Advances in Geosciences, vol. 26, pp. 83-87, 2010.

Boudry, Pierre, and others. Current status and potential of genomic selection to improve selective breeding in the main aquaculture species of International Council for the Exploration of the Sea (ICES) member countries. Aquaculture Reports, vol. 20, pp. 100700-100700, 2021.

Breitburg, Denise, and others. Declining oxygen in the global ocean and coastal waters. Science, vol. 359, No. 6371, 2018.

Bryant, Edward. Tsunami: The Underrated Hazard. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008.

Bui, Q. D., and others. A holistic approach to salinity intrusion vulnerability assessment using geospatial technologies: An application for mekong delta of vietnam. International Journal of Disaster Risk Reduction, vol. 113, 2024.

Cape, M. R., and others. Circumpolar deep water impacts glacial meltwater export and coastal biogeochemical cycling along the west Antarctic Peninsula. Frontiers in Marine Science, vol. 6, No. MAR, 2019.

Cardoso, P. G., and others. The impact of extreme flooding events and anthropogenic stressors on the macrobenthic communities' dynamics. Estuarine, Coastal and Shelf Science, vol. 76, No. 3, pp. 553-565, 2008.
Casas-Prat, M., and others. Wind-wave climate changes and their impacts. Nature Reviews Earth and Environment, vol. 5, No. 1, pp. 23-42, 2024.
Casas-Prat, M. and Sierra, J. P. Trend analysis of wave direction and associated impacts on the Catalan coast. Climatic Change, vol. 115, No. 3-4, pp. 667-691, 2012.
Casella, Elisa, and others. Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management. Estuarine, Coastal and Shelf Science, vol. 149, pp. 160-167, 2014.
Catto, J. L. Reviews of Geophysics Extratropical cyclone classification and its use. Reviews of Geophysics, vol. 54, pp. 486-520, 2016.
Catto, Jennifer L., and others. The Future of Midlatitude Cyclones. Current Climate Change Reports, vol. 5, No. 4, pp. 407-420, 2019.
Cazenave, Anny and Moreira, Lorena. Contemporary sea-level changes from global to local scales: a review. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 478, No. 2261, 2022.
Cenedese, C. and Straneo, F. Icebergs Melting. Annual Review of Fluid Mechanics, vol. 55, pp. 377-402, 2023.
Cerveny, Randall S., and others. WMO assessment of weather and climate mortality extremes: Lightning, tropical cyclones, tornadoes, and hail. Weather, Climate, and Society, vol. 9, No. 3, pp. 487-497, 2017.
Chang, Qinpeng, and others. Effect of subsurface dams on saltwater intrusion and fresh groundwater discharge. Journal of Hydrology, vol. 576, pp. 508-519, 2019.
Chang, S. E., and others. Community vulnerability to coastal hazards: Developing a typology for disaster risk reduction. Applied Geography, vol. 91, pp. 81-88, 2018.
Chen, J. and Zhang, L. "Risk Assessment and Risk-Benefit Assessment", in *Nutritional Toxicology*. (2022).
Cheung, William W. L. and Frölicher, Thomas L. Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. Scientific Reports, vol. 10, No. 1, pp. 6678-6678, 2020.
Chinchiolo, J. Landslide repair and severe erosion mitigation case studies in sensitive coastal areas. In Proceedings of the Landslides and Engineered Slopes: Protecting Society through Improved Understanding - Proceedings of the 11th International and 2nd North American Symposium on Landslides and Engineered Slopes, 2012, pp. 1581-1585, 2012.
Chinchiolo, J. and Barrett, C. Landslide repair and severe erosion mitigation case studies in sensitive coastal areas. In Proceedings of the Coastal Engineering Practice -

Proceedings of the 2011 Conference on Coastal Engineering Practice, pp. 605-615, 2011.
Chong, Y. J., and others. Climate change and salinity in drinking water as a global problem: using remote-sensing methods to monitor surface water salinity. International Journal of Remote Sensing, vol. 35, No. 4, pp. 1585-1599, 2014.
Christie, E. K., and others. Regional coastal flood risk assessment for a tidally dominant, natural coastal setting: North Norfolk, southern North Sea. Coastal Engineering, vol. 134, pp. 177-190, 2018.
Cinner, J. E., and others. Sixteen years of social and ecological dynamics reveal challenges and opportunities for adaptive management in sustaining the commons. Proceedings of the National Academy of Sciences, vol. 116, No. 52, pp. 26474-26483, 2019.
Coleman, J.M. Deltas: Processes of Deposition and Models for Exploration. Boston, MA: Burgess Publishing Company,
Conley, D. C. "Drivers: Waves and Tides", in *Coastal Environments and Global Change*. (2015).
Conrad, Patricia A., and others. Operationalizing a One Health approach to global health challenges. Comparative Immunology, Microbiology and Infectious Diseases, vol. 36, No. 3, pp. 211-216, 2013.
Cook, B. I., and others. Revisiting the leading drivers of Pacific coastal drought variability in the contiguous United States. Journal of Climate, vol. 31, No. 1, pp. 25-43, 2018.
Cornwall, Christopher E., and others. Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proceedings of the National Academy of Sciences, vol. 118, No. 21, 2021.
Couasnon, A., and others. Measuring compound flood potential from river discharge and storm surge extremes at the global scale. Natural Hazards and Earth System Sciences, vol. 20, No. 2, pp. 489-504, 2020.
Coulson, Sophie, and others. A detection of the sea level fingerprint of Greenland Ice Sheet melt. Science, vol. 377, No. 6614, pp. 1550-1554, 2022.
Dai, A. Drought under global warming: A review. Wiley Interdisciplinary Reviews: Climate Change, vol. 2, No. 1, pp. 45-65, 2011.
Dai, A. Increasing drought under global warming in observations and models. Nature Climate Change, vol. 3, No. 1, pp. 52-58, 2013.
Daniell, J. E. "The Socioeconomic Impact of Earthquake Disasters", in *Earthquake Hazard, Risk and Disasters*. (2014).
Dankers, R., and others. First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. Proceedings of the National Academy of Sciences of the United States of America, vol. 111, No. 9, pp. 3257-3261, 2014.

Datta, Bithin, and others. Modeling and control of saltwater intrusion in a coastal aquifer of Andhra Pradesh, India. Journal of Hydro-environment Research, vol. 3, No. 3, pp. 148-159, 2009.

de Jong, M. P. C., and others. Meteorologically generated long-period waves and their impact on the Dutch primary national flooding protection system. Natural Hazards, vol. 106, No. 2, pp. 1421-1443, 2021.

De Risi, R., and others. "A way forward to resilient infrastructures against earthquake-tsunami multi-hazard", in *Routledge Handbook of Sustainable and Resilient Infrastructure*. (2018).

Dedekorkut-Howes, Ayşın, and others. When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. Journal of Environmental Planning and Management, vol. 63, No. 12, pp. 2102-2143, 2020.

Denamiel, Cléa, and others. Climate projections of meteotsunami hazards. Frontiers in Marine Science, vol. 10, 2023.

Denamiel, Cléa, and others. Destructive Potential of Planetary Meteotsunami Waves beyond the Hunga Tonga-Hunga Ha'apai Volcano Eruption. Bulletin of the American Meteorological Society, vol. 104, No. 1, pp. E178-E191, 2023.

Di Luccio, Diana, and others. Monitoring and Modelling Coastal Vulnerability and Mitigation Proposal for an Archaeological Site (Kaulonia, Southern Italy). Sustainability, vol. 10, No. 6, pp. 2017-2017, 2018.

Dietz, S. and Koninx, F. Economic impacts of melting of the Antarctic Ice Sheet. Nature Communications, vol. 13, No. 1, 2022.

DiGiacomo, P. M., and others. Coastal pollution hazards in southern California observed by SAR imagery: Stormwater plumes, wastewater plumes, and natural hydrocarbon seeps. Marine Pollution Bulletin, vol. 49, No. 11-12, pp. 1013-1024, 2004.

Dissanayake, P., and others. Climate change impacts on coastal wave dynamics at Vougot beach, France. Journal of Marine Science and Engineering, vol. 9, No. 9, 2021.

Doalos, United Nations. The Second World Ocean Assessment. New York: 2021.

Doney, Scott C., and others. The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. Annual Review of Environment and Resources, vol. 45, No. 1, pp. 83-112, 2020.

Doocy, S., and others. The Human Impact of Tsunamis: A Historical Review of Events 1900-2009 and Systematic Literature Review. PLoS Currents, No. APR 2013, 2013.

Doocy, S., and others. The Human Impact of Volcanoes: A Historical Review of Events 1900-2009 and Systematic Literature Review. PLoS Currents, No. APR 2013, 2013.

Doubleday, Zoë A. and Connell, Sean D. Weedy futures: can we benefit from the species that thrive in the marine Anthropocene? Frontiers in Ecology and the Environment, vol. 16, No. 10, pp. 599-604, 2018.

Draut, A. E., and others. Supply and dispersal of flood sediment from a steep, tropical watershed: Hanalei Bay, Kaua'i, Hawai'i, USA. Bulletin of the Geological Society of America, vol. 121, No. 3-4, pp. 574-585, 2009.

DSE. Victorian Coastal Hazard Guide. Melbourne: Victorian Government Department of Sustainability and Environment, 2012.

Duc Tran, D., and others. Extent of saltwater intrusion and freshwater exploitability in the coastal Vietnamese Mekong Delta assessed by gauging records and numerical simulations. Journal of Hydrology, vol. 630, 2024.

Dupouy, G., and others. Propagating spatial and thematic uncertainties in mountain natural hazard assessment process. In Proceedings of the Risk, Reliability and Safety: Innovating Theory and Practice - Proceedings of the 26th European Safety and Reliability Conference, ESREL 2016, pp. 44-44, 2017.

Durand, G., and others. Sea-Level Rise: From Global Perspectives to Local Services. Frontiers in Marine Science, vol. 8, 2022.

Dusek, Gregory, and others. A meteotsunami climatology along the U.S. East Coast. Bulletin of the American Meteorological Society, vol. 100, No. 7, pp. 1329-1345, 2019.

Earl-Spurr, Craig, and others. Forecasting tropical cyclone wind hazards and impacts: Summary from the Tenth International Workshop on Tropical Cyclones (IWTC-10). In Proceedings of the Tropical Cyclone Research and Review, pp. 113-122, 2023.

Eccles, R., and others. A review of the effects of climate change on riverine flooding in subtropical and tropical regions. Journal of Water and Climate Change, vol. 10, No. 4, pp. 687-707, 2019.

Elfrink, Berry and Baldock, Tom. Hydrodynamics and sediment transport in the swash zone: a review and perspectives. Coastal Engineering, vol. 45, No. 3-4, pp. 149-167, 2002.

Emanuel, Kerry, and others. The Surprising Roles of Turbulence in Tropical Cyclone Physics. Atmosphere, vol. 14, 2023.

Emanuel, K. A. The theory of hurricanes. Annual Review of Fluid Mechanics, vol. 23, pp. 179-196, 1991.

Espinosa, F. R., and others. Economic evaluation of recovering natural protection with concurrent relocation of the population threatened by Tsumani hazards in central coastal Ecuador. Science of Tsunami Hazards, vol. 36, No. 4, pp. 293-306, 2017.

Europe, W. H. O. Health promotion: a discussion document on the concept and principles: summary report of the Working Group on Concept and Principles of Health Promotion. Copenhagen: 1984.

Fakhruddin, B. S. H. M. and Eslamian, S. "Analysis of drought factors affecting the economy", in *Handbook of Drought and Water Scarcity: Principles of Drought and Water Scarcity*. (2017).

Falkenberg, Laura J., and others. Ocean Acidification and Human Health. International Journal of Environmental Research and Public Health, vol. 17, No. 12, pp. 4563-4563, 2020.

Falkenberg, Laura J., and others. Biotic habitats as refugia under ocean acidification. Conservation Physiology, vol. 9, No. 1, 2021.

Fassbender, Andrea J., and others. Amplified Subsurface Signals of Ocean Acidification. Global Biogeochemical Cycles, vol. 37, No. 12, 2023.

Ferguson, G. and Gleeson, T. Vulnerability of coastal aquifers to groundwater use and climate change. Nature Climate Change, vol. 2, No. 5, pp. 342-345, 2012.

Figlus, Jens. "Chapter 4 - Modeling the movement of water and sediment in coastal environments", in *Coastal Flood Risk Reduction*, Samuel Brody Yoonjeong Lee and Baukje Bee Kothuis, eds. (Elsevier, 2022).

Fleming, C. S., and others. Indicators and participatory processes: a framework for assessing integrated climate vulnerability and risk as applied in Los Angeles County, California. Natural Hazards, vol. 115, No. 3, pp. 2069-2095, 2023.

Fox, Michael D., and others. Increasing Coral Reef Resilience through Successive Marine Heatwaves. Geophysical Research Letters, vol. 48, No. 17, 2021.

Furnas, M. J. River plumes and coral reefs. In Proceedings of the Encyclopedia of Earth Sciences Series, pp. 934-938, 2011.

Gaertner, Miguel Ángel, and others. Simulation of Medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution. Climate Dynamics, vol. 51, No. 3, pp. 1041-1057, 2018.

Gallina, V., and others. A multi-risk methodology for the assessment of climate change impacts in coastal zones. Sustainability (Switzerland), vol. 12, No. 9, 2020.

Garmestani, A., and others. The Role of Social-Ecological Resilience in Coastal Zone Management: A Comparative Law Approach to Three Coastal Nations. Frontiers in Ecology and Evolution, vol. 7, 2019.

Garrabou, Joaquim, and others. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Global Change Biology, vol. 28, No. 19, pp. 5708-5725, 2022.

Gasparotti, C. Risk assessment of marine oil spills. Environmental Engineering and Management Journal, vol. 9, No. 4, pp. 527-534, 2010.

Ge, J., and others. Impacts of fluvial flood on physical and biogeochemical environments in estuary–shelf continuum in the East China Sea. Journal of Hydrology, vol. 598, 2021.

Ghosh, A. Quantitative approach on erosion hazard, vulnerability and risk assessment: case study of Muriganga–Saptamukhi interfluve, Sundarban, India. Natural Hazards, vol. 87, No. 3, pp. 1709-1729, 2017.

Gillet-Chaulet, F., and others. Greenland ice sheet contribution to sea-level rise from a new-generation ice-sheet model. Cryosphere, vol. 6, No. 6, pp. 1561-1576, 2012.

Grabemann, I. and Weisse, R. Climate change impact on extreme wave conditions in the North Sea: An ensemble study. Ocean Dynamics, vol. 58, No. 3-4, pp. 199-212, 2008.
Gulev, S. K. and Grigorieva, V. Last century changes in ocean wind wave height from global visual wave data. Geophysical Research Letters, vol. 31, No. 24, pp. 1-4, 2004.
Guo, L., and others. The Impacts of Climate Change on the Autumn North Atlantic Wave Climate. Atmosphere - Ocean, vol. 53, No. 5, pp. 491-509, 2015.
Haasnoot, Marjolijn, and others. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change, vol. 23, No. 2, pp. 485-498, 2013.
Haasnoot, Marjolijn, and others. Pathways to coastal retreat. Science, vol. 372, No. 6548, pp. 1287-1290, 2021.
Haque, M. M., and others. "Drought losses to local economy", in Handbook of Drought and Water Scarcity: Principles of Drought and Water Scarcity. (2017).
Harris, R. M. B., and others. Biological responses to the press and pulse of climate trends and extreme events. Nature Climate Change, vol. 8, No. 7, pp. 579-587, 2018.
Hart, Robert E. A cyclone phase space derived from thermal wind and thermal asymmetry. Monthly Weather Review, vol. 131, No. 4, pp. 585-616, 2003.
He, Ming-Xia, and others. Harbour dredging and fish mortality in an aquaculture zone: assessment of changes in suspended particulate matter using multi-sensor remote-sensing data. International Journal of Remote Sensing, vol. 35, No. 11-12, pp. 4383-4398, 2014.
Heidarzadeh, Mohammad and Rabinovich, Alexander B. Combined hazard of typhoon-generated meteorological tsunamis and storm surges along the coast of Japan. Springer Netherlands, 2021.
Hemer, M. A., and others. Variability and trends in the directional wave climate of the Southern Hemisphere. International Journal of Climatology, vol. 30, No. 4, pp. 475-491, 2010.
Hemer, M. A., and others. Projected changes in wave climate from a multi-model ensemble. Nature Climate Change, vol. 3, No. 5, pp. 471-476, 2013.
Heming, Julian T., and others. Review of Recent Progress in Tropical Cyclone Track Forecasting and Expression of Uncertainties. Tropical Cyclone Research and Review, vol. 8, No. 4, pp. 181-218, 2019.
Hingst, M. C., and others. Beyond the Wedge: Impact of Tidal Streams on Salinization of Groundwater in a Coastal Aquifer Stressed by Pumping and Sea-Level Rise. Water Resources Research, vol. 60, No. 10, 2024.
Hobday, Alistair J., and others. A hierarchical approach to defining marine heatwaves. Progress in Oceanography, vol. 141, pp. 227-238, 2016.

Holbrook, Neil J., and others. Keeping pace with marine heatwaves. Nature Reviews Earth & Environment, vol. 1, No. 9, pp. 482-493, 2020.
Holman, R. A. Extreme value statistics for wave run-up on a natural beach. Coastal Engineering, vol. 9, No. 6, pp. 527-544, 1986.
Hoque, Muhammad Al Amin, and others. Tropical cyclone disaster management using remote sensing and spatial analysis: A review. International Journal of Disaster Risk Reduction, vol. 22, No. September 2016, pp. 345-354, 2017.
Howley, C., and others. Assessment of water quality from the Normanby River catchment to coastal flood plumes on the northern Great Barrier Reef, Australia. Marine and Freshwater Research, vol. 69, No. 6, pp. 859-873, 2018.
Hsu, Chu-En, and others. Total water levels along the South Atlantic Bight during three along-shelf propagating tropical cyclones: relative contributions of storm surge and wave runup. Natural Hazards and Earth System Sciences, vol. 23, No. 12, pp. 3895-3912, 2023.
Hu, H., and others. An observation study of the combined river discharge and sea level impact on the duration of saltwater intrusion in Pearl River estuary–Modaomen waterway. Natural Hazards, vol. 120, No. 1, pp. 409-428, 2024.
Huang, Chenfu, and others. Evaluating essential processes and forecast requirements for meteotsunami-induced coastal flooding. Natural Hazards, vol. 110, No. 3, pp. 1693-1718, 2022.
Hughes, M. Coastal waves, water levels, beach dynamics and climate change. Gold Coast: 2016.
Hunt, Julian David and Byers, Edward. Reducing sea level rise with submerged barriers and dams in Greenland. Mitigation and Adaptation Strategies for Global Change, vol. 24, No. 5, pp. 779-794, 2019.
Huss, Matthias, and others. Quantifying the overall effect of artificial glacier melt reduction in Switzerland, 2005–2019. Cold Regions Science and Technology, vol. 184, pp. 103237, 2021.
Hyndman, R. D. and Wang, K. The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime. Journal of Geophysical Research: Solid Earth, vol. 100, No. B11, pp. 22133-22154, 1995.
Intergovernmental Oceanographic Commission (IOC). Tsunami Glossary. Paris: United Nations Educational, Scientific, and Cultural Organization (UNESCO), 2019.
Intergovernmental Oceanographic Commission (IOC). Standard Guidelines for the Tsunami Ready Recognition Programme. Paris: United Nations Educational, Scientific, and Cultural Organization (UNESCO), 2022.
Intergovernmental Oceanographic Commission (IOC). Research, Development and Implementation Plan for the Ocean

Decade Tsunami Programme. Paris: United Nations Educational, Scientific, and Cultural Organization (UNESCO), 2023.
IPCC. The Ocean and Cryosphere in a Changing Climate. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2019.
IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021.
IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2022.
IPCC. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2023.
ISC. ISC-GEM Catalogue. 2024. https://www.isc.ac.uk/iscgem/overview.php, 2024
Islek, F., and others. Evaluation of regional climate models and future wave characteristics in an enclosed sea: A case study of the Black Sea. Ocean Engineering, vol. 262, 2022.
Jacob, T., and others. Recent contributions of glaciers and ice caps to sea level rise. Nature, vol. 482, No. 7386, pp. 514-518, 2012.
Jaiswal, K. and Wald, D. J. Estimating economic losses from earthquakes using an empirical approach. Earthquake Spectra, vol. 29, No. 1, pp. 309-324, 2013.
Johnson, T., and others. Bridging the broadsound: A case study in assessing coastal hazards in dynamic but data poor areas. In Proceedings of the Australasian Coasts and Ports 2019 Conference, pp. 1287-1293, 2019.
Kamranzad, B. and Mori, N. Future wind and wave climate projections in the Indian Ocean based on a super-high-resolution MRI-AGCM3.2S model projection. Climate Dynamics, vol. 53, No. 3-4, pp. 2391-2410, 2019.
Kappes, M. S., and others. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Applied Geography, vol. 32, No. 2, pp. 577-590, 2012.
Khan, S. A., and others. Accelerating Ice Loss from Peripheral Glaciers in North Greenland. Geophysical Research Letters, vol. 49, No. 12, 2022.
Kim, Jihwan and Omira, Rachid. Combined surge-meteotsunami dynamics: A numerical model for hurricane Leslie on the coast of Portugal. Ocean Modelling, vol. 189, 2024.
Kirezci, Ebru, and others. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Scientific Reports, vol. 10, No. 1, pp. 11629, 2020.

Knutson, Thomas, and others. Tropical cyclones and climate change assessment: Part I: Detection and Attribution. Bulletin of the American Meteorological Society, vol. 100, No. 10, pp. 1987-2007, 2019.

Knutson, Thomas, and others. Tropical cyclones and climate change assessment: Part II: Projected Response to Anthropogenic Warming. Bulletin of the American Meteorological Society, vol. 101, No. 3, pp. E303-E322, 2020.

Koks, E. E., and others. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. Environmental Science and Policy, vol. 47, pp. 42-52, 2015.

Komar, P. D., and others. "Ocean wave climates: Trends and variations due to earth's changing climate", in *Handbook of Coastal and Ocean Engineering*. (2009).

Kunze, Sven. Unraveling the Effects of Tropical Cyclones on Economic Sectors Worldwide: Direct and Indirect Impacts. Environmental and Resource Economics, vol. 78, No. 4, pp. 545-569, 2021.

Laino, E. and Iglesias, G. Beyond coastal hazards: A comprehensive methodology for the assessment of climate-related hazards in European coastal cities. Ocean and Coastal Management, vol. 257, 2024.

Laino, E. and Iglesias, G. Multi-hazard assessment of climate-related hazards for European coastal cities. Journal of Environmental Management, vol. 357, 2024.

Lake, S. P. Drought and Aquatic Ecosystems: Effects and Responses. 2011.

Lamers, Alex, and others. Forecasting tropical cyclone rainfall and flooding hazards and impacts. Tropical Cyclone Research and Review, vol. 12, No. 2, pp. 100-112, 2023.

Lamont-Doherty Earth Observatory (LDEO). Subduction zones and earthquakes. 2024. https://www.ldeo.columbia.edu/~djs/aleut/info_for_public.html, 2024

Lay, Thorne and Wallace, Terry C. Modern Global Seismology. Academic Press, 1995.

Le Bris, Arnault, and others. Climate vulnerability and resilience in the most valuable North American fishery. Proceedings of the National Academy of Sciences, vol. 115, No. 8, pp. 1831-1836, 2018.

Leake, J., and others. Predicted wave climate for the UK: Towards an integrated model of coastal impacts of climate change. In Proceedings of the Proceedings of the International Conference on Estuarine and Coastal Modeling, pp. 393-406, 2008.

Learning Geology. Relation of Volcanism to Plate Tectonics. 2024. https://geologylearn.blogspot.com/2016/03/relation-of-volcanism-to-plate-tectonics.html, 2024

Lee, Woo-Dong, and others. Runup characteristics of a tsunami-like wave on a slope beach. Ocean Engineering, vol. 259, pp. 111897-111897, 2022.

Leroux, M. D., and others. Recent Advances in Research and Forecasting of Tropical Cyclone Track, Intensity, and Structure at Landfall. Tropical Cyclone Research and Review, vol. 7, No. 2, pp. 85-105, 2018.

Lesani, S. and Niksokhan, M. H. Climate change impact on Caspian Sea wave conditions in the Noshahr Port. Ocean Dynamics, vol. 69, No. 11-12, pp. 1287-1310, 2019.

Levin, Boris W. and Nosov, Mikhail. Physics of Tsunamis. Springer International Publishing, 2016.

Levin, Lisa A. "Oxygen minimum zone benthos: adaptation and community response to hypoxia", in *Oceanography and Marine Biology, An Annual Review, Volume 41*. (CRC Press, 2003).

Levin, Lisa A. Manifestation, Drivers, and Emergence of Open Ocean Deoxygenation. Annual Review of Marine Science, vol. 10, No. 1, pp. 229-260, 2018.

Lewis, Clare, and others. Meteotsunami in the United Kingdom: the hidden hazard. Natural Hazards and Earth System Sciences, vol. 23, No. 7, pp. 2531-2546, 2023.

Li, J., and others. Establishing a Risk Assessment Framework for Marine Assets and Assessing Typhoon Lekima Storm Surge for the Laizhou Bay Coastal Area of the Bohai Sea, China. Journal of Marine Science and Engineering, vol. 10, No. 2, 2022.

Ličer, Matjaž, and others. Numerical study of Balearic meteotsunami generation and propagation under synthetic gravity wave forcing. Ocean Modelling, vol. 111, pp. 38-45, 2017.

Linham, M. M. and Nicholls, R. J. Adaptation technologies for coastal erosion and flooding: A review. Proceedings of the Institution of Civil Engineers: Maritime Engineering, vol. 165, No. 3, pp. 95-111, 2012.

Lionello, Piero, and others. The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid-21st century. Global and Planetary Change, vol. 151, pp. 80-91, 2017.

Liu, Yang, and others. The regional impacts of climate change on coastal environments and the aquaculture of Japanese scallops in northeast Asia: case studies from Dalian, China, and Funka Bay, Japan. International Journal of Remote Sensing, vol. 35, No. 11-12, pp. 4422-4440, 2014.

Lobeto, H., and others. Future behavior of wind wave extremes due to climate change. Scientific Reports, vol. 11, No. 1, 2021.

Lockley, A., and others. Glacier geoengineering to address sea-level rise: A geotechnical approach. Advances in Climate Change Research, vol. 11, No. 4, pp. 401-414, 2020.

Lockley, Andrew, and others. Glacier geoengineering to address sea-level rise: A geotechnical approach. Advances in Climate Change Research, vol. 11, No. 4, pp. 401-414, 2020.

Loughlin, S., and others. "Geophysical Risk – volcanic activity", in *Science for disaster risk management 2017: knowing better and losing less*, K. Poljanšek M. Marin Ferrer T. De Groeve and I. Clark, eds. (Luxembourg, Publication Office of EU, 2017).

Mack, E. A., and others. Coastal typology: An analysis of the spatiotemporal relationship between socioeconomic development and shoreline change. Land, vol. 9, No. 7, 2020.

Mafi-Gholami, D., and others. Mangrove regional feedback to sea level rise and drought intensity at the end of the 21st century. Ecological Indicators, vol. 110, 2020.

Maiolo, Mario, and others. A Stepwise Approach to Beach Restoration at Calabaia Beach. Water, vol. 12, No. 10, pp. 2677, 2020.

Majidi, A. G., and others. The impact of climate change on the wave energy resource potential of the Atlantic Coast of Iberian Peninsula. Ocean Engineering, vol. 284, 2023.

Mansour, Abbas M. and Abdelkareem, Mohamed "Climate change and risk assessment of the Red Sea region, Egypt", in *Oceanographic and Marine Environmental Studies around the Arabian Peninsula*, Najeeb M.A. Rasul and Ian C.F. Stewart, eds. (London, CRC Press, 2024).

Marques, C. A., and others. "Aquifer contamination by coastal floods in the plain of costa da caparica, almada (portugal)", in *Advances in Science, Technology and Innovation*. (2020).

McAdam, Ronan, and others. Seasonal forecasting of subsurface marine heatwaves. Communications Earth & Environment, vol. 4, No. 1, pp. 225-225, 2023.

Meier, M. F., and others. Glaciers dominate eustatic sea-level rise in the 21st century. Science, vol. 317, No. 5841, pp. 1064-1067, 2007.

Merlotto, A., and others. Hazard, vulnerability and coastal erosion risk assessment in Necochea Municipality, Buenos Aires Province, Argentina. Journal of Coastal Conservation, vol. 20, No. 5, pp. 351-362, 2016.

Meucci, A., and others. 140 Years of Global Ocean Wind-Wave Climate Derived from CMIP6 ACCESS-CM2 and EC-Earth3 GCMs: Global Trends, Regional Changes, and Future Projections. Journal of Climate, vol. 36, No. 6, pp. 1605-1631, 2023.

Miglietta, Mario Marcello and Rotunno, Richard. Development mechanisms for Mediterranean tropical-like cyclones (Medicanes). Quarterly Journal of the Royal Meteorological Society, vol. 145, No. 721, pp. 1444-1460, 2019.

Mignan, A., and others. "Multi-Risk Assessment and Governance", in Handbook of Disaster Risk Reduction & Management: Climate Change and Natural Disasters. (2017).

Miller, Jack, and others. The Feasibility and Governance of Cyclone Interventions. Climate Risk Management, vol. 41, pp. 100535-100535, 2023.

Milner, A. M., and others. River ecosystem resilience to extreme flood events. International Journal of Business Innovation and Research, vol. 17, No. 3, pp. 8354-8363, 2018.

Mishra, A. K., and others. Anatomy of a local-scale drought: Application of assimilated remote sensing products, crop model, and statistical methods to an agricultural drought study. Journal of Hydrology, vol. 526, pp. 15-29, 2015.
Mishra, A. K. and Singh, V. P. A review of drought concepts. Journal of Hydrology, vol. 391, No. 1-2, pp. 202-216, 2010.
Miyan, M. A. Droughts in Asian least developed countries: Vulnerability and sustainability. Weather and Climate Extremes, vol. 7, pp. 8-23, 2015.
Moftakhari, Hamed R., and others. Compounding effects of sea level rise and fluvial flooding. Proceedings of the National Academy of Sciences, vol. 114, No. 37, pp. 9785-9790, 2017.
Mondal, P., and others. The spread and cost of saltwater intrusion in the US Mid-Atlantic. Nature Sustainability, vol. 6, No. 11, pp. 1352-1362, 2023.
Monismith, S. G., and others. Structure and flow-induced variability of the subtidal salinity field in northern San Francisco Bay. Journal of Physical Oceanography, vol. 32, No. 11, pp. 3003-3019, 2002.
Monserrat, S., and others. Meteotsunamis: Atmospherically induced destructive ocean waves in the tsunami frequency band. Natural Hazards and Earth System Science, vol. 6, No. 6, pp. 1035-1051, 2006.
Moore, W. S. and Joye, S. B. Saltwater Intrusion and Submarine Groundwater Discharge: Acceleration of Biogeochemical Reactions in Changing Coastal Aquifers. Frontiers in Earth Science, vol. 9, 2021.
Mori, N., and others. Extreme wave climate change projection at the end of 21st century. In Proceedings of the Asian and Pacific Coasts, 2011 - Proceedings of the 6th International Conference, pp. 341-348, 2011.
Morris, Bradley D., and others. Evaluation of Runup Characteristics on the NSW Coast. Journal of Coastal Research, vol. 75, No. sp1, pp. 1187-1191, 2016.
Moss, R. H., and others. The next generation of scenarios for climate change research and assessment. Nature, vol. 463, No. 7282, pp. 747-756, 2010.
Moulin, A., and others. Projections of the Adriatic wave conditions under climate changes. Frontiers in Climate, vol. 6, 2024.
Murgulet, D. and Tick, G. The extent of saltwater intrusion in southern Baldwin County, Alabama. Environmental Geology, vol. 55, No. 6, pp. 1235-1245, 2008.
Muzeau, J. P., and others. "Actions due to volcanic eruptions", in Urban Habitat Constructions under Catastrophic Events: COST C26 Action Final Report. (2010).
Narayan, Siddharth, and others. The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. PLoS ONE, vol. 11, No. 5, pp. e0154735-e0154735, 2016.

Nastos, P. T., and others. Risk management framework of environmental hazards and extremes in Mediterranean ecosystems. Natural Hazards and Earth System Sciences, vol. 21, No. 6, pp. 1935-1954, 2021.

Nawarat, Khin, and others. Coastal hardening and what it means for the world's sandy beaches. Nature Communications, vol. 15, No. 1, pp. 10626, 2024.

Neijnens, Floris K., and others. Early Warning Signals for Rate-induced Critical Transitions in Salt Marsh Ecosystems. Ecosystems, vol. 24, No. 8, pp. 1825-1836, 2021.

Nicholls, Robert J., and others. Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 376, No. 2119, pp. 20160448-20160448, 2018.

NIED. Network Center for Earthquake, Tsunami and Volcano. 2024. https://www.bosai.go.jp/e/research/center/network.html, 2024

Oh, H., and others. Sources and uncertainties of future global drought risk with ISIMIP2b climate scenarios and socioeconomic indicators. Science of the Total Environment, vol. 859, 2023.

Oliver, Eric C. J., and others. Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. Frontiers in Marine Science, vol. 6, 2019.

Oliver, H., and others. Meltwater-Enhanced Nutrient Export from Greenland's Glacial Fjords: A Sensitivity Analysis. Journal of Geophysical Research: Oceans, vol. 125, No. 7, 2020.

Orio, Alessandro, and others. Deoxygenation impacts on Baltic Sea cod: Dramatic declines in ecosystem services of an iconic keystone predator. Ambio, vol. 51, No. 3, pp. 626-637, 2022.

Oschlies, Andreas, and others. Drivers and mechanisms of ocean deoxygenation. Nature Geoscience, vol. 11, No. 7, pp. 467-473, 2018.

Osemwegie, I. and Boko-Koiadia, A. N. "Climate Variability and Water Availability in Riparian Rural Communities of the Ebrié Lagoon in Côte d'Ivoire", in *Handbook of Climate Change Resilience, Volume 1-4*. (2019).

Pattiaratchi, Charitha B. and Wijeratne, E. M. S. Are meteotsunamis an underrated hazard? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 373, No. 2053, pp. 20140377-20140377, 2015.

Pelletier, Marguerite C., and others. Resilience of aquatic systems: Review and management implications. Aquatic Sciences, vol. 82, No. 2, pp. 44-44, 2020.

Perry, D. C., and others. Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. Journal of Environmental Management, vol. 270, 2020.

Pershing, Andrew, and others. Evidence for Adaptation from the 2016 Marine Heatwave in the Northwest Atlantic Ocean. Oceanography, vol. 31, No. 2, 2018.
Pinardi, N., and others. Ocean Decade Vision 2030 White Papers - Challenge 6: Increase Community Resilience to Ocean Hazards. Paris: UNESCO-IOC, 2024.
Polk, Mariko A. and Eulie, Devon O. Effectiveness of Living Shorelines as an Erosion Control Method in North Carolina. Estuaries and Coasts, vol. 41, No. 8, pp. 2212-2222, 2018.
Rabinovich, Alexander B. Twenty-Seven Years of Progress in the Science of Meteorological Tsunamis Following the 1992 Daytona Beach Event. Pure and Applied Geophysics, vol. 177, No. 3, pp. 1193-1230, 2020.
Raible, Christoph C., and others. A review of past changes in extratropical cyclones in the northern hemisphere and what can be learned for the future. Wiley Interdisciplinary Reviews: Climate Change, vol. 12, No. 1, pp. 1-21, 2021.
Raksmey, M. and Hamid, S. A. S. Physical modelling approach for assessing the effect of climate change on groundwater at coastal area. Malaysian Construction Research Journal, vol. 33, No. 1, pp. 83-92, 2021.
Ramakrishnan, Ratheesh, and others. Wave induced coastal flooding along the southwest coast of India during tropical cyclone Tauktae. Scientific Reports, vol. 12, No. 1, pp. 19966-19966, 2022.
Ravindra Chary, G., and others. "Drought hazards and mitigation measures", in *Natural and Anthropogenic Disasters: Vulnerability, Preparedness and Mitigation*. (2010).
Reguero, B. G., and others. A recent increase in global wave power as a consequence of oceanic warming. Nature Communications, vol. 10, No. 1, 2019.
Revell, David, and others. A Holistic Framework for Evaluating Adaptation Approaches to Coastal Hazards and Sea Level Rise: A Case Study from Imperial Beach, California. Water, vol. 13, No. 9, pp. 1324-1324, 2021.
Rocle, Nicolas, and others. Moving towards multi-level governance of coastal managed retreat: Insights and prospects from France. Ocean & Coastal Management, vol. 213, pp. 105892-105892, 2021.
Romero-Martín, R., and others. Mapping cumulative compound hydrometeorological and marine-induced risks on the NW Mediterranean coast. Scientific Reports, vol. 14, No. 1, 2024.
Rosendahl Appelquist, L. Generic framework for meso-scale assessment of climate change hazards in coastal environments. Journal of Coastal Conservation, vol. 17, No. 1, pp. 59-74, 2013.
Rosendahl Appelquist, L. and Balstrøm, T. Application of the Coastal Hazard Wheel methodology for coastal multi-hazard assessment and management in the state of Djibouti. Climate Risk Management, vol. 3, pp. 79-95, 2014.

Rosendahl Appelquist, L. and Halsnæs, K. The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate. Journal of Coastal Conservation, vol. 19, No. 2, pp. 157-179, 2015.

Ruggiero, P., and others. Wave Runup, Extreme Water Levels and the Erosion of Properties Backing Beaches. Journal of Coastal Research, vol. 17, No. 2, 2001.

Safi, A., and others. Synergy of climate change and local pressures on saltwater intrusion in coastal urban areas: effective adaptation for policy planning. Water International, vol. 43, No. 2, pp. 145-164, 2018.

Sandersen, Håkan T. , and others. "Climate Change and Norwegian Arctic Aquaculture: Perception, Relevance, and Adaptation", in *Arctic Yearbook 2020*. (2020).

Sanuy, M., and others. Linking source with consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches. Natural Hazards and Earth System Sciences, vol. 18, No. 7, pp. 1825-1847, 2018.

Sanuy, M., and others. A Bayesian Network methodology for coastal hazard assessments on a regional scale: The BN-CRAF. Coastal Engineering, vol. 157, 2020.

Saviz Naeini, Saeed and Snaiki, Reda. A physics-informed machine learning model for time-dependent wave runup prediction. Ocean Engineering, vol. 295, pp. 116986-116986, 2024.

Schultz, David M., and others. Extratropical Cyclones: A Century of Research on Meteorology's Centerpiece. Meteorological Monographs, vol. 59, pp. 16.11-16.56, 2019.

Sejr, M. K., and others. Glacial meltwater determines the balance between autotrophic and heterotrophic processes in a Greenland fjord. Proceedings of the National Academy of Sciences of the United States of America, vol. 119, No. 52, 2022.

Senese, Antonella, and others. The non-woven geotextiles as strategies for mitigating the impacts of climate change on glaciers. Cold Regions Science and Technology, vol. 173, pp. 103007, 2020.

Šepić, Jadranka, and others. Multi-Meteotsunami Event in the Adriatic Sea Generated by Atmospheric Disturbances of 25–26 June 2014. Pure and Applied Geophysics, vol. 173, No. 12, pp. 4117-4138, 2016.

Shaw, T.A., and others. Storm track processes and the opposing influences of climate change. Nature Geoscience, vol. 9, No. 9, pp. 656-664, 2016.

Shen, Y., and others. Flood risk assessment and increased resilience for coastal urban watersheds under the combined impact of storm tide and heavy rainfall. Journal of Hydrology, vol. 579, 2019.

Shimura, T., and others. Future projection of ocean wave climate: Analysis of SST impacts on wave climate changes in the Western North Pacific. Journal of Climate, vol. 28, No. 8, pp. 3171-3190, 2015.

Shimura, T., and others. Future projection of ocean wave climate change using multi-SST ensemble experiments. In Proceedings of the Proceedings of the Coastal Engineering Conference, 2014.

Shishaye, H. A. "Fate of Coastal Aquifers under the Changing Climate and Hydrologic Extremes: Review and Modeling Scenarios", in *Handbook of Climate Change Management: Research, Leadership, Transformation*. (2021).

Shore, A., and others. On a Reef Far, Far Away: Anthropogenic Impacts Following Extreme Storms Affect Sponge Health and Bacterial Communities. Frontiers in Marine Science, vol. 8, 2021.

Siders, A. R., and others. The case for strategic and managed climate retreat. Science, vol. 365, No. 6455, pp. 761-763, 2019.

Sina, B., and others. Integrating Sea Level Considerations into Civil Engineering Practice. In Proceedings of the Proceedings of the World Congress on New Technologies, 2024.

Singh, N. P., and others. Vulnerability and policy relevance to drought in the semi-arid tropics of Asia - A retrospective analysis. Weather and Climate Extremes, vol. 3, pp. 54-61, 2014.

Singhvi, Ankita, and others. The grey – green spectrum: A review of coastal protection interventions. Journal of Environmental Management, vol. 311, pp. 114824-114824, 2022.

Skufina, T. P., and others. Actual and forecast impact assessment of earthquakes on the global economic system. Journal of Mining Institute, vol. 238, pp. 465-473, 2019.

Smith, Kathryn E., and others. Biological Impacts of Marine Heatwaves. Annual Review of Marine Science, vol. 15, No. 1, pp. 119-145, 2023.

Smith, Kathryn E., and others. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. Science, vol. 374, No. 6566, 2021.

Snyder, Brian F. and Ruyle, Leslie E. A just compensation for leaving it in the ground: Climate easements and oil development. Environmental Science & Policy, vol. 112, pp. 181-188, 2020.

Sperling, Erik A., and others. Biodiversity response to natural gradients of multiple stressors on continental margins. Proceedings of the Royal Society B: Biological Sciences, vol. 283, No. 1829, pp. 20160637-20160637, 2016.

Squire, V. A. Ocean Wave Interactions with Sea Ice: A Reappraisal. Annual Review of Fluid Mechanics, vol. 52, pp. 37-60, 2020.

Stahl, K., and others. Impacts of European drought events: Insights from an international database of text-based reports. Natural Hazards and Earth System Sciences, vol. 16, No. 3, pp. 801-819, 2016.

Stammer, Detlef, and others. Causes for Contemporary Regional Sea Level Changes. Annual Review of Marine Science, vol. 5, No. 1, pp. 21-46, 2013.

Straneo, F. and Heimbach, P. North Atlantic warming and the retreat of Greenland's outlet glaciers. Nature, vol. 504, No. 7478, pp. 36-43, 2013.
Sühring, Nicole, and others. Effects of storms on fisheries and aquaculture: An Icelandic case study on climate change adaptation. Arctic, Antarctic, and Alpine Research, vol. 55, No. 1, 2269689, 2023.

Tabari, H. and Willems, P. Sustainable development substantially reduces the risk of future drought impacts. Communications Earth and Environment, vol. 4, No. 1, 2023.
Tamisiea, Mark E. Ongoing glacial isostatic contributions to observations of sea level change. Geophysical Journal International, vol. 186, No. 3, pp. 1036-1044, 2011.
Tan, Karsoon, and others. Selective breeding of edible bivalves and its implication of global climate change. Reviews in Aquaculture, vol. 12, No. 4, pp. 2559-2572, 2020.
Tanim, A. H., and others. Integrated socio-environmental vulnerability assessment of coastal hazards using data-driven and multi-criteria analysis approaches. Scientific Reports, vol. 12, No. 1, 2022.
Tebaldi, Claudia, and others. Extreme sea levels at different global warming levels. Nature Climate Change, vol. 11, No. 9, pp. 746-751, 2021.
Teixidó, Núria, and others. Functional changes across marine habitats due to ocean acidification. Global Change Biology, vol. 30, No. 1, 2024.
Terra, C., and others. Using Hydrologic Model Data to Inform Time-Lapse ERT Investigations of Coastal Processes. In Proceedings of the SEG Technical Program Expanded Abstracts, pp. 2110-2112, 2022.
Thomsen, S. K. and Green, D. J. Predator-mediated effects of severe drought associated with poor reproductive success of a seabird in a cross-ecosystem cascade. Global Change Biology, vol. 25, No. 5, pp. 1642-1652, 2019.
Thrusfield, M. and Kelly, L. "Risk analysis", in *Veterinary Epidemiology: Fourth Edition*. (2017).
Tiggeloven, Timothy, and others. Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. Natural Hazards and Earth System Sciences, vol. 20, No. 4, pp. 1025-1044, 2020.
Trebilco, R., and others. Warming world, changing ocean: mitigation and adaptation to support resilient marine systems. Reviews in Fish Biology and Fisheries, vol. 32, No. 1, pp. 39-63, 2022.
Tully, K., and others. The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. BioScience, vol. 69, No. 5, pp. 368-378, 2019.
Turcotte, Donald and Schubert, Gerald. Geodynamics- Applications of continuum physics to geological problems. Cambridge University Press, 2002.
UNCC. Technical guide on sea level rise. United Nations Climate Change, 2025.

UNDRR. Tsunamis account for $280 billion in economic losses over last twenty years. 2018. https://www.undrr.org/news/tsunamis-account-280-billion-economic-losses-over-last-twenty-years, 2018
UNDRR. World Tsunami Awareness Day. 2024. https://tsunamiday.undrr.org, 2024
UNESCO, I.O.C. MSP Global Policy Brief: Climate Change and Marine Spatial Planning (IOC Policy Brief no 3). Paris: 2021.
UNFCCC. Ocean and climate change dialogue 2023: Informal summary report by the co-facilitators of the Ocean and
Climate Change Dialogue 2023–2024. United Nations Framework Convention on Climate Change, 2023.
UNFCCC. Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat. United Nations Framework Convention on Climate Change, 2024a.
UNFCCC. Ocean and climate change dialogue 2024: Informal summary report by the co-facilitators of the Ocean and
Climate Change Dialogue 2023–2024. United Nations Framework Convention on Climate Change, 2024b.
UNFCCC. Progress in the process to formulate and implement national adaptation plans: Note by the secretariat. United Nations Framework Convention on Climate Change, 2024c.

USGS. The Science of Earthquakes. 2024. https://www.usgs.gov/programs/earthquake-hazards/science-earthquakes, 2024
van der Gun, Jac. "Chapter 24 - Groundwater resources sustainability", in *Global Groundwater*, Abhijit Mukherjee Bridget R. Scanlon Alice Aureli Simon Langan Huaming Guo and Andrew A. McKenzie, eds. (Elsevier, 2021).
van der Meer, Jentsje W. and Stam, Cor-Jan M. Wave Runup on Smooth and Rock Slopes of Coastal Structures. Journal of Waterway, Port, Coastal, and Ocean Engineering, vol. 118, No. 5, pp. 534-550, 1992.
van Vuuren, D. P., and others. The representative concentration pathways: An overview. Climatic Change, vol. 109, No. 1, pp. 5-31, 2011.
Vicente-Serrano, S. M., and others. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate, vol. 23, No. 7, pp. 1696-1718, 2010.
Vilibic, Ivica, and others. Modern approaches in meteotsunami research and early warning. Frontiers in Marine Science, vol. 3, No. MAY, 2016.
Vilibić, Ivica, and others. Modern Approaches in Meteotsunami Research and Early Warning. Frontiers in Marine Science, vol. 3, 2016.

Visschers, L. L. B., and others. Accelerated migration of mangroves indicate large-scale saltwater intrusion in Amazon coastal wetlands. Science of the Total Environment, vol. 836, 2022.

Vitousek, Sean, and others. Doubling of coastal flooding frequency within decades due to sea-level rise. Scientific Reports, vol. 7, No. 1, pp. 1399-1399, 2017.

von Schuckmann, K., and others. "The state of the global ocean", in *8th edition of the Copernicus Ocean State Report (OSR8)*. (2024).

Voolstra, Christian R., and others. Mitigating the ecological collapse of coral reef ecosystems. EMBO reports, vol. 24, No. 4, 2023.

Vousdoukas, Michalis I., and others. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nature Communications, vol. 9, No. 1, pp. 2360-2360, 2018.

Vousdoukas, Michalis I., and others. Sandy coastlines under threat of erosion. Nature Climate Change, vol. 10, No. 3, pp. 260-263, 2020.

Vu, M. T., and others. Simulation of hydrodynamic changes and salinity intrusion in the lower Vietnamese Mekong Delta under climate change-induced sea level rise and upstream river discharge. Regional Studies in Marine Science, vol. 78, 2024.

Wahl, Thomas, and others. Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nature Climate Change, vol. 5, No. 12, pp. 1093-1097, 2015.

Wainwright, D. J., and others. An argument for probabilistic coastal hazard assessment: Retrospective examination of practice in New South Wales, Australia. Ocean and Coastal Management, vol. 95, pp. 147-155, 2014.

Wakelin, S., and others. "Marine heatwaves and cold-spells, and their impact on fisheries in the southern North Sea", in *Copernicus Marine Service Ocean State Report, Issue 5*, K. von Schuckmann Pierre-Yves Le Traon and Neville Smith, eds. (2021).

Wallemacq, P. and Rowena, H. Economic Losses, Poverty and Disasters 1998-2017. Centre for Research on the Epidemiology of Disasters (CRED) & UN Office for Disaster Risk Reduction (UNISDR), 2018.

Wang, Danyang and Lin, Yanluan. Size and structure of dry and moist reversible tropical cyclones. Journal of the Atmospheric Sciences, vol. 77, No. 6, pp. 2091-2114, 2020.

Wang, S., and others. Uncertainties in riverine and coastal flood impacts under climate change. Water (Switzerland), vol. 13, No. 13, 2021.

Wang, Xiaolan L., and others. Inter-comparison of extra-tropical cyclone activity in nine reanalysis datasets. Atmospheric Research, vol. 181, pp. 133-153, 2016.

Wang, X. L. and Swail, V. R. Changes of extreme Wave Heights in northern Hemisphere Oceans and related atmospheric circulation regimes. Journal of Climate, vol. 14, No. 10, pp. 2204-2221, 2001.

Wang, X. L. and Swail, V. R. Climate change signal and uncertainty in projections of ocean wave heights. Climate Dynamics, vol. 26, No. 2-3, pp. 109-126, 2006.
Ward, Philip J., and others. Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries. Environmental Research Letters, vol. 13, No. 8, pp. 084012, 2018.
Wardlow, B. D., and others. "Advancements in satellite remote sensing for drought monitoring", in *Drought and Water Crises: Integrating Science, Management, and Policy, Second Edition*. (2017).
Werner, A. D., and others. Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources, vol. 51, pp. 3-26, 2013.
Werner, A. D. and Simmons, C. T. Impact of sea-level rise on sea water intrusion in coastal aquifers. Ground Water, vol. 47, No. 2, pp. 197-204, 2009.
Wilhite, D. A. and Glantz, M. H. Understanding: The drought phenomenon: The role of definitions. Water International, vol. 10, No. 3, pp. 111-120, 1985.
Winarta, B., and others. Flood Inundation Assessment under Climate Change Scenarios in Kuantan River Basin, Malaysia. In Proceedings of the IOP Conference Series: Earth and Environmental Science, 2019.
Winarta, B., and others. Flood Inundation Assessment under Climate Change Scenarios in Kuantan River Basin, Malaysia. IOP Conference Series: Earth and Environmental Science, vol. 328, No. 1, pp. 012013, 2019.
Winter, Gundula, and others. Steps to Develop Early Warning Systems and Future Scenarios of Storm Wave-Driven Flooding Along Coral Reef-Lined Coasts. Frontiers in Marine Science, vol. 7, 2020.
WMO. WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services. Geneva, Switzerland: 2015.
WMO. State of the global climate in 2023. Geneva, Switzerland: 2024.
Wood, M., and others. Risk of compound flooding substantially increases in the future Mekong River delta. Natural Hazards and Earth System Sciences, vol. 24, No. 10, pp. 3627-3649, 2024.
Woods, P. J., and others. A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change. ICES Journal of Marine Science, vol. 79, No. 2, pp. 463-479, 2022.
World Glacier Monitoring Service (WGMS). Contribution to sea evel rise. 2024. https://wgms.ch/sea-level-rise/, 2024
Wright, L. D., and others. "Impacts of coastal waters and flooding on human health", in *Coastal Research Library*. (2019).

Xie, Yida, and others. Applying Artificial Cover to Reduce Melting in Dagu Glacier in the Eastern Qinghai-Tibetan Plateau. Remote Sensing, vol. 15, No. 7, pp. 1755, 2023.
Xing, G., and others. Wave and Meso-Scale Eddy Climate in the Arctic Ocean. Atmosphere, vol. 14, No. 6, 2023.
Xu, Fumin and Perrie, William. Extreme Waves and Wave Run-up in Halifax Harbour under Climate Change Scenarios. Atmosphere-Ocean, vol. 50, No. 4, pp. 407-420, 2012.
Yihdego, Y. "Drought and groundwater quality in coastal areas", in Handbook of Drought and Water Scarcity: Environmental Impacts and Analysis of Drought and Water Scarcity. (2017).
Young, I. R., and others. Global trends in wind speed and wave height. Science, vol. 332, No. 6028, pp. 451-455, 2011.
Yuan, J., and others. Numerical modelling and quantification of coastal urban compound flooding. Journal of Hydrology, vol. 630, 2024.
Zemp, Michael, and others. Brief communication: Ad hoc estimation of glacier contributions to sea-level rise from the latest glaciological observations. The Cryosphere, vol. 14, No. 3, pp. 1043-1050, 2020.
Zemp, M., and others. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature, vol. 568, No. 7752, pp. 382-386, 2019.
Zhou, M., and others. Surveying a Floating Iceberg With the USV SEADRAGON. Frontiers in Marine Science, vol. 8, 2021.
Zoback, Mary Lou. “Epicenters” of resilience. Science, vol. 346, No. 6207, pp. 283-283, 2014.

Section 5B

Chapter 5: Equity

Proposed title: Equity, justice, and human rights in the ocean

Coordinating lead author: Nathan J. Bennett, Global Science, WWF; People and the Ocean Specialist Group, Commission on Environmental Economic and Social Policy, International Union for the Conservation of Nature; Institute for the Oceans and Fisheries, University of British Columbia

Lead authors: Jorn Schmidt and Roberto de Pinho

Co-authors:

- Jessica Blythe, Brock University
- Elena Finkbeiner, Conservation International
- Mia Strand, Nelson Mandela University
- Edward H. Allison, WorldFish
- Bolanle Erinosho, University of Derby
- Caroline Ferguson Irlanda, Stanford University
- Lora E Fleming, European Centre for Environment and Human Health, University of Exeter Medical School, Penryn, Cornwall UK
- Stefan Gelcich, Universidad Catolica & Millennium Institute on Coastal Social Ecological Systems
- Quentin Hanich, Australian National Centre for Ocean Resources and Security (ANCORS), University of Wollongong
- Alana Malinde S.N. Lancaster, The University of the West Indies, Cave Hill Campus
- Rocio Lopez de la Lama, University of British Columbia
- Richard A Nyiawung, University of Waterloo
- Joeri Scholtens, University of Amsterdam
- Samiya Ahmed Selim, University of Liberal Arts Bangladesh
- Sebastian Villasante, University of Santiago de Compostela
- Colette C.C. Wabnitz, Institute for the Oceans and Fisheries, University of British Columbia; Center for Ocean Solutions, Stanford University; and Stockholm Resilience Centre, Stockholm University

Key points:

- Equity, justice and human rights issues are widespread in the ocean.

- Ocean benefits are inequitably distributed across groups, nations, and regions of the world, notably in fisheries, the ocean economy, and access to marine ecosystem services.
- Environmental justice concerns are pervasive, as the impacts of marine pollution and plastics, climate change, fisheries declines, and environmental degradation are disproportionately impacting coastal populations and inequitably distributed globally.
- Human rights violations are prevalent in the ocean, occurring in fisheries, in the ocean economy, in relation to a healthy environment and climate change, and in marine conservation.
- Participation of all affected parties, which is foundational to the achievement of equity, justice, and human rights, is needed in ocean governance at all scales, from local to global.
- Existing ocean governance processes lack adequate participation and inclusivity.
- Social equity, justice and human rights are often inadequately integrated into ocean decision-making processes, policies, and practices.
- Social equity, justice and human rights are useful frameworks to guide best practices and governance for a sustainable and inclusive ocean.
- States have a key role to play in ensuring that equity, environmental justice, and human rights are central to future ocean governance.

Table of Contents:

1. Introduction 2

2. Equity in distribution of the ocean's benefits 3

3. Environmental justice and the ocean 6

4. Human rights and the ocean 8

5. Participation in ocean governance 11

6. Conclusion 13

7. References 16

Main Chapter Text

1. Introduction

Humanity has always been deeply connected to and dependent on the ocean. This is especially so for coastal populations, island nations, and countries adjacent to the ocean. Yet, throughout history, some groups within society and some nations and States have had greater access to and captured more benefits from the ocean. Inequities in distribution of the ocean's benefits persist today, amplified by a growing global demand for ocean resources (1) and the capture of large shares of the ocean economy by few corporations and countries (2,3). For instance, global fisheries are dominated by higher income countries (4,5). Meanwhile, Indigenous Peoples and small-scale fishers often lack adequate access and harvests to make a livelihood and support adequate nutrition security while industrial fleets fish nearby (6–8).

Simultaneously, climate change, pollution and biodiversity declines are placing increased pressure on the ocean environment with disproportionate impacts on resource-dependent coastal populations and less wealthy nation-states (9–11). Toxic pollution from oil development and spills are affecting the environment, fisheries, and food security for countless coastal communities worldwide (12–14). Human rights violations are also pervasive - in global fisheries (15–19), in the ocean economy (20–23), and in relation to a healthy ocean environment (24).

This list of issues is emblematic of the widespread and growing inequities, injustices and human rights issues occurring across the global ocean. Meanwhile, ocean governance frameworks have tried to keep apace with the accelerating environmental changes and declines - through an ever increasing and complex set of institutions, regulations, and management efforts (25,26). Yet, local people and communities have often been inadequately included in ocean governance and decision-making processes; and there has been insufficient attention to equity, justice, and human rights in the formulation and implementation of marine policies, management and conservation efforts (2,27,28).

This chapter provides a broad overview of the following interconnected substantive and procedural issues: a) equity in distribution of the ocean's benefits; b) environmental justice and the ocean; c) human rights and the ocean; and d) participation in ocean governance (see Box 1 for definitions). It concludes with best practices for bringing equity, justice and human rights into the center of ocean governance.

Box 1 - Definitions of key terms used in this chapter

Distributional Equity - The level of fairness in access to and benefits from marine resources and opportunities, among groups, countries, and regions of the world, which is influenced by historical and contextual factors.

Environmental Justice - The distribution of exposure to and impacts of environmental hazards and harms, in particular for populations subject to social and structural marginalization.

Human Rights - Rights that are universal and inherent to the dignity and thriving of all human beings, including civil, political, economic, social and cultural rights, as well as the right to a clean, sustainable and healthy environment. Indigenous Peoples, traditional and local communities have unique rights that are fundamental to their culture, livelihoods, and dignity.

Participatory Ocean Governance - Decision-making processes that represent all affected groups and provide equitable opportunities for people to access information, provide inputs, influence outcomes and seek justice.

2. Equity in distribution of the ocean's benefits

Society receives a myriad of benefits from the ocean, including food, oxygen, transportation, health, inspiration, recreation, heritage, employment, and climate regulation, among others (29–34). However, marine resources and ecosystem services do not flow to or benefit all people equitably (35–38).

Distributional equity refers to the level of fairness in access to and benefits from resources and opportunities derived from coastal and marine environments. Examples of ocean inequities include: unequal distribution of fish allocations and catches among countries (38,39); limited and insecure tenure and access rights for small-scale fishers, women and minorities (40–43); restricted engagement of low and middle income countries in high seas activities; and consolidation of the ocean economy with relatively few transnational corporations (3,44,45).

Some authors argue that inequity is a systemic feature of the ocean economy, embedded in existing political and economic systems that have been shaped by historical legacies of colonialism and exploitation (46–48). Current arrangements often favor wealthy and

powerful states, corporations, and individuals, resulting in benefits accumulated by a few, harms from development often borne by coastal communities and the most vulnerable, and considerable disparities in wealth, health, food security, and economic opportunities (2,3).

This section further explores how the benefits of the ocean are inequitably distributed across groups, countries and regions of the world, focusing on three examples where there is evidence that this is occurring: ecosystem services, fisheries, and the ocean economy.

Equity in Ecosystem Services

Ecosystem services (ES) refers to the benefits provided by nature to people such as air, water and food (49). The benefits of marine ecosystem services, such as fishery production and coastal protection, are often unequally distributed, which has negative impacts on the well-being of coastal communities and groups who are marginalized (36,50). Around the world, local people can find themselves excluded from beaches that they use for recreational, cultural or livelihood purposes (51–53). Native Hawaiians, for example, experience barriers to accessing the diverse cultural values provided by beaches due to tourism and infrastructure development (51).

Many processes and factors, such as insufficient recognition and participation of all user groups in decision-making, insecure tenure rights, and lack of access to resources, contribute to the uneven distribution of coastal ecosystem services and associated benefits. Tenure and access, for example, are key mechanisms supporting benefits from marine and coastal ecosystem services (54,55). The erosion of marine tenure undermines local communities' rights to access their traditional fishing grounds, depriving them of benefits while exacerbating disparities in wealth and food security (56). Without secure access, communities lack the power to manage and protect their resources (57). Furthermore, disconnection from ancestral fishing practices erodes cultural identity and social cohesion (58).

Equity in Fisheries

Global fisheries provide multiple social and economic benefits to society. Fisheries supply 3.2 billion people with a significant portion (>20%) of their protein intake, and provide more than 60 million full-time or part-time jobs (39,59).

However, fisheries benefits are inequitably distributed among countries. At a global scale, the top 8 producers of capture fisheries (China, Indonesia, India, Peru, Russia, United States, Vietnam and Japan) account for more than 51% of the total catch (39). Wealthy countries are also responsible for 97% of industrial fishing on the high seas and 78% within the exclusive economic zones (EEZs) of lower income countries (4). Heavily subsidized distant water fishing fleets can deplete stocks that lower income countries depend on for viable fisheries livelihoods and food security, thus exacerbating existing inequalities (5). Meanwhile, fisheries access agreements often produce limited economic benefits for host countries (60,61). Developing State industrial fishing aspirations can be further disadvantaged in regional and international negotiations over international interests in fisheries conservation and catch limits (62).

Fisheries benefits are also inequitably distributed among groups within countries. Small-scale fisheries (SSF) constitute 90% of the employment in fisheries globally and contribute 40% of the catch (63,64), providing food security and livelihoods to local communities. However, despite their contribution, small-scale fishers continue to be marginalized in decision-making and their tenure rights threatened (65). Small-scale fishers can often struggle to access and benefit from fisheries due to regulatory barriers, limited access to capital, lack of technology, and limited access to fishing grounds and allocation of catch (66,67). SSF also lack direct access to markets, and are often dependent on middlemen leading to reduced profit margins, compared to larger companies that can sell directly to consumers or international markets (66,67). At the same time, the environmental degradation associated with subsidized overfishing by industrial fleets disproportionately affects catches and income potential of small-scale fishers (7,68).

Equity in the Ocean Economy

The ocean economy has been growing rapidly and has spurred a rush to claim ocean space and resources (1,69,70). While so-called “blue economy” policies and interventions claim to contribute simultaneously to economic prosperity, environmental integrity, and coastal communities (71–73), evidence suggests that benefits from the ocean economy are highly inequitable. For example, the 10 largest corporations in eight selected ocean economy industries (including oil and gas, tourism, seafood, wind-energy and shipping) generated, on average, 45% of the respective total industry revenues (3). The biggest 100 companies accounted for a total of USD 1.1 trillion in revenues in 2018, representing 60% of the total (3). Control over growing marine biotechnology markets is also highly concentrated, with a single corporation registering 47% and 10 countries registering 98% of all patented marine sequences (35).

Despite the promise of jobs and other economic benefits from development of the ocean economy, there can be unmet expectations for local communities. Oil and gas extraction often produces huge wealth for foreign corporations and national elites; yet, hiring and procurement of goods seldom benefits local communities (74–76). Similarly, shrimp aquaculture, which is resource and technology intensive and requires access to global markets, is seldom locally owned, often provides few jobs for local communities, and simultaneously undermines local fisheries livelihoods (77–80). When social equity is overlooked in blue growth it can lead to accelerated processes of coastal and ocean grabbing (81,82), which refers to "....dispossession or appropriation of use, control or access to ocean space or resources from prior resource users, rights holders or inhabitants" (83). Highly concentrated economic ownership in the ocean economy thereby leads to "unjust uneconomic growth" - which produces few local economic benefits and numerous negative social externalities for local communities (84).

Furthermore, the unequal distribution of benefits is enabled by the exploitation of workers (85). In 2015, seafarers on average worked 77 hours per week and investigations uncovered widespread forced labour on fishing vessels (18,86). Intense market pressure to reduce costs, combined with weak oversight and accountability for marine industries, has created conditions enabling exploitative labour practices (85).

Conclusion

The benefits of the ocean are inequitably distributed across groups, countries, and regions of the world due to a number of structural and contextual factors. Structural drivers of ocean inequality include: policies that prioritize access, allocation and benefits for industrial fishing fleets over the livelihoods, needs and aspirations of small-scale fisheries; lack of recognition and enforcement of marine tenure and access for rights-holders, including small-scale fishers, Indigenous Peoples, and other traditional coastal communities; economic disparities that allow wealthier countries and corporations to exploit more marine resources; governance mechanisms and decision-making processes that prioritise the interests of historically industrialised nation-states over developing state aspirations; corruption and weak rule of law; and persistent racist and colonial structures that continue to shape ocean policies and practices (2,45,47,56,87–89). Inadequate governance and decision-making processes can often exclude marginalized groups and communities, undermining their ability to advocate for access to, benefits from, and sustainable management of their marine resources (28,57,90,91).

Inequity in the distribution of ocean benefits is driven by and reproduces significant economic disparities - leading to persistent imbalances that undermine local economies, jeopardize food security, and exacerbate poverty (2). Additional factors such as climate change, environmental declines and global flows of pollution and waste further exacerbate these

inequalities by disproportionately impacting those regions and groups who are dependent on marine ecosystems and have fewer resources to adapt (92).

3. Environmental justice and the ocean

Environmental justice research demonstrates that populations such as Black and Afro-descendant communities, Indigenous Peoples, women, children, and socio-economically marginalised groups bear a disproportionate burden from polluting industries and waste disposal (93,94), climate change, and environmental degradation (93,95–99). Environmental justice issues can impact populations close to the source or in regions of the world far from where the issue is produced.

This section outlines how environmental justice issues related to marine pollution and plastics, climate change, fisheries declines, and environmental degradation are disproportionately impacting coastal populations and inequitably distributed globally.

Environmental Justice, Marine Pollution and Plastics

Pollution and plastics increasingly infiltrate and affect the ocean. Various pollutants, including persistent organic pollutants (POPs), trace metals, hydrocarbons, sewage, fertilisers, pesticides, flame retardants, and pharmaceuticals, enter the ocean from various point and nonpoint sources (100,101). An estimated 4.8-12.7 million metric tons of plastic waste, ranging from nano to macro-plastics, are discharged into the ocean each year (102,103).

Marine pollutants and plastics harm marine species, fish and biodiversity (104), and the health, food security, livelihoods, and wellbeing of coastal populations (105–107). For example, toxic substances, such as methylmercury accumulate in seafood, pose risks that can affect the health and food security of fish dependent communities, and especially women and children (106,108,109). Oil spills, such as the Exxon Valdez and Deepwater Horizon, have caused long-term economic and psychosocial damage (13,110–112). In coastal Cameroon, plastic waste now exceeds fish in the catches of small-scale fishers (113).

Some groups (including communities of colour, Indigenous Peoples and Afro-descendant groups, women, and children) are more exposed and susceptible to the health effects of pollutants (106,114). For example, Afro-American communities in Louisiana face disproportionate pollution from offshore oil and gas production (115,116). Arctic Inuit women are among the most contaminated humans on the planet due to the persistence and bioaccumulation of POPs in aquatic food chains (117–119). Global flows in the disposal of pollution and waste also disproportionately impact lower income countries (120), such is the case for both shipbreaking and disposal (121,122) and plastics (123,124).

Environmental Justice and Climate Change

Anthropogenic climate change is causing changing weather patterns, stronger storms, heatwaves, warming waters, shifting currents and nutrient cycling, deoxygenation and acidification, and sea level rise (9,10). These changes are affecting marine species, such as influencing fish reproduction, growth, and distribution (9,125–128), and stressing mangrove, seagrass, saltmarsh and coral reef ecosystems (9,129–133).

Coastal populations are facing direct and indirect climate impacts. For example, changes in fish and shellfish stocks are threatening jobs, revenues and food security (134–139), while rising seas and storms damage infrastructure and force communities to retreat (140–148). Displacement of Indigenous Peoples' coastal communities is disruptive to long held identities, cultures and traditions linked to the ocean (149).

Climate change impacts different individuals and groups inequitably. Black, Afro-descendant Indigenous Peoples, migrant, and low-income populations tend to live in areas more exposed to flooding and storms (140,150,151), and often have lower capacity to respond (152). Small-scale fishers and Indigenous Peoples are more susceptible to the impacts of climate-related declines in marine ecosystems, ecosystem services, and fisheries on livelihoods, food security and culture (153–155). Adaptation efforts can further marginalise coastal communities, women, Indigenous and Afro-descendant Peoples, and persons belonging to minority groups when their voices and needs are excluded or ignored (141,156,157).

Climate change exposure varies by geography. Coastal communities in Arctic and Equatorial regions will likely experience the largest increases in temperatures and changes in fish species composition (158–161). Countries in Asia, Africa, Southeast Asia and the Pacific Islands near the equator will be most exposed to impacts on fisheries livelihoods, food security and nutrition (139,154,158,160,162). Low-lying, densely populated regions and cities in Africa, Asia and the Pacific are highly susceptible to sea level rise (142,163,164). Moreover, lower

income countries, which are least responsible for fossil fuel and other pollutant emissions, will suffer most from ocean-related climate impacts (9,165).

Environmental Justice and Fisheries Declines

Globally, fish stocks are in decline due to overfishing, destructive fishing, ineffective management, habitat loss, and climate change. An estimated 37.7% of wild fish stocks are fished at biologically unsustainable levels, continuing the trend of overfishing (39,166). Despite increased fishing effort since the 1990s (167), catch peaked in 1996 and has since declined (168).

The negative impacts of overfishing and fisheries declines are unevenly distributed. Indigenous Peoples and small-scale fishers are particularly susceptible to declines in fish and shellfish due to their high reliance on fishing and harvesting for livelihoods and subsistence. Women, whose contributions to fish harvesting, processing and trade are often unrecognized, are particularly impacted (169,170). In the Pacific, for instance, women account for 56% of small-scale catches (171). In Senegal, female traders are severely affected by foreign fishing vessels and the demand of fishmeal factories (172).

Wealthy countries often capture a greater portion of fisheries benefits, while driving the declines in fisheries that impact lower income countries. Distant water fleets from high income countries make up 78% of industrial fisheries in low income countries (4), where seafood provides vital micronutrients critical to human health (173). These subsidised fleets undermine the catches, livelihoods and food security of small-scale fishing communities (7,68,174). Illegal, unregulated and unreported (IUU) fishing in West Africa, largely by foreign fleets, accounts for between 30%-50% of the catch and drives important food species towards extinction (175,176).

Environmental Justice and Environmental Degradation

Marine habitats are being destroyed and ecosystems degraded at alarming rates. For example, an estimated 19% of seagrasses, 30% of coral reefs, 35% of mangroves, and 50% of salt marshes have been lost or degraded (177–179). Human activities threaten ecosystems and the essential goods and services they provide (9,180,181), including: food, medicine, livelihoods, carbon sequestration, storm protection, cultural heritage, health, and wellbeing (36,182–187).

However, these losses and their impacts vary among groups and by geography are not felt equally. Indigenous Peoples' populations in the Canadian Arctic are directly affected by the changes in the distribution, health and abundance of beluga populations that are central to their diets and culture (188). Low income coastal countries are more vulnerable to the effects of climate change on coral reef fisheries and food security (189). Future losses of coastal protection will likely impact Africa and Southeast Asia the most (190).

Conclusion

Environmental justice issues are widespread across the world's oceans (191,192). The effects of marine pollution and plastics, climate change, fisheries declines, and environmental degradation are inequitably distributed across social groups and geographies. Groups and countries with strong ties and high reliance on the ocean are more exposed and vulnerable to the effects of these environmental issues. This is compounded for groups that are subject to historical or ongoing social, economic or political marginalisation, including various racial groups, Indigenous Peoples, women, younger persons, migrants, and groups with a lower socio-economic status (191,192).

Many environmental justice issues are often localized, stemming from weak environmental laws, poor implementation, or the lack of accountability in ocean economy development or resource harvesting and management. At the same time, global environmental injustices exist in the ocean, as some regions face more pollution, overfishing, environmental degradation and climate impacts (192). These issues persist due to the continuation of global practices that enable high consumption in wealthy countries to drive resource extraction, waste dumping and climate change impacts in less wealthy regions of the world (114,120).

4. Human rights and the ocean

International law acknowledges a universal set of human rights that underpin human dignity and security. The International Bill of Human Rights, which includes the 1948 Universal Declaration of Human Rights (UNHDR) (193), recognizes that all people have a fundamental set of civil, political, economic, social and cultural rights (194,195). The responsibility of society to safeguard the human rights of individuals from groups subject to discrimination (ethnic, religious and minority groups) and from vulnerable groups (women, children, older persons, persons with disabilities) is further clarified in subsequent conventions (196–199).

The UN Declarations on the Rights of Indigenous Peoples (UNDRIP) and on the Rights of Peasants (UNDROP) recognize that Indigenous Peoples and traditional communities have unique rights associated with their status and connection to the environment (200,201). The recent recognition by the United Nations General Assembly of the human right to a clean, healthy and sustainable environment recognizes that clean air, safe and stable climate, healthy ecosystems and biodiversity, safe and sufficient water, non-toxic environments, and healthy and sustainable food are necessary for the realization of other human rights (eg, to life, health, food, livelihoods, security) and the rights of specific groups (ie, Indigenous Peoples, SSF, women and children) (202). Countless other international human rights (e.g., Convention on the Elimination of All Forms of Discrimination Against Women (CEDAW) (197)), labor (e.g., International Covenant on the Protection of the Rights of all Migrant Workers (203) and Work in Fishing Convention C188 (204)) and voluntary (e.g. the Small Scale Fisheries Guidelines (205) and the Voluntary Guidelines on Tenure (206)) instruments and frameworks are also relevant in the context of oceans, too numerous to comprehensively review here.

Human rights are universal - which means they apply to everyone, everywhere, including in marine and coastal environments (24,207). Yet, human rights violations are rife in the ocean. Here, we examine substantive human rights issues in fisheries, the ocean economy, marine conservation, and in relation to a healthy ocean.

Human Rights Issues in Fisheries

Human rights violations are widespread in fisheries. Evidence of human trafficking, forced labor, child labor, and alarming working and living conditions on fishing vessels have been uncovered through journalism and research (19,208). While this issue first emerged in southeast Asia (209–211), subsequent investigations have uncovered abuses across the globe (17,18,212,213).

Fishers are vulnerable to human rights abuses due to numerous conditions inherent to the sector: isolation, length of time at sea, transnational operations, and restricted labor supply (214). Migrant workers are especially vulnerable in some places and situations due to unregulated recruitment, withholding of identity documents, debt bondage, and a lack of rights to organize (17,213). These issues have been notoriously difficult to address due to the complexity of fisheries, vastness of the ocean, and intersection with organized crime (215,216). Of note, the Western and Central Pacific Fisheries Commission (WCPFC) recently adopted the world's first binding minimum standards for crew labour conditions by a regional fisheries management organisation (RFMO) (217). This sets an important global precedent.

Furthermore, human and labour rights violations occur across the supply chain (15,218), particularly affecting women, who make particularly important contributions in the post-harvest sector, including processing and trading (64). Gender roles and systemic discrimination across different cultural contexts lead to increased risk and vulnerability for women in fisheries (219), including to gender-based and sexual violence (220–223). Despite representing 40% of fishworkers globally (64), women are often invisibilized (171) and excluded from human rights protection efforts in fisheries (224).

Numerous pervasive human rights issues also affect small-scale fisheries globally (19,225,226), such as food and livelihood insecurity resulting from overfishing by foreign fleets (224,227–230); the erasure of traditional knowledge and cultural practices; and forced eviction or disrupted access to territories, lands, and waters (226,231). These issues emerge in large part due to inadequate recognition of, attention to, and protection of small-scale fishers' human, tenure, and access rights in fisheries management (21,232). Women, Afro-descendent populations, and Indigenous Peoples involved in small-scale fisheries are often even more subject to exclusionary and punitive practices (42,233–235).

Another source of human rights violations in small-scale fisheries is when management measures put in place by states to address overfishing and IUU fishing undermine their rights and lead to their criminalization (236).

Human Rights Issues in the Ocean Economy

There is growing evidence that various sectors across the broader ocean economy have undermined human rights in different ways. An example is the aquaculture industry. A sector-wide impact assessment of salmon farming in Chile shows that it is infringing on labour rights, the right to a healthy environment, and the rights of Indigenous Peoples (237). Simultaneously, aquaculture feed relies in large part on industrial fishing practices and fishmeal factories, which in certain regions, including West Africa are contributing to overfishing of small-pelagic fisheries, and undermining of local fisheries and coinciding rights to livelihoods and food security (172,238–240).

Spatial displacement, dispossession and appropriation are also common features of the ocean economy that undercut tenure and access rights of coastal communities, small-scale fishers and Indigenous Peoples (81,232,241). Ocean and coastal grabbing is prevalent in sectors such as aquaculture, coastal tourism, oil infrastructure development and post-disaster reconstruction (83,241–247). The rapid global expansion of shipping and port infrastructures

has displaced communities and small-scale fishers from traditional fishing sites, which impacts their rights to food and livelihoods, particularly in Africa and Latin America (248–250).

Violence against local people and ocean defenders - individuals and groups who are organizing and taking action to resist developments that threaten the ocean environment and their human rights - is prevalent in some places where dispossession, displacement, ocean grabbing, and conflict result from development pressures, which threatens the rights to security of the person and to life (20,251,252).

Human rights violations will continue to occur in the rapidly accelerating ocean economy if states and businesses do not take their obligations and responsibilities seriously to respect, protect and fulfill human rights. There is also a high likelihood that any future development of deep sea mining will have substantial impacts on human rights (253). This stands in contrast with the foundational principle enshrined in UNCLOS particularly article 140, which states that activities in the Area must be carried out for the benefit of humankind as a whole (254).

Human Rights Issues Related to a Healthy Ocean

Mounting anthropogenic pressures on the ocean environment also threaten the right to a clean, healthy and sustainable environment (24,202,255). Human rights to a healthy ocean are being undermined by marine pollution and plastics, the effects of climate change, degradation of habitats and biodiversity, and fisheries declines (24,106,255).

Oil exploration and extraction, for example, produces pollution that affects rights to livelihoods, food and health of small-scale fishing communities globally (12). In Quintero-Puchuncaví Bay, Chile, communities have endured decades of pollution from a “sacrifice zone” where thermoelectric, petrochemical, oil refining, chemical, and copper processing plants are concentrated - undermining their right to a non-toxic environment, healthy food, and clean air (256–258). The prevalence of plastics in the ocean and on beaches threatens the rights of youth and future generations to be able to experience and live in clean environments (259).

Climate-related changes, including ocean warming, acidification, extreme weather, sea level rise, and storm surges, are affecting the right to a safe and stable climate, which is foundational to rights to food, livelihoods, security and life (9,11,24,255). This is particularly true for people who are highly reliant on marine resources, living in low-lying coastal cities and residents of small island developing states (192).

A growing number of national court cases worldwide have used arguments related to the right to a healthy environment to: halt threatening fishing activities (260,261), stop a major coal port (262), stop oil and gas exploration (263), and mandate restoration (264). Yet, a concerning, emerging trend is that ocean defenders who speak up for the protection of human rights to a healthy ocean are being marginalized, silenced, threatened, and even murdered for their efforts (20).

Human Rights Violations in Marine Conservation

Evidence of concerning practices by governments and NGOs in the name of conservation (including substantive and procedural human rights violations, and rights violations specific to Indigenous Peoples and women) began to emerge in the early 2000s (265–271). Prevalent human rights violations in the context of the conservation of terrestrial wildlife and ecosystems are related to: the lack of participation in decision-making or Free, Prior, and Informed Consent; forced displacement and restrictions on resource access; and impacts on rights to livelihoods, food and culture among others (269).

However, recent scholarship has highlighted how pervasive human and Indigenous Peoples' rights issues are in marine conservation (272). For example, marine protected areas (MPAs) designated in the context of historical injustices associated with apartheid in South Africa, along with failure to address ongoing inequities, resulted in weakening of local governance rights and processes, the loss of tenure rights and access to resources, loss of culture and sense of place (273).

Likewise, in the Chagos archipelago, forced displacement of Chagossians by UK and US governments has been prolonged and exacerbated by continued displacement under a conservation pretext and the establishment of a MPA (274). Similar evidence of displacement and dispossession by inappropriate conservation and management measures, referred to as ocean grabbing (83), exist across many different contexts such as in Guinea-Bissau (275), Malaysia (276), and Tanzania (277).

While some violations persist, and there is a need for restitution and remedial action in many places, conservation organizations have recognized and taken numerous measures to address past issues related to human rights in marine conservation. Notably, the Kunming-Montreal Global Biodiversity Framework acknowledges the importance of respecting and protecting human rights, including Indigenous Peoples' rights, and taking a human rights-based approach to conservation (278). Global conservation organizations and governments have made progress through implementing environmental and social safeguards, improving

participation and increasing benefit sharing mechanisms, as well as advancing support for conservation initiatives led by Indigenous Peoples and local communities (272,279).

Conclusion

States have an obligation, and businesses have a responsibility, to promote, respect and protect human rights from the coastal margins to the high seas (280,281). Yet, numerous human rights violations persist - in fisheries, in the ocean economy, and due to threats to a healthy ocean environment. Furthermore, marine conservation and fisheries management approaches often inadequately consider human rights. While there is a growing recognition of the human rights issues occurring in marine and coastal environments, many national and international ocean governance frameworks and processes still neglect to explicitly recognize and require attention to human rights (24).

5. Participation in ocean governance

Participation in governance is foundational to the realisation of equity, justice and human rights in the ocean. Achievement of more equitable distribution of the ocean's benefits and reducing environmental injustices, for example, is enabled by recognition and representation of diverse groups in ocean governance processes (192,282).

The realisation of substantive human rights related to a healthy ocean also necessitates attention to procedural elements, which includes access to information, public participation in decision-making and access to justice (24,202). Regional agreements, such as the Aarhus Convention and the Ezcazú Agreement (283,284), underscore the importance of participation of all affected parties in environmental matters as a matter of human rights.

Participatory ocean governance requires that all rights holders and stakeholders are recognized, that all affected actors and diverse perspectives are included, and that insights from natural science, social science, and traditional knowledge are represented in decision-making (285,286). Particular attention is needed to ensure formerly excluded or silenced populations, such as Indigenous Peoples, small-scale fishers and women (91,287), are effectively included in

ocean governance, planning and management processes (288). It is important that inclusion is not tokenistic but rather influences and shapes policies and management (289–291).

This section briefly examines how participatory ocean governance processes are at various scales.

Participation in National and Local Ocean Governance

Over the past few decades, there have been increasing efforts to make marine conservation, fisheries management and ocean economy planning processes more participatory. In practice, however, ocean governance at national and local scales varies substantially in the level and quality of participation.

Acknowledging and including a diversity of actors, including Indigenous Peoples, local communities, small-scale fishers, women's groups, and other local groups, is key to achieving participatory local and national ocean governance processes (292). Yet, in the context of marine conservation, for example, Indigenous Peoples and local communities often continue to be excluded from planning and management of marine protected areas (MPAs), for example (272,293).

In South Africa, decision-making processes related to the establishment and management of MPAs have excluded subsistence and small-scale fishers, Indigenous Peoples and coastal communities (273,288,294). On the other end of the spectrum is Haida Gwaii in Canada, where plans for marine protection, stewardship and governance have been co-developed between the Indigenous Haida Nation and the provincial government of British Columbia, with representation from the Haida governing council (295).

In general, advances in national policies that aim to improve participation and inclusion in fisheries have taken the forms of co-management (296). For instance, in Chile, the progressive institutionalisation of co-management has included: introducing Territorial User Rights for Fisheries (TURFs) in 1991 (297,298), creating collective action arenas in 2013 (299) and adopting voluntary conservation areas by artisanal fishers in 2024. In 2011, Belize committed to establishing TURFs called 'managed access areas' throughout its territorial sea (aka Exclusive Economic Zone) using two pilot sites at Port Honduras and Glover's Reef marine reserves, which were scaled up to ensure fishing rights for small-scale operators and communities throughout its territorial sea (300,301). In Peru, a co-management scheme was

introduced for the profitable scallop mariculture sector, addressing significant challenges relating to management, corruption, pollution, and enforcement (302).

Fisheries co-management processes in different countries have been more or less successful at incorporating the various elements necessary for effective participation - which includes policy-making processes that are co-produced and include fishers (303,304), clear roles and adequate capacity (305), integration of diverse knowledge systems (306), support for local stewardship (307) and agency for managing seascapes (308). Nevertheless, women are often inadequately included in fisheries decision-making processes (309,310).

Participation in International and Regional Ocean Governance

At the international level, the limited agency of less powerful states and the level of civil society participation in ocean governance processes are concerns. For example, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (hereafter BBNJ Agreement) was adopted in 2023 under the auspices of the UN, addressing issues of environmental impact assessments, area-based management tools including marine protected areas, capacity building and technology transfer, and marine genetic resources including benefit sharing. Despite lengthy negotiations intended to balance various interests and priorities, the BBNJ process has been critiqued for offering limited opportunities for participation of civil society, Indigenous Peoples and other interested non-State actors (311,312). There has also been significant inequities in terms of participation, representation and influence of States with smaller economies (89).

Most of the world’s oceans are now covered by at least one Regional Fisheries Management Organization (RFMO), and the United Nations Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA) institutionalised the duty to cooperate and requires all parties to apply all conservation and management measures established by all existing RFMOs. UNFSA limits access to straddling fish stocks and tuna fisheries to parties that at the very least agree to implement the RFMO’s measures. RFMOs have the potential to increase the participation and agency of less wealthy and powerful States in ocean governance(313). However, some would argue that they have not adequately considered the interests of smaller or emerging economies, particularly vis-a-vis the equitable allocation of fishing opportunities and the disproportionate burdens of conservation measures, which often favour historically developed fishing states over developing States(313–315), or non-State actors such as Indigenous Peoples and local communities. Yet, there has been positive developments in RFMOs such as the WCPFC where

collective bargaining by small island developing States has helped to ensure that their interests are more effectively considered.

UNFSA also recognises the need to avoid adverse impacts on, and ensure access to fisheries by, subsistence, small-scale and artisanal fishers, women fishworkers, and Indigenous Peoples, and requires parties to avoid transferring, directly or indirectly, a disproportionate burden of conservation action onto developing States (316). Unfortunately, however, only the Western and Central Pacific Fisheries Commission (WCPFC) has adopted any measures that explicitly implement this requirement in practice (317).

Conclusion

A major challenge for the realisation of equity, justice and human rights is effective participation in ocean governance processes. While local and national ocean governance processes are making progress, inclusivity in regional and international ocean governance processes is still limited. In particular, lower and middle income nation-states have less power and voice in regional and international ocean governance processes, and the opportunities for civil society organisations and groups to participate and contribute are limited.

In general, approaches to ocean governance, from local to international, continue to under-represent certain groups (e.g., Indigenous Peoples and small-scale fisheries) (282). Furthermore, legacies of colonialism and levels of development continue to impact who is involved, what knowledge systems and values are considered, and the overall quality and equity of ocean governance processes (91,282).

6. Conclusion

This chapter examines equity, justice, and human rights issues in the ocean. Benefits from fisheries, ecosystem services, and the ocean economy are inequitably distributed among groups, countries and regions of the world. Marine pollution and plastics, climate change, environmental degradation, and fisheries declines disproportionately affect some groups and geographies. Human rights violations occur in fisheries, the ocean economy, marine conservation and in relation to a healthy environment.

Behind these omnipresent issues are: an ocean economy that prioritizes the economy over human wellbeing; power asymmetries driven by wealth accumulation and colonial histories; increasing privatization and consolidated ownership of the ocean economy; and ocean governance processes that overlook equity, justice and human rights. While current levels of participation in ocean governance processes remain largely insufficient to lay the necessary foundation for the achievement of equity, justice, and human rights, there is significant potential to strengthen future ocean governance.

Best practices

In that context, this chapter provides five best practices for how equity, justice, and human rights can be centered in ocean governance and management (Figure 1).

1. *Recognize the unique relationships, dependence and rights of diverse peoples to the ocean.* Humanity depends on the ocean; however, different groups have unique relationships with the ocean. To lay the groundwork for effective participation and the promotion of equity, justice and human rights in ocean governance, society must formally acknowledge how diverse individuals, groups, communities, countries and nations relate to, rely on, and have rights to the ocean and integrate these considerations into ocean governance. For example, different communities depend on marine ecosystem services to a greater or lesser extent for various domains of wellbeing. Coastal Indigenous People and small-scale fishers have deep cultural connections that depend on access and tenure rights, but these are often unrecognized or have been eroded. A social science perspective, grounded in traditional and local knowledge, can support the integration of social considerations into ocean governance.

2. *Ensure equitable representation and meaningful participation in ocean governance processes at all scales.* Participation is foundational to achieving equity, justice, and human rights in ocean governance, and is a key pathway to achieving sustainability. However, there are major shortcomings in the level of inclusivity and participation in local, national, and international ocean governance. International human rights law mandates the participation of all affected parties in environmental decisions, which is underpinned by access to information and access to justice (202,283,284). Explicit recognition and representation of all stakeholders and rights holders is a first step towards more equitable governance processes. Effective participation requires transforming social cultural norms as well as attention to various procedural elements - including access to information, funding, capacity, facilitation, accountability and conflict resolution - to avoid tokenistic participation and ensure all groups can influence decision-making.

3. *Pursue equity in the distribution of benefits from the ocean.* Without adequate controls, the ocean economy risks increasing inequality, undermining achievement of global sustainable development goals related to decent work, poverty reduction, gender

equality and food security (2,318). Addressing inequalities requires that ocean governance policies, processes and practices prioritize human wellbeing alongside environmental sustainability. Practical policy measures include social impact assessments, benefit sharing mechanisms, implementing tenure and access rights for coastal communities, and gender equality practices. Tackling corruption, impunity, tax evasion and enforcing fair labor practices is also essential. These solutions must consider actions to address systemic inequities in ownership and seek redress for historical disadvantages.

4. *Address the drivers, sources and disproportionate impacts of environmental injustices in the ocean.* Certain segments of society and regions of the world bear the brunt of marine environmental issues. At the highest level, bold policies and actions are needed to address the root drivers behind each of the growing issues that are leading to environmental injustices - marine pollution and plastics, climate change, fisheries declines, and environmental degradation. Governments must create and enforce environmental policies and management actions to lessen the burden on the oceans; for example, through banning chemical pollutants, curtailing point source and nonpoint source pollution, reducing plastic production and improving waste management, and addressing overfishing. Corporate actors might also be further incentivized or forced to improve technologies and sustainability of their practices (319,320). Some would argue that environmental justice issues in the ocean also persist due to enduring racism, colonialism, and a capitalist economy that enables inequitable global flows of resources to wealthy countries and waste to less wealthy countries. These challenging issues must be brought into question.

5. *Embed human rights in national and international ocean governance frameworks and management practices*. Under international human rights treaties and law, governments have an obligation and businesses and other civil society organizations have a responsibility to promote, respect, protect, and ~~fulfill~~fulfil human rights (24,255,280,321). This applies both within territorial seas and in areas beyond national jurisdiction. Despite some progress, global ocean governance processes and agreements should more explicitly acknowledge human rights agreements and obligations (24), and national marine policies and management practices (e.g., related to marine conservation, fisheries, and the ocean economy) must better recognize and make provisions to protect human rights. Businesses engaged in the ocean economy must uphold human rights in their operations and supply chains, and States are obliged to regulate, monitor and prevent human rights abuses by the private sector (280). States and civil society organizations should adopt human rights-based approaches, including requiring economic and social impact assessments and Free, Prior and Informed Consent, in fisheries management, marine conservation, restoration and climate adaptation efforts (272,322). The tenure and access rights of Indigenous Peoples and small-scale fisheries should be acknowledged and respected in ocean governance (200,201,205,206). Ocean defenders must be safeguarded in their right to gather, organize and advocate for the ocean, their territorial rights, and human rights. Finally, all duty bearers - governments, businesses, and civil society organizations who have obligations and responsibilities - must be held to account for not upholding human rights related to the ocean (272).

In summary, this chapter has highlighted the types and scope of ocean-related distributional inequities, environmental injustices, and human rights violations. Future ocean governance requires a fundamental shift to center equity, justice, and human rights in ocean policy, management, and sustainability efforts. States have a responsibility to ensure inclusive and participatory decision-making and management, promote the equitable distribution of benefits from the ocean, address environmental injustices, and embed human rights in ocean governance frameworks. Creating robust ocean policy frameworks and implementing concrete and effective management actions on these priorities are essential to upholding broader international commitments related to human rights and sustainable development.

7. References

1. Jouffray JB, Blasiak R, Norström AV, Österblom H, Nyström M. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth. 2020 Jan 24;2(1):43–54.

2. Österblom H, Wabnitz CCC, Tladi D, Allison EH, Arnaud-Haond S, Bebbington J, et al. Towards Ocean Equity. In: Lubchenco J, Haugan PM, editors. The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy. Cham: Springer International Publishing; 2023. p. 485–521.

3. Virdin J, Vegh T, Jouffray JB, Blasiak R, Mason S, Österblom H, et al. The Ocean 100: Transnational corporations in the ocean economy. Sci Adv. 2021;7(3):eabc8041.

4. McCauley DJ, Jablonicky C, Allison EH, Golden CD, Joyce FH, Mayorga J, et al. Wealthy countries dominate industrial fishing. Sci Adv. 2018;4(8):eaau2161.

5. Tickler D, Meeuwig JJ, Palomares ML, Pauly D, Zeller D. Far from home: Distance patterns of global fishing fleets. Sci Adv. 2018;4(8):eaar3279.

6. Amnesty International. The human cost of overfishing: How the overuse of fisheries resources in Sanyang threatens human rights. London, UK: Amnesty International; 2023.

7. Andreoli V, Meeuwig JJ, Skerritt DJ, Schuhbauer A, Sumaila UR, Zeller D. Fisheries subsidies exacerbate inequities in accessing seafood nutrients in the Indian Ocean. Npj Ocean Sustain. 2023 Dec 8;2(1):1–9.

8. EJF. At the Tipping Point: How bottom trawling is precipitating the collapse of Senegal's artisanal fisheries. Environmental Justice Foundation; 2022.

9. Bindoff NL, Cheung WWL, Kairo JG, Arístegui J, Guinder VA, Hallberg R, et al. Changing Ocean, Marine Ecosystems, and Dependent Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change; 2019. p. 142.

10. IPCC. Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovermental Panel on Climate Change; 2019.

11. IPCC. Chapter 3: Oceans and Coastal Ecosystems and their Services. Bonn, Germany: IPCC; 2021.

12. Andrews N, Bennett NJ, Le Billon P, Green SJ, Cisneros-Montemayor AM, Amongin S, et al. Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. Energy Res Soc Sci. 2021 May;75:102009.

13. Gill DA, Picou JS, Ritchie LA. The Exxon Valdez and BP Oil Spills: A Comparison of Initial Social and Psychological Impacts. Am Behav Sci. 2012;56(1):3–23.

14. O'Rourke D, Connolly S. Just Oil? The Distribution of Environmental and Social Impacts of Oil Production and Consumption. Annu Rev Environ Resour. 2003;28(1):587–617.

15. Garcia Lozano AJ, Decker Sparks JL, Durgana DP, Farthing CM, Fitzpatrick J, Krough-Poulsen B, et al. Decent work in fisheries: Current trends and key considerations for future research and policy. Mar Policy. 2022;136:104922.

16. Marschke M, Vandergeest P. Slavery scandals: Unpacking labour challenges and policy responses within the off-shore fisheries sector. Mar Policy. 2016;68:39–46.

17. Murphy C. Tackling Vulnerability to Labour Exploitation through Regulation: The Case of Migrant Fishermen in Ireland. Ind Law J. 2017;46(3):417–34.

18. Stringer C, Whittaker DH, Simmons G. New Zealand's turbulent waters: the use of forced labour in the fishing industry. Glob Netw. 2016;16(1):3–24.

19. Teh LCL, Caddell R, Allison EH, Finkbeiner EM, Kittinger JN, Nakamura K, et al. The role of human rights in implementing socially responsible seafood. PLOS ONE. 2019;14(1):e0210241.

20. Bennett NJ, López de la Lama R, Le Billon P, Ertör I, Morgera E. Ocean defenders and human rights. Front Mar Sci. 2023;9:1089049.

21. Figueroa I, Saavedra-Díaz LM, Satizábal P, Narváez GN, Velásquez-Mendoza Y. Justicia en territorios pesqueros: violaciones a los derechos humanos en la pesca artesanal en la Corte Constitucional de Colombia. Estud Socio-Juríd. 2023;25(2).

22. Lamb V, Marschke M, Rigg J. Trading Sand, Undermining Lives: Omitted Livelihoods in the Global Trade in Sand. Ann Am Assoc Geogr. 2019;109(5):1511–28.

23. Morgera E, Lily H. Public participation at the International Seabed Authority: An international human rights law analysis. Rev Eur Comp Int Environ Law. 2022;31(3):374–88.

24. Bennett NJ, Morgera E, Boyd D. The human right to a clean, healthy and sustainable ocean. Npj Ocean Sustain. 2024;3(1):1–8.

25. Campbell LM, Gray NJ, Fairbanks L, Silver JJ, Gruby RL, Dubik BA, et al. Global Oceans Governance: New and Emerging Issues. Annu Rev Environ Resour. 2016;41(1):517–43.

26. Partelow S, Hadjimichael M, Hornidge AK, editors. Ocean Governance: Knowledge Systems, Policy Foundations and Thematic Analyses. Cham: Springer International Publishing; 2023.

27. Bennett NJ. Navigating a just and inclusive path towards sustainable oceans. Mar Policy. 2018;97:139–46.

28. Crosman KM, Allison EH, Ota Y, Cisneros-Montemayor AM, Singh GG, Swartz W, et al. Social equity is key to sustainable ocean governance. Npj Ocean Sustain. 2022;1(1):1–9.

29. Grorud-Colvert K, Ward M. The Ocean: An Introduction to the Marine Environment. In: Spalding AK, Suman DO, editors. Oceans and Society: An Introduction to Marine Studies. London, UK: Routledge; 2023.

30. Isson TT, Planavsky NJ, Coogan LA, Stewart EM, Ague JJ, Bolton EW, et al. Evolution of the Global Carbon Cycle and Climate Regulation on Earth. Glob Biogeochem Cycles. 2020;34(2):e2018GB006061.

31. Kearney A, O'Leary M, Platten S. Sea Country: Plurality and knowledge of saltwater territories in Indigenous Australian contexts. Geogr J. 2023;189(1):104–16.

32. Lane JM, Pretes M. Maritime dependency and economic prosperity: Why access to oceanic trade matters. Mar Policy. 2020;121:104180.

33. Waiti J, Wheaton B, Peters K, Anderson J, Davies A, Steinberg P. Culture: Indigenous Māori knowledges of the ocean and leisure practices. In: The Routledge Handbook of Ocean Space. London, UK: Routledge; 2022.

34. Wester J, Broad K, Herrero Backe K, Callwood K, Fielding R, Jacquet J, et al. Chapter 3 - Culture and historic value as ways of understanding complex human health-ocean linkages. In: Fleming LE, Alcantara Creencia LB, Gerwick WH, Goh HC, Gribble MO, Maycock B, et al., editors. Oceans and Human Health (Second Edition). San Diego: Academic Press; 2023;p. 39–70.

35. Blasiak R, Jouffray JB, Wabnitz CCC, Sundström E, Österblom H. Corporate control and global governance of marine genetic resources. Sci Adv. 2018;4(6):eaar5237.

36. Blythe J, Armitage D, Alonso G, Campbell D, Esteves Dias AC, Epstein G, et al. Frontiers in coastal well-being and ecosystem services research: A systematic review. Ocean Coast Manag. 2020;185:105028.

37. Elias M, Zaremba H, Tavenner K, Ragasa C, Paez Valencia AM, Choudhury A, et al. Towards gender equality in forestry, livestock, fisheries and aquaculture. Glob Food Secur. 2024;41:100761.

38. Hicks CC, Gephart JA, Koehn JZ, Nakayama S, Payne HJ, Allison EH, et al. Rights and representation support justice across aquatic food systems. Nat Food. 2022;3(10):851–61.

39. FAO. The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action. Rome: Food and Agriculture Organization of the United Nations; 2024.

40. FAO. A Review of Women's Access to Fish in Small-Scale Fisheries. Rome, Italy: Food and Agriculture Organization of the United Nations; 2015. (FAO Fisheries and Aquaculture Circular). Report No.: FIRO/C1098.

41. FAO, Duke University, WorldFish. Illuminating Hidden Harvests: The contributions of small-scale fisheries to sustainable development. Rome: FAO/Duke University/WorldFish; 2023.

42. Jentoft S, Stacey N, Sunde J, González M. The Small-Scale Fisheries of Indigenous Peoples: A Struggle for Secure Tenure Rights. In: Chuenpagdee R, Jentoft S, editors.

Transdisciplinarity for Small-Scale Fisheries Governance: Analysis and Practice. Cham: Springer International Publishing; 2019; p. 263–82..

43. Pinkerton E. Strategies and Policies Supporting Small-Scale Fishers' Access and Conservation Rights in a Neoliberal World. In: Chuenpagdee R, Jentoft S, editors. Transdisciplinarity for Small-Scale Fisheries Governance: Analysis and Practice. Cham: Springer International Publishing; 2019; p. 241–61.

44. Österblom H, Jouffray JB, Folke C, Crona B, Troell M, Merrie A, et al. Transnational Corporations as 'Keystone Actors' in Marine Ecosystems. PLOS ONE. 2015;10(5):e0127533.

45. Frantzeskaki N, Lambertucci SA, Carr ER, Dempsey J, Karamidehkordi E, Sengupta A, et al. IPBES Transformative Change Assessment: Chapter 4. Overcoming the challenges of achieving transformative change towards a sustainable world. In: Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat; 2025.

46. Clark TP. Racial capitalism and the sea: Development and change in Black maritime labour, and what it means for fisheries and a blue economy. Fish Fish. 2022;23(3); 648-662.

47. Clark TP, Cisneros-Montemayor AM. Colonialism and the Blue Economy: confronting historical legacies to enable equitable ocean development. Ecol Soc. 2024;29(3).

48. Pease PB. Undoing Privilege: Unearned Advantage and Systemic Injustice in an Unequal World. Bloomsbury Publishing; 2021. 337 p.

49. Millennium Ecosystem Assessment. Ecosystems and human well-being: Synthesis. Washington, D.C.: World Resources Institute and Island Press; 2005.

50. Drakou EG, Virdin J, Pendleton L. Mapping the global distribution of locally-generated marine ecosystem services: The case of the West and Central Pacific Ocean tuna fisheries. Ecosyst Serv. 2018;31:278–88.

51. Gould RK, Morse CE, Brooks J, Adams A. "So Much for Access:" Difference, Benefits, and Barriers at Hawaii's Shorelines. Geogr Rev. 2022;112(4):532–49.

52. Middleton DR. Development And Multiple Use: Conflict On An Ecuadorian Beach.

Urban Anthropol Stud Cult Syst World Econ Dev. 1988;17(4):351–64.

53. Montgomery MC, Chakraborty J, Grineski SE, Collins TW. An environmental justice assessment of public beach access in Miami, Florida. Appl Geogr. 2015;62:147–56.

54. Fisher JA, Patenaude G, Giri K, Lewis K, Meir P, Pinho P, et al. Understanding the relationships between ecosystem services and poverty alleviation: A conceptual framework. Ecosyst Serv. 2014;7:34–45.

55. Langemeyer J, Benra F, Nahuelhual L, Zoderer BM. Ecosystem Services Justice: The Emergence of a Critical Research Field. Ecosyst Serv. 2024;69:101655.

56. Tholan B, Basurto X, Cohen PJ, Franz N, Himes-Cornell A, Govan H, et al. Accounting for existing tenure and rights over marine and freshwater systems. Npj Ocean Sustain. 2024;3(1):1–12.

57. Bennett NJ, Kaplan-Hallam M, Augustine G, Ban N, Belhabib D, Brueckner-Irwin I, et al. Coastal and Indigenous community access to marine resources and the ocean: A policy imperative for Canada. Mar Policy. 2018;87:186–93.

58. Patankar V, D'Souza E, Alcoverro T, Arthur R. Erosion of Traditional Marine Management Systems in the Face of Disturbances in the Nicobar Archipelago. Hum Ecol. 2015;43(5):697–707.

59. Teh LCL, Sumaila UR. Contribution of marine fisheries to worldwide employment. Fish Fish. 2013;14(1):77–88.

60. Belhabib D, Sumaila UR, Lam VWY, Zeller D, Billon PL, Kane EA, et al. Euros vs. Yuan: Comparing European and Chinese Fishing Access in West Africa. PLOS ONE. 2015;10(3):e0118351.

61. Manach FL, Chaboud C, Copeland D, Cury P, Gascuel D, Kleisner KM, et al. European Union's Public Fishing Access Agreements in Developing Countries. PLOS ONE. 2013;8(11):e79899.

62. Andriamahefazafy M, Haas B, Campling L, Le Manach F, Goodman C, Adams TJH, et al. Advancing tuna catch allocation negotiations: an analysis of sovereign rights and fisheries access arrangements. Npj Ocean Sustain. 2024;3(1):1–8.

63. Basurto X, Gutierrez NL, Franz N, Mancha-Cisneros M del M, Gorelli G, Aguión A, et al. Illuminating the multidimensional contributions of small-scale fisheries. Nature.

2025;637(8047):875–84.

64. FAO. Illuminating Hidden Harvests: the contributions of small-scale fisheries to sustainable development. FAO; 2023.

65. Islam MM, Chuenpagdee R. Towards a classification of vulnerability of small-scale fisheries. Environ Sci Policy. 2022;134:1–12.

66. Bailey M, Bush S, Oosterveer P, Larastiti L. Fishers, Fair Trade, and finding middle ground. Fish Res. 2016;182:59–68.

67. Pita C, Ford A. Sustainable seafood and small-scale fisheries. London, UK: IIED; 2023.

68. Skerritt DJ, Schuhbauer A, Villasante S, Cisneros-Montemayor AM, Bennett NJ, Mallory TG, et al. Mapping the unjust global distribution of harmful fisheries subsidies. Mar Policy. 2023;152:105611.

69. Barbesgaard M. Blue growth: savior or ocean grabbing? J Peasant Stud. 2018;45(1):130–49.

70. OECD. The Ocean Economy in 2030. Organization for Ecomonomic Cooperation and Development; 2016.

71. Bennett NJ, Cisneros-Montemayor AM, Blythe J, Silver JJ, Singh G, Andrews N, et al. Towards a sustainable and equitable blue economy. Nat Sustain. 2019;2:991–3.

72. Cisneros-Montemayor AM, Moreno-Báez M, Reygondeau G, Cheung WWL, Crosman KM, González-Espinosa PC, et al. Enabling conditions for an equitable and sustainable blue economy. Nature. 2021;591(7850):396–401.

73. Silver JJ, Gray NJ, Campbell LM, Fairbanks LW, Gruby RL. Blue Economy and Competing Discourses in International Oceans Governance. J Environ Dev. 2015;24(2):135-160.

74. Ablo AD. Local content and participation in Ghana's oil and gas industry: Can enterprise development make a difference? Extr Ind Soc. 2015;2(2):320–7.

75. Obi CI. Oil Extraction, Dispossession, Resistance, and Conflict in Nigeria's Oil-Rich Niger Delta. Can J Dev Stud Rev Can Détudes Dév. 2010;30(1–2):219–36.

76. Oteng-Ababio M. 'The Oil is Drilled in Takoradi, but the Money is Counted in Accra': The Paradox of Plenty in the Oil City, Ghana. J Asian Afr Stud. 2018;53(2):268–84.

77. Bergquist DA. Sustainability and local people's participation in coastal aquaculture: Regional differences and historical experiences in Sri Lanka and the Philippines. Environ Manage. 2007;40(5):787–802.

78. Nickerson DJ. Trade-offs of mangrove area development in the Philippines. Ecol Econ. 1999;28(2):279–98.

79. Primavera JH. Socio-economic impacts of shrimp culture. Aquac Res. 1997;28(10):815–27.

80. Stonich SC, Bort JR, Ovares LL. Globalization of shrimp mariculture: The impact on social justice and environmental quality in Central America. Soc Nat Resour. 1997;10(2):161–79.

81. Bennett NJ, Blythe J, White CS, Campero C. Blue growth and blue justice: Ten risks and solutions for the ocean economy. Marine Policy. 2021;125:104387.

82. Das J. Blue Economy, Blue Growth, Social Equity and Small-scale Fisheries: A Global and National Level Review. Stud Soc Sci Res. 2023;4(1):38.

83. Bennett NJ, Govan H, Satterfield T. Ocean grabbing. Mar Policy. 2015;57:61–8.

84. Nogué-Algueró B. Growth in the docks: ports, metabolic flows and socio-environmental impacts. Sustain Sci. 2020;15;11-30.

85. Campling L, Colás A. Capitalism and the sea: Sovereignty, territory and appropriation in the global ocean. Environ Plan Soc Space. 2018;36(4):776–94.

86. Vandergeest P, Tran O, Marschke M. Modern day slavery in Thai fisheries: academic critique, practical action. Crit Asian Stud. 2017;49(3):461–4.

87. Bennett NJ, Villasante S, Espinosa-Romero MJ, Lopes PFM, Selim SA, Allison EH. Social sustainability and equity in the blue economy. One Earth. 2022;5(9):964–8.

88. O'Neill BF, Schneider MJ, Lozano AG. Toward a Critical Environmental Justice Approach to Ocean Equity. Environ Justice. 2025;18(2):90-99.

89. Sparks JLD, Sliva SM. An intersectionality-based analysis of high seas policy making stagnation and equity in United Nations negotiations. Journal of Community Practice. 2019;27:260–78.

90. Bodwitch H, Hamelin KM, Paul K, Reid J, Bailey M. Indigenous self-determination in

fisheries governance: implications from New Zealand and Atlantic Canada. Front Mar Sci. 2024;11:1297975.

91. Strand M, Retter GB, Khan M, Frid A, Hudson M, Leonard K, et al. Co-producing Sustainable Ocean Plans with Indigenous and traditional knowledge holders. High Level Panel on the Sustainable Ocean Economy, World Resources Institute; 2024.

92. Prellezo R, Da-Rocha JM, Palomares MLD, Sumaila UR, Villasante S. Building climate resilience, social sustainability and equity in global fisheries. Npj Ocean Sustain. 2023;2(1):1–7.

93. Bullard RD. Unequal Protection: Environmental Justice and Communities of Color. Sierra Club Books; 1994.

94. Cutter SL. Race, class and environmental justice. Prog Hum Geogr. 1995;19(1):111–22.

95. Brulle RJ, Pellow DN. Environmental Justice: Human Health and Environmental Inequalities. Annu Rev Public Health. 2006;27(1):103–24.

96. Bullard RD. Dumping In Dixie: Race, Class, And Environmental Quality, Third Edition. 4th edition. New York: Routledge; 2018.

97. Cutter SL. Hazards Vulnerability and Environmental Justice. Routledge; 2012.

98. Sikor T. The justices and injustices of ecosystem services. New York: Routledge; 2013.

99. Tsosie R. Indigenous People and Environmental Justice: The Impact of Climate Change The Climate of Environmental Justice: Taking Stock. Univ Colo Law Rev. 2007;78:1625–78.

100. Arias AH, Botte SE. Coastal and Deep Ocean Pollution. CRC Press; 2020.

101. Frid CLJ, Caswell BA. Marine Pollution. Oxford University Press; 2017.

102. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science. 2015;347(6223):768–71.

103. Thevenon F, Carroll C, Sousa J, editors. Plastic debris in the ocean: the characterization of marine plastics and their environmental impacts, situation analysis report. Gland, Switzerland: International Union for Conservation of Nature; 2015.

104. Beiras R. Marine Pollution: Sources, Fate and Effects of Pollutants in Coastal Ecosystems. Elsevier; 2018.

105. Bowen RE, Depledge MH, Carlarne CP, Fleming LE. Oceans and Human Health: Implications for Society and Well-Being. John Wiley & Sons; 2014.

106. Landrigan PJ, Stegeman JJ, Fleming LE, Allemand D, Anderson DM, Backer LC, et al. Human Health and Ocean Pollution. Ann Glob Health. 2020;86(1):151.

107. UNEP. Neglected: Environmental Justice Impacts of Marine Litter and Plastic Pollution. Nairobi, Kenya: United Nations Environment Programme; 2021.

108. Donatuto JL, Satterfield TA, Gregory R. Poisoning the body to nourish the soul: Prioritising health risks and impacts in a Native American community. Health Risk Soc. 2011;13(2):103–27.

109. Probyn E. The ocean returns: Mapping a mercurial Anthropocean. Soc Sci Inf. 2018;57(3):386–402.

110. Chang SE, Stone J, Demes K, Piscitelli M. Consequences of oil spills: a review and framework for informing planning. Ecol Soc. 2014:26269587.

111. Palinkas L, Petterson JS, Russell JC, Downs MA. Ethnic Differences in Symptoms of Post-traumatic Stress after the Exxon Valdez Oil Spill. Prehospital Disaster Med. 2004;19(1):102–12.

112. Picou JS, Formichella C, Marshall BK, Arata C. Community impacts of the Exxon Valdez oil spill: A synthesis and elaboration of social science research. Synth Three Decades Res Socioecon Eff Relat Offshore Pet Dev Coast Alsk. 2009;279–310.

113. Suh N. Ocean pollution, food security, and health in coastal fishing communities in Limbe, Cameroon. Agriculture, Health and Nutrition Academy. 2024.

114. Liboiron M. Pollution Is Colonialism. Pollution Is Colonialism. Durham, NC: Duke University Press; 2021.

115. Maldonado JK. Seeking Justice in an Energy Sacrifice Zone: Standing on Vanishing Land in Coastal Louisiana. New York, NY: Taylor & Francis Group, Routledge; 2018.

116. Randolph N. Pipeline Logic and Culpability: Establishing a Continuum of Harm for Sacrifice Zones. Frontiers in Environmental Science. 2021;9.

117. AMAP. AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change. Tromsø, Norway: Arctic Monitoring and Assessment Programme (AMAP); 2021.

118. Ghisari M, Eiberg H, Long M, Bonefeld-Jørgensen EC. Polymorphisms in Phase I and Phase II genes and breast cancer risk and relations to persistent organic pollutant exposure: a case–control study in Inuit women. Environ Health. 2014;13(1):19.

119. Wielsøe M, Kern P, Bonefeld-Jørgensen EC. Serum levels of environmental pollutants is a risk factor for breast cancer in Inuit: a case control study. Environ Health. 2017;16(1):56.

120. Okafor-Yarwood I, Adewumi IJ. Toxic waste dumping in the Global South as a form of environmental racism: Evidence from the Gulf of Guinea. Afr Stud. 2020;79(3):285–304.

121. Frey RS. Breaking Ships in the World-System: An Analysis of Two Ship Breaking Capitals, Alang-Sosiya, India and Chittagong, Bangladesh. J World-Syst Res. 2015;21(1):25–49.

122. Wan Z, Wang L, Chen J, Sperling D. Ship scrappage records reveal disturbing environmental injustice. Marine Policy. 2021;130.

123. Pedra AS, Gonçalves LCS. Third World approaches to the international law: warnings and the urgency to face the plastic soup. Revista Internacional de Direito Ambiental. 2020;25: 11-38.

124. UNEP. Drowning in Plastics – Marine Litter and Plastic Waste Vital Graphics. Nairobi, Kenya: United Nations Environment Programme; 2021.

125. du Pontavice H, Gascuel D, Reygondeau G, Maureaud A, Cheung WWL. Climate change undermines the global functioning of marine food webs. Glob Change Biol. 2020;26(3):1306–18.

126. Morley JW, Selden RL, Latour RJ, Frölicher TL, Seagraves RJ, Pinsky ML. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PLOS ONE. 2018;13(5):e0196127.

127. Pinsky ML, Selden RL, Kitchel ZJ. Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities. Annu Rev Mar Sci. 2020;12(1):153–79.

128. Poloczanska ES, Burrows MT, Brown CJ, García Molinos J, Halpern BS, Hoegh-Guldberg O, et al. Responses of Marine Organisms to Climate Change across Oceans. Front Mar Sci. 2016;3.

129. Doney SC, Ruckelshaus M, Emmett Duffy J, Barry JP, Chan F, English CA, et al. Climate Change Impacts on Marine Ecosystems. Annu Rev Mar Sci. 2012;4(1):11–37.

130. Gilman EL, Ellison J, Duke NC, Field C. Threats to mangroves from climate change and adaptation options: A review. Aquat Bot. 2008;89(2):237–50.

131. IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Geneva, Switzerland: Intergovernmental Panel on Climate Change; 2022.

132. Klein SG, Geraldi NR, Anton A, Schmidt-Roach S, Ziegler M, Cziesielski MJ, et al. Projecting coral responses to intensifying marine heatwaves under ocean acidification. Glob Change Biol. 2022;28(5):1753-1765.

133. Sippo JZ, Lovelock CE, Santos IR, Sanders CJ, Maher DT. Mangrove mortality in a changing climate: An overview. Estuar Coast Shelf Sci. 2018;215:241–9.

134. Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, et al. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob Change Biol. 2010;16(1):24–35.

135. Doney SC, Busch DS, Cooley SR, Kroeker KJ. The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. Annu Rev Environ Resour. 2020;45(1):83–112.

136. Fernandes JA, Papathanasopoulou E, Hattam C, Queirós AM, Cheung WWWL, Yool A, et al. Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. Fish Fish. 2017;18(3):389–411.

137. Lam VWY, Cheung WWL, Reygondeau G, Sumaila UR. Projected change in global fisheries revenues under climate change. Sci Rep. 2016;6:32607.

138. Narita D, Rehdanz K, Tol RSJ. Economic costs of ocean acidification: a look into the impacts on global shellfish production. Clim Change. 2012;113(3):1049–63.

139. Tigchelaar M, Cheung WWL, Mohammed EY, Phillips MJ, Payne HJ, Selig ER, et al. Compound climate risks threaten aquatic food system benefits. Nat Food. 2021;2(9):673–82.

140. Ahmed S, Eklund E. Climate change impacts in coastal Bangladesh: Migration, gender and environmental injustice. Asian Affairs. 2021;52:155–74.

141. Dannenberg AL, Frumkin H, Hess JJ, Ebi KL. Managed retreat as a strategy for climate change adaptation in small communities: public health implications. Clim Change. 2019;153(1):1–14.

142. Dasgupta S, Wheeler D, Bandyopadhyay S, Ghosh S, Roy U. Coastal dilemma: Climate change, public assistance and population displacement. World Dev. 2022;150:105707.

143. Hauer ME. Migration induced by sea-level rise could reshape the US population landscape. Nat Clim Change. 2017;7(5):321–5.

144. Heberger M, Cooley H, Herrera P, Gleick PH, Moore E. Potential impacts of increased coastal flooding in California due to sea-level rise. Clim Change. 2011;109(1, SI):229–49.

145. Liwenga ET, Ndaki P, Chengula F, Kalokola R. Coastal Communities' Perceptions on Climate Change Impacts and Implications for Adaptation Strategies in Mtwara, Southern Tanzania. In: Yanda PZ, Bryceson I, Mwevura H, Mung'ong'o CG, editors. Climate Change and Coastal Resources in Tanzania: Studies on Socio-Ecological Systems' Vulnerability, Resilience and Governance. Cham: Springer International Publishing; 2019. p. 155–68.

146. Rahimi R, Tavakol-Davani H, Graves C, Gomez A, Fazel Valipour M. Compound Inundation Impacts of Coastal Climate Change: Sea-Level Rise, Groundwater Rise, and Coastal Precipitation. Water. 2020;12(10):2776.

147. Ryan BJ, Franklin RC, Burkle FM, Watt K, Aitken P, Smith EC, et al. Defining, Describing, and Categorizing Public Health Infrastructure Priorities for Tropical Cyclone, Flood, Storm, Tornado, and Tsunami-Related Disasters. Disaster Med Public Health Prep. 2016;10(4):598–610.

148. Schwerdtle P, Bowen K, McMichael C. The health impacts of climate-related migration. BMC Med. 2018;16(1):1.

149. Weir T, Dovey L, Orcherton D. Social and cultural issues raised by climate change in Pacific Island countries: an overview. Reg Environ Change. 2017;17(4):1017–28.

150. Gotham KF, Campanella R, Lauve-Moon K, Powers B. Hazard Experience, Geophysical

Vulnerability, and Flood Risk Perceptions in a Postdisaster City, the Case of New Orleans. Risk Anal. 2018;38(2):345–56.

151. Hardy RD, Milligan RA, Heynen N. Racial coastal formation: The environmental injustice of colorblind adaptation planning for sea-level rise. Geoforum. 2017;87:62–72.

152. Senapati S, Gupta V. Socio-economic vulnerability due to climate change: Deriving indicators for fishing communities in Mumbai. Mar Policy. 2017;76:90–7.

153. Guillotreau P, Campling L, Robinson J. Vulnerability of small island fishery economies to climate and institutional changes. Curr Opin Environ Sustain. 2012;4(3):287–91.

154. Lauria V, Das I, Hazra S, Cazcarro I, Arto I, Kay S, et al. Importance of fisheries for food security across three climate change vulnerable deltas. Sci Total Environ. 2018;640–641:1566–77.

155. Marushka L, Kenny TA, Batal M, Cheung WWL, Fediuk K, Golden CD, et al. Potential impacts of climate-related decline of seafood harvest on nutritional status of coastal First Nations in British Columbia, Canada. PLOS ONE. 2019;14(2):e0211473.

156. Bunce M, Brown K, Rosendo S. Policy misfits, climate change and cross-scale vulnerability in coastal Africa: how development projects undermine resilience. Environ Sci Policy. 2010;13(6):485–97.

157. Sovacool BK. Bamboo Beating Bandits: Conflict, Inequality, and Vulnerability in the Political Ecology of Climate Change Adaptation in Bangladesh. World Dev. 2018;102:183–94.

158. Asch R, Cheung W, Reygondeau G. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. Mar Policy. 2017;88.

159. Ford JD, Clark D, Pearce T, Berrang-Ford L, Copland L, Dawson J, et al. Changing access to ice, land and water in Arctic communities. Nat Clim Change. 2019;9(4):335.

160. Holbrook NJ, Hernaman V, Koshiba S, Lako J, Kajtar JB, Amosa P, et al. Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. Glob Planet Change. 2021;103680.

161. Lam VWY, Cheung WWL, Sumaila UR. Marine capture fisheries in the Arctic: winners

or losers under climate change and ocean acidification? Fish Fish. 2016;17(2):335–57.

162. Golden CD, Allison EH, Cheung WWL, Dey MM, Halpern BS, McCauley DJ, et al. Nutrition: Fall in fish catch threatens human health. Nature. 2016;534(7607):317–20.

163. Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLOS ONE. 2015;10(3):e0118571.

164. Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, et al. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change; 2019. p. 126.

165. Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, Olivier JGJ, et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environ Res Lett. 2021;16(7):073005.

166. Fromentin JM, Emery MR, Donaldson J, Danner MC, Hallosserie A, Kieling D, et al. Summary for policymakers of the thematic assessment of the sustainable use of wild species of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). IPBES secretariat, Bonn, Germany: Intergovernmental Science; 2022.

167. Bell JD, Watson RA, Ye Y. Global fishing capacity and fishing effort from 1950 to 2012. Fish Fish. 2017;18(3):489–505.

168. Pauly D, Zeller D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat Commun. 2016;7(1):10244.

169. Gopal N, Hapke HM, Kusakabe K, Rajaratnam S, Williams MJ. Expanding the horizons for women in fisheries and aquaculture. Gend Technol Dev. 2020;24(1):1–9.

170. Harper S, Grubb C, Stiles M, Sumaila UR. Contributions by Women to Fisheries Economies: Insights from Five Maritime Countries. Coast Manag. 2017;1–16.

171. Harper S, Zeller D, Hauzer M, Pauly D, Sumaila UR. Women and fisheries: Contribution to food security and local economies. Mar Policy. 2013;39:56–63.

172. Sall A. Diambari Sine: Women's fish processing organization leads the resistance against industrial fisheries and fishmeal factories in Senegal. The Ocean Defenders

Project. 2024. Available from: https://oceandefendersproject.org/case-study/diambari-sine-womens-fish-organization/

173. Hicks CC, Cohen PJ, Graham NAJ, Nash KL, Allison EH, D'Lima C, et al. Harnessing global fisheries to tackle micronutrient deficiencies. Nature. 2019;574(7776):95–8.

174. Zeller D, Pauly D. Viewpoint: Back to the future for fisheries, where will we choose to go? Glob Sustain. 2019;2.

175. Daniels A, Gutierrez M, Fanjul G, Guerena A, Matheson I, Watkins K. Western Africa's Missing Fish: The impact of illegal, unreported and unregulated fishing and under-reporting catches by foreign fleets. London, UK: Overseas Development Institute; 2016.

176. Watkins K. Grain, fish money: financing Africa's green and blue revolutions: Africa Progress Report 2014. Geneva: Africa Progress Panel; 2014.

177. Barbier EB. Marine ecosystem services. Curr Biol. 2017;27(11):R507–10.

178. Dunic JC, Brown CJ, Connolly RM, Turschwell MP, Côté IM. Long-term declines and recovery of meadow area across the world's seagrass bioregions. Glob Change Biol. 2021;27(17):4096–109.

179. Romañach SS, DeAngelis DL, Koh HL, Li Y, Teh SY, Raja Barizan RS, et al. Conservation and restoration of mangroves: Global status, perspectives, and prognosis. Ocean Coast Manag. 2018;154:72–82.

180. IPBES. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). Bonn, Germany: IPBES secretariat; 2019.

181. IPBES. Summary for Policymakers of the thematic assessment of the underlying causes of biodiversity loss and the determinants of transformative change and options for achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E., Frantzeskaki, N., Gosnell, H., Gurung, J., Lambertucci, S., Leventon, J., Liao, C., Reyes García, V., Shannon, L., Villasante, S., Wickson, F., Zinngrebe, Y., and Perianin, L. (editors). Bonn, Germany: IPBES secretariat; 2024.

182. Barbier EB, Hacker SD, Kennedy C, Koch EW, Stier AC, Silliman BR. The value of estuarine and coastal ecosystem services. Ecol Monogr. 2011;81(2):169–93.

183. Cisneros-Montemayor AM, Pauly D, Weatherdon LV, Ota Y. A Global Estimate of Seafood Consumption by Coastal Indigenous Peoples. PLOS ONE. 2016;11(12):e0166681.

184. Costanza R. The ecological, economic, and social importance of the oceans. Ecol Econ. 1999;31(2):199–213.

185. Islam MM, Pal S, Hossain MM, Mozumder MMH, Schneider P. Coastal Ecosystem Services, Social Equity, and Blue Growth: A Case Study from South-Eastern Bangladesh. Journal of Marine Science and Engineering. 2020;8.

186. Woodhead AJ, Hicks CC, Norström AV, Williams GJ, Graham NAJ. Coral reef ecosystem services in the Anthropocene. Funct Ecol. 2019;33(6):1023–34.

187. Cullen-Unsworth LC, Nordlund LM, Paddock J, Baker S, McKenzie LJ, Unsworth RKF. Seagrass meadows globally as a coupled social–ecological system: Implications for human wellbeing. Mar Pollut Bull. 2014;83(2):387–97.

188. Loseto LL, Hoover C, Ostertag S, Whalen D, Pearce T, Paulic J, et al. Beluga whales (Delphinapterus leucas), environmental change and marine protected areas in the Western Canadian Arctic. Estuar Coast Shelf Sci. 2018;212:128–37.

189. Hughes S, Yau A, Max L, Petrovic N, Davenport F, Marshall M, et al. A framework to assess national level vulnerability from the perspective of food security: The case of coral reef fisheries. Environ Sci Policy. 2012;23:95–108.

190. Chaplin-Kramer R, Sharp RP, Weil C, Bennett EM, Pascual U, Arkema KK, et al. Global modeling of nature's contributions to people. Science. 2019;366(6462):255–8.

191. Blythe JL, Gill DA, Claudet J, Bennett NJ, Gurney GG, Baggio JA, et al. Blue justice: a review of emerging scholarship and resistance movements. Camb Prisms Coast Futur. 2023;1(e15):1–12.

192. Bennett NJ, Alava JJ, Ferguson CE, Blythe J, Morgera E, Boyd D, et al. Environmental (in)justice in the Anthropocene ocean. Mar Policy. 2023 Jan 1;147:105383.

193. United Nations. The Universal Declaration of Human Rights. United Nations; 1948.

194. United Nations. International Covenant on Economic, Social and Cultural Rights. New York: United Nations; 1966.

195. United Nations. International Covenant on Civil and Political Rights. New York: United Nations; 1976.

196. United Nations. International Convention on the Elimination of All Forms of Racial Discrimination. New York: United Nations; 1965.

197. United Nations. Convention on the Elimination of All Forms of Discrimination against Women (CEDAW). New York: United Nations General Assembly; 1979.

198. United Nations. Convention on the Rights of the Child. New York: United Nations; 1989.

199. United Nations. Convention on the Rights of Persons with Disabilities. New York: United Nations General Assembly; 2006.

200. UN Human Rights Council. United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas (UN Doc. A/HRC/RES/39/12). Geneva, Switzerland: United Nations; 2018.

201. United Nations. United Nations Declaration on the Rights of Indigenous Peoples. Washington, DC: United Nations; 2007.

202. United Nations. The Human Right to a Clean, Healthy and Sustainable Environment (UN Doc. A/RES/76/300). New York, NY: United Nations; 2022.

203. UN OHCHR. International Convention on the Protection of the Rights of All Migrant Workers and Members of Their Families. Geneva, Switzerland: United Nations Office of the High Commissioner on Human Rights; 1990.

204. ILO. Convention C188 - Work in Fishing Convention, 2007 (No. 188). Geneva, Switzerland: International Labour Organization; 2007.

205. FAO. Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication. Rome: Food and Agriculture Organization of the United Nations; 2015.

206. FAO. Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security. Rome: Food and Agriculture

Organization of the United Nations; 2012.

207. Barnes RA, Bogojevic S, Rayfuse R, editors. Environmental Rights in Marine Spaces. In: Environmental Rights in Europe and Beyond. Bloomsbury Publishing; 2018.

208. Urbina I. The Outlaw Ocean: Journeys Across the Last Untamed Frontier. Knopf Doubleday Publishing Group; 2019.

209. EJF. Sold to the Sea: Human Trafficking in Thailand's Fishing Industry. London, UK: Environmental Justice Foundation; 2013.

210. ILO. Caught at Sea: Forced Labour and Trafficking in Fisheries. Geneva, Switzerland: International Labour Organization; 2013.

211. Levitt T. Our love of cheap seafood is tainted by slavery: how can it be fixed? The Guardian. 2016 Oct 7.

212. Lawrance F, McSweeney E, Kelly A, Heywood M, Susman M, Kelly C, et al. Revealed: trafficked migrant workers abused in Irish fishing industry. The Guardian. 2015 Nov 2 .

213. Marschke M, Vandergeest P. Slavery scandals: Unpacking labour challenges and policy responses within the off-shore fisheries sector. Mar Policy. 2016;68:39–46.

214. ILO. Forced Labour and Human Trafficking in Fisheries. Geneva, Switzerland: International Labour Organization; 2013.

215. Belhabib D, Le Billon P. Fish crimes in the global oceans. Sci Adv. 2022;8(12):eabj1927.

216. Witbooi E, Ali KD, Santosa MA, Hurley G, Husein Y, Maharaj S, et al. Organised Crime in the Fisheries Sector. In: Lubchenco J, Haugan PM, editors. The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy. Cham: Springer International Publishing; 2023. p. 593–617.

217. Haas B, Azmi K, Ziyad A, Rambourg C, Tessnow-von Wysocki I. Bula from Fiji – the 21st Annual Meeting of the Western and Central Pacific Fisheries Commission - Ocean Equity Research. Ocean Equity Research. 2024. Available from: https://oceanequityresearch.org/news/bula-from-fiji-the-21st-annual-meeting-of-the-wcpfc/

218. Nakamura K, Bishop L, Ward T, Pramod G, Thomson DC, Tungpuchayakul P, et al.

Seeing slavery in seafood supply chains. Sci Adv. 2018;4(7):e1701833.

219. Manyungwa CL, Hara MM, Chimatiro SK. Women's engagement in and outcomes from small-scale fisheries value chains in Malawi: effects of social relations. Marit Stud. 2019;18(3):275–85.

220. Lowen M. Kenya's battle to end "sex for fish" trade. BBC News. 2014 Feb 17; Available from: https://www.bbc.com/news/world-africa-26186194

221. Mangubhai S, Barclay KM, Lawless S, Makhoul N. Gender-based violence: Relevance for fisheries practitioners. Fish Fish. 2023;24(4):582–94.

222. Nathenson P, Slater S, Higdon P, Aldinger C, Ostheimer E. No sex for fish: empowering women to promote health and economic opportunity in a localized place in Kenya. Health Promot Int. 2017;32(5):800–7.

223. Yadao-Evans W, Kauhiona DB. Reflections on gender, fisheries and managing the environment: Solomon Islands case study. Women Fish Inf Bull. 2019;30:10–9.

224. Finkbeiner EM, Fitzpatrick J, Yadao-Evans W. A call for protection of women's rights and economic, social, cultural (ESC) rights in seafood value chains. Mar Policy. 2021;128:104482.

225. Allison E, Åsgård B, Willmann R. Human rights approaches to governing fisheries. Marit Stud. 2011;10:5–13.

226. Sharma C. Securing economic, social and cultural rights of small-scale and artisanal fisherworkers and fishing communities. Marit Stud. 2011;10(2):41–61.

227. Aheto DW, Okyere I, Asare NK, Eshilley J, Odoi JO. Fish species transshipped at sea (Saiko fish) in Ghana with a note on implications for marine conservation. 2020. Available from: https://www.researchsquare.com/article/rs-41329/v1

228. EJF. Stolen at Sea: How illegal 'saiko' fishing is fuelling the collapse of Ghana's fisheries. Environmental Justice Foundation; 2019.

229. Simmons AM. Chinese Fishing Practices and Their Global Implications. In: OCEANS 2023 - MTS/IEEE US Gulf Coast. Biloxi, MS, USA: IEEE; 2023. p. 1–11.

230. FAO. Small-scale fisheries and the human right to adequate food. Rome, Italy: FAO; 2021.

231. Ratner BD, Åsgård B, Allison EH. Fishing for justice: Human rights, development, and fisheries sector reform. Glob Environ Change. 2014;27:120–30.

232. Cohen PJ, Allison EH, Andrew NL, Cinner J, Evans LS, Fabinyi M, et al. Securing a Just Space for Small-Scale Fisheries in the Blue Economy. Front Mar Sci. 2019;6.

233. Galappaththi M, Armitage D, Collins AM. Women's experiences in influencing and shaping small-scale fisheries governance. Fish Fish. 2022;23(5):1099–120.

234. Mbatha P. Unravelling the perpetuated marginalization of customary livelihoods on the coast by plural and multi-level conservation governance systems. Mar Policy. 2022;143:105143.

235. Satizábal P. The unintended consequences of 'responsible fishing' for small-scale fisheries: Lessons from the Pacific coast of Colombia. Mar Policy. 2018;89:50–7.

236. Song AM, Scholtens J, Barclay K, Bush SR, Fabinyi M, Adhuri DS, et al. Collateral damage? Small-scale fisheries in the global fight against IUU fishing. Fish Fish. 2020;21(4):831–43.

237. Fuentes AR, Bansal T, Núñez FP. The Salmon Industry and Human Rights in Chile: Sector-Wide Impact Assessment. Santiago, Chile and Copenhagen, Denmark: Instituto Nacional de Derechos Humanos and Danish Institute for Human Rights; 2021.

238. Cashion T, Le Manach F, Zeller D, Pauly D. Most fish destined for fishmeal production are food-grade fish. Fish Fish. 2017;18(5):837–44.

239. Jobe FH. Fishmeal Production and the Dispossession of Women in The Gambia. Fem Afr. 2023;4(1):43–73.

240. Koigi B. China fishmeal factory a threat to Gambia's coastal communities. Fair Planet. 2019. Available from: https://www.fairplanet.org/story/china-fishmeal-factory-a-threat-to-gambia%e2%80%99s-coastal-communities/

241. Narchi NE, Moura GGM, Leddy G. Blue Economies and Ocean Grabbing in Latin America. Lat Am Perspect. 2024 Sep 28;0094582X241283774.

242. Barbesgaard M. Blue growth: saviour or ocean grabbing? 2018;45(1):130-149.

243. Franz T, Gómez D, Idrobo CJ, Corzo O. Development and Well-being: Maritime

Infrastructure and Ocean Grabbing on the Colombian Pacific Coast. Lat Am Perspect. 2024;51(3):232–48.

244. Owusu V, Lawer ET, Adjei M, Ogbe M. Impact of offshore petroleum extraction and "ocean grabbing" on small-scale fisheries and coastal livelihoods in Ghana. Marit Stud. 2023;22(2):17.

245. Silva HJH da, Pierri N. Mariculture Policies and Ocean Grabbing in Brazil. Lat Am Perspect. 2024;51(3):151–68.

246. Mesmain M. Ocean Grabbing: Plundering a Common Resource. In: Wilson HW, editor. US national debate topic, 2014-2015 The ocean. (The Reference Shelf; vol. 86 (3)). Amenia, NY: Grey House Publishing; 2014.

247. Bavinck M, Berkes F, Charles A, Dias ACE, Doubleday N, Nayak P, et al. The impact of coastal grabbing on community conservation – a global reconnaissance. Marit Stud. 2017;16(1):8.

248. Contested Ports. Contested Ports. 2020. People, ports and power. Available from: https://www.contestedports.com

249. Lawer ET. Examining stakeholder participation and conflicts associated with large scale infrastructure projects: the case of Tema port expansion project, Ghana. Marit Policy Manag. 2019;46(6):735–56.

250. Okafor-Yarwood I, Kadagi NI, Miranda NAF, Uku J, Elegbede IO, Adewumi IJ. The Blue Economy–Cultural Livelihood–Ecosystem Conservation Triangle: The African Experience. Front Mar Sci. 2020;7.

251. Bennett NJ, Le Billon P, Belhabib D, Satizábal P. Local marine stewardship and ocean defenders. Npj Ocean Sustain. 2022;1(1):3.

252. The Ocean Defenders Project. Ocean Defenders: Protectors of Our Ocean Environment and Human Rights. Vancouver, Canada: The Peopled Seas Initiative; 2025.

253. UN OHCHR. Key Human Rights Considerations on the Impact of Seabed Mining. United Nations Office of the High Commissioner on Human Rights; 2023.

254. UN. United Nations Convention on the Law of the Sea (UNCLOS). New York: United Nations; 1982.

255. Puentes Riaño A. The ocean and human rights - Report of the Special Rapporteur on the human right to a clean, healthy and sustainable environment, Astrid Puentes Riaño (UN Doc. A/HRC/58/59). Geneva, Switzerland: United Nations Human Rights Council; 2024.

256. Galaz FP. The complex energy transition of Chile's "sacrifice zones". Dialogue Earth. 2021. Available from: https://dialogue.earth/en/pollution/42193-the-complex-energy-transition-of-chiles-sacrifice-zones/

257. Panez A, Bolados P, Espinoza Almonacid L, Jerez B. Sacrifice Zones and Socio-environmental Recovery in Chile: Failures and opportunities of the environmental policy. Ambiente Soc. 2023;26.

258. Valenzuela-Fuentes K, Alarcón-Barrueto E, Torres-Salinas R. From Resistance to Creation: Socio-Environmental Activism in Chile's "Sacrifice Zones." Sustainability. 2021;13(6):3481.

259. O'Meara N. Human Rights and the Global Plastics Treaty to Protect Health, Ocean Ecosystems and Our Climate. Int J Mar Coast Law. 2023;38(3):480–515.

260. Davide, Jr. J. Alfredo Tano and others v. Hon. Gov. Salvador P. Socrates and others. Supreme Court of the Philippines. Docket Number: G.R. No. 110249, PHSC 1472. 1997.

261. Vasquez DV. Walter Brenes Soto v. Instituto Costaricense de Pesca y Acuicultura, el Estado y el Sistema Nacional de Areas de Conservacion. Docket Number: 17-008322-1027-CA. Supreme Court of Costa Rica, First Chamber. 2023.

262. Nyamweya P, Ngugi J, Jaden PT, Mativo JM. Mohamed Ali Baadi and others v Attorney General & 11 others. Docket Number: eKLR High Court, Petition NO 22 OF 2012. High Court of Kenya at Nairobi. 2018.

263. Mbenenge JP. Sustaining the Wild Coast NPC and Others v Minister of Mineral Resources and Energy and Others. Docket Number: 3491/2021, ZAECMKHC 55; 2022 (6) SA 589 (ECMk). Eastern Cape High Court, Makhanda, South Africa. 2022.

264. Velasco, Jr. PJ. Concerned Citizens of Manila Bay v. Metropolitan Manila Development Authority and others. Docket Number: G.R. Nos. 171947-48. Supreme Court of the Philippines. 2008.

265. Agrawal A, Redford K. Conservation and displacement: An overview. Conserv Soc.

2009;7(1):1.

266. Brockington D, Igoe J, Schmidt-Soltau K. Conservation, human rights, and poverty reduction. Conserv Biol. 2006;20(1):250–2.

267. Brockington D, Igoe J. Eviction for Conservation: A Global Overview. Conserv Soc. 2006;4(3):424.

268. Chapin M. A Challenge to Conservationists. World Watch Magazine. 2004;17–31.

269. Springer J, Campese J, Painter M. Conservation and human rights: Key issues and contexts. Scoping Paper. Washington, DC: Conservation Initiative on Human Rights, WWF; 2011.

270. Tauli-Corpuz V. Report of the Special Rapporteur of the Human Rights Council on the rights of indigenous peoples (UN Doc. A/71/229). New York: United Nations General Assembly; 2016.

271. West P, Igoe J, Brockington D. Parks and peoples: The social impact of protected areas. Annu Rev Anthropol. 2006;35(1):251–77.

272. Smallhorn-West P, Allison E, Gurney G, Karnad D, Kretser H, Lobo AS, et al. Why human rights matter for marine conservation. Front Mar Sci. 2023;10:1089154.

273. Sowman M, Sunde J. Social impacts of marine protected areas in South Africa on coastal fishing communities. Ocean Coast Manag. 2018;157:168–79.

274. Sand PH. Fortress Conservation Trumps Human Rights? The “Marine Protected Area” in the Chagos Archipelago. J Environ Dev. 2012;21(1):36–9.

275. Cross H. Displacement, disempowerment and corruption: challenges at the interface of fisheries, management and conservation in the Bijagós Archipelago, Guinea-Bissau. Oryx. 2016;50(4):693–701.

276. Hill A. Blue grabbing: Reviewing marine conservation in Redang Island Marine Park, Malaysia. Geoforum. 2017;79(Supplement C):97–100.

277. Kamat VR. Dispossession and disenchantment: The micropolitics of marine conservation in southeastern Tanzania. Mar Policy. 2018;88:261–8.

278. CBD. Kunming-Montreal Global biodiversity framework. Montreal, Canada: Convention on Biological Diversity; 2022.

279. Ford-Learner N, Addison J, Smallhorn-West P. Conservation and human rights: The public commitments of international conservation organizations. Conserv Lett. 2024;17(4):e13035.

280. UN Human Rights Office of the High Commissioner. Guiding Principles on Business and Human Rights: Implementing the United Nations “Protect, Respect and Remedy” Framework. New York and Geneva: United Nations; 2011.

281. United Nations. Declaration on the Right and Responsibility of Individuals, Groups and Organs of Society to Promote and Protect Universally Recognized Human Rights and Fundamental Freedoms (UN Doc. A/RES/53/144). New York: United Nations; 1998.

282. Spalding AK, Grorud-Colvert K, Allison EH, Amon DJ, Collin R, de Vos A, et al. Engaging the tropical majority to make ocean governance and science more equitable and effective. Npj Ocean Sustain. 2023;2(1):1–4.

283. UNECE. Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters. Aarhus, Denmark: United Nations Economic Commission for Europe; 1998.

284. United Nations. Regional Agreement on Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean (Escazú Agreement). Escazú, Costa Rica: United Nations; 2018.

285. Haas B, Jaeckel A, Pouponneau A, Sacedon R, Singh GG, Cisneros-Montemayor AM. The use of influential power in ocean governance. Front Mar Sci. 2023;10:1045887.

286. Gosnell H, Reyes García V, Zinngrebe Y, Almeida Magris R, Benessaiah K, Bonilla-Moheno M, et al. IPBES Transformative Change Assessment: Chapter 5. Realizing a sustainable world for nature and people: transformative strategies, actions and roles for all. In: Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat; 2025.

287. UNESCO-IOC, UNESCO-LINKS. Engaging Indigenous Peoples and Local Communities, and Embracing Indigenous and Local Knowledge in Marine Spatial Planning, volume 2: good practices. Paris, France: UNESCO; 2024. Report No.: IOC Technical Series No. 189, Volume 2.

288. Strand M. Arts-based participatory research for more equitable ocean governance in South Africa. PhD Dissertation, Faculty of Business and Economic Sciences at the Nelson Mandela University. 2023.

289. Bennett NJ, Katz L, Yadao-Evans W, Ahmadia GN, Atkinson S, Ban NC, et al. Advancing social equity in and through marine conservation. Front Mar Sci. 2021;8:711538.

290. Flannery W, Healy N, Luna M. Exclusion and non-participation in Marine Spatial Planning. Mar Policy. 2018;88(Supplement C):32–40.

291. Rivers N, Strand M, Fernandes M, Metuge D, Lemahieu A, Nonyane CL, et al. Pathways to integrate Indigenous and local knowledge in ocean governance processes: Lessons from the Algoa Bay Project, South Africa. Front Mar Sci. 2023;9:1084674.

292. Short RE, Gelcich S, Little DC, Micheli F, Allison EH, Basurto X, et al. Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. Nat Food. 2021;2(9):733–41.

293. Gill DA, Blythe J, Bennett N, Evans L, Brown K, Turner RA, et al. Triple exposure: Reducing negative impacts of climate change, blue growth, and conservation on coastal communities. One Earth. 2023;6(2):118–30.

294. Peer N, Muhl EK, Janna J, Brown M, Zukulu S, Mbatha P. Community and Marine Conservation in South Africa: Are We Still Missing the Mark? Front Mar Sci. 2022;9:884442.

295. Jones R, Doubleday N, Bailey M, Paul K, Taylor F, Pulsifer P. 2 Status of Reconciliation and Indigenous Ocean Management in Canada. In: Sumaila UR, Armitage D, Bailey M, Cheung W, editors. Sea Change: Charting a Sustainable Future for Oceans in Canada. University of British Columbia Press; 2024. p. 14–42.

296. Cinner JE, McClanahan TR, MacNeil MA, Graham NAJ, Daw TM, Mukminin A, et al. Comanagement of coral reef social-ecological systems. Proc Natl Acad Sci. 2012;109(14):5219–22.

297. Gelcich S, Hughes TP, Olsson P, Folke C, Defeo O, Fernández M, et al. Navigating transformations in governance of Chilean marine coastal resources. Proc Natl Acad Sci. 2010;107(39):16794–9.

298. Gelcich S, Fernández M, Godoy N, Canepa A, Prado L, Castilla JC. Territorial User Rights for Fisheries as Ancillary Instruments for Marine Coastal Conservation in Chile.

Conserv Biol. 2012;26(6):1005–15.

299. Gelcich S, Reyes-Mendy F, Rios M. Early assessments of marine governance transformations: insights and recommendations for implementing new fisheries management regimes. Ecol Soc. 2019;24(1):12.

300. Fujita R, Epstein L, Battista W, Karr K, Higgins P, Landman J, et al. Scaling territorial use rights in fisheries (TURFs) in Belize. Bull Mar Sci. 2017;93(1):137–53.

301. Fujita R, Tourgee A, Carcamo R, Epstein L, Gedamke T, McDonald G, et al. Assessing and Managing Small-Scale Fisheries in Belize. In: Salas S, Barragán-Paladines MJ, Chuenpagdee R, editors. Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean. Cham: Springer International Publishing; 2019. p. 177–95.

302. López de la Lama R, Valdés-Velasquez A, Huicho L, Morales E, Rivera-Ch M. Exploring the building blocks of social capital in the Sechura Bay (Peru): Insights from Peruvian scallop (*Argopecten purpuratus*) aquaculture. Ocean Coast Manag. 2018;165:235–43.

303. Barceló M, Tengö M, Simonetti JA, Gelcich S. Exploring links between local knowledge, values and livelihoods in land-sea interface: insights on emerging tradeoffs and change in Southern Chile. Ecosyst People. 2024;20(1):2329562.

304. Sorice MG, Donlan CJ, Boyle KJ, Xu W, Gelcich S. Scaling participation in payments for ecosystem services programs. PLOS ONE. 2018;13(3):e0192211.

305. Estévez RA, Jerez G, Gelcich S. Assessing Procedural Justice in the Administration of Small-Scale Benthic Fisheries in Chile. Front Mar Sci. 2021;8:636120.

306. Norström AV, Cvitanovic C, Löf MF, West S, Wyborn C, Balvanera P, et al. Principles for knowledge co-production in sustainability research. Nat Sustain. 2020;3:182–90.

307. Bennett NJ, Whitty TS, Finkbeiner E, Pittman J, Bassett H, Gelcich S, et al. Environmental Stewardship: A Conceptual Review and Analytical Framework. Environ Manage. 2018;61(4): 597-614.

308. Bandura A. Exercise of Human Agency Through Collective Efficacy. Curr Dir Psychol Sci. 2000;9(3):75–8.

309. Lawless S, Cohen PJ, Mangubhai S, Kleiber D, Morrison TH. Gender equality is diluted in commitments made to small-scale fisheries. World Dev. 2021;140:105348.

310. Mangubhai S, Lawless S. Exploring gender inclusion in small-scale fisheries management and development in Melanesia. Mar Policy. 2021;123:104287.

311. Morgera E, Snow B, Strand M, Vadrot A, Langlet A, Rodríguez SR. Participation at BBNJ negotiations matters. One Ocean Hub & MARIPOLDATA. 2022. Available from: https://oneoceanhub.org/participation-at-bbnj-negotiations-matters/

312. Strand M, Morgera E, Ntona M, Kenny A, Sauer W, Lavelle J, et al. Policy Brief: Advancing participation in the conservation & sustainable use of marine biodiversity of areas beyond national jurisdiction (BBNJ). One Ocean Hub; 2022. Available from: https://oneoceanhub.org/wp-content/uploads/2022/08/Policy-brief_7_R1_BBNJ-_OOH.pdf

313. Sinan H, Andriamahefazafy M, Robertson K. David against Goliath? The rise of coastal states at the Indian Ocean Tuna commission. Front Mar Sci. 2022;9:983391.

314. Seto K, Galland GR, McDonald A, Abolhassani A, Azmi K, Sinan H, et al. Resource allocation in transboundary tuna fisheries: A global analysis. Ambio. 2021;50(1):242–59.

315. Seto K, Hanich Q. The Western and Central Pacific Fisheries Commission and the New Conservation and Management Measure for Tropical Tunas. Asia-Pac J Ocean Law Policy. 2018;3(1):146–51.

316. United Nations. Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA) (New York, 4 August 1995, in force 11 December 2001) 2167 UNTS 3. New York: United Nations General Assembly; 1995.

317. WCPFC. CMM 2013-06 - Conservation and Management Measure on the criteria for the consideration of conservation and management proposals | Monitoring and Evaluation. Western and Central Pacific Fisheries Commission; 2013. Available from: https://cmm.wcpfc.int/measure/cmm-2013-06

318. United Nations. Sustainable Development Goals. New York: United Nations; 2015.

319. Blasiak R, Dauriach A, Jouffray JB, Folke C, Österblom H, Bebbington J, et al. Evolving Perspectives of Stewardship in the Seafood Industry. Front Mar Sci. 2021;8:671837.

320. Österblom H, Bebbington J, Blasiak R, Sobkowiak M, Folke C. Transnational

Corporations, Biosphere Stewardship, and Sustainable Futures. Annu Rev Environ Resour. 2022;47(1).

321. Knox J. Report of the Special Rapporteur on the issue of human rights obligations relating to the enjoyment of a safe, clean, healthy and sustainable environment. Framework principles on human rights and the environment (UN Doc. A/HRC/37/59). New York, NY: United Nations General Assembly; 2018.

322. One Ocean Hub. Applying coherently the human rights-based approach to small-scale fisheries for achieving multiple Sustainable Development Goals. One Ocean Hub. 2023.

Section 5B

Chapter 6: Gender

Coordinating author: Leandra R. Gonçalves[1]

Lead authors: Ellen Johannesen[2], Elena Mengo[3], Renis Auma Ojwala[4], Luciana Yokoyama Xavier[5], Mina Ogbanga[6] , Momoko Kitada[4] and Luceni Hellebrandt[7]

[1] Federal University of São Paulo. Institute of Marine Sciences. goncalves.leandra@unifesp.br

[2] Norwegian Institute for Water Research, Denmark

[3] Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Lowestoft, NR33 0HT, UK

[4] World Maritime University, Fiskehamnsgatan 1, 211 18 Malmö, Sweden.

[5] University of São Paulo, Oceanographic Institute.

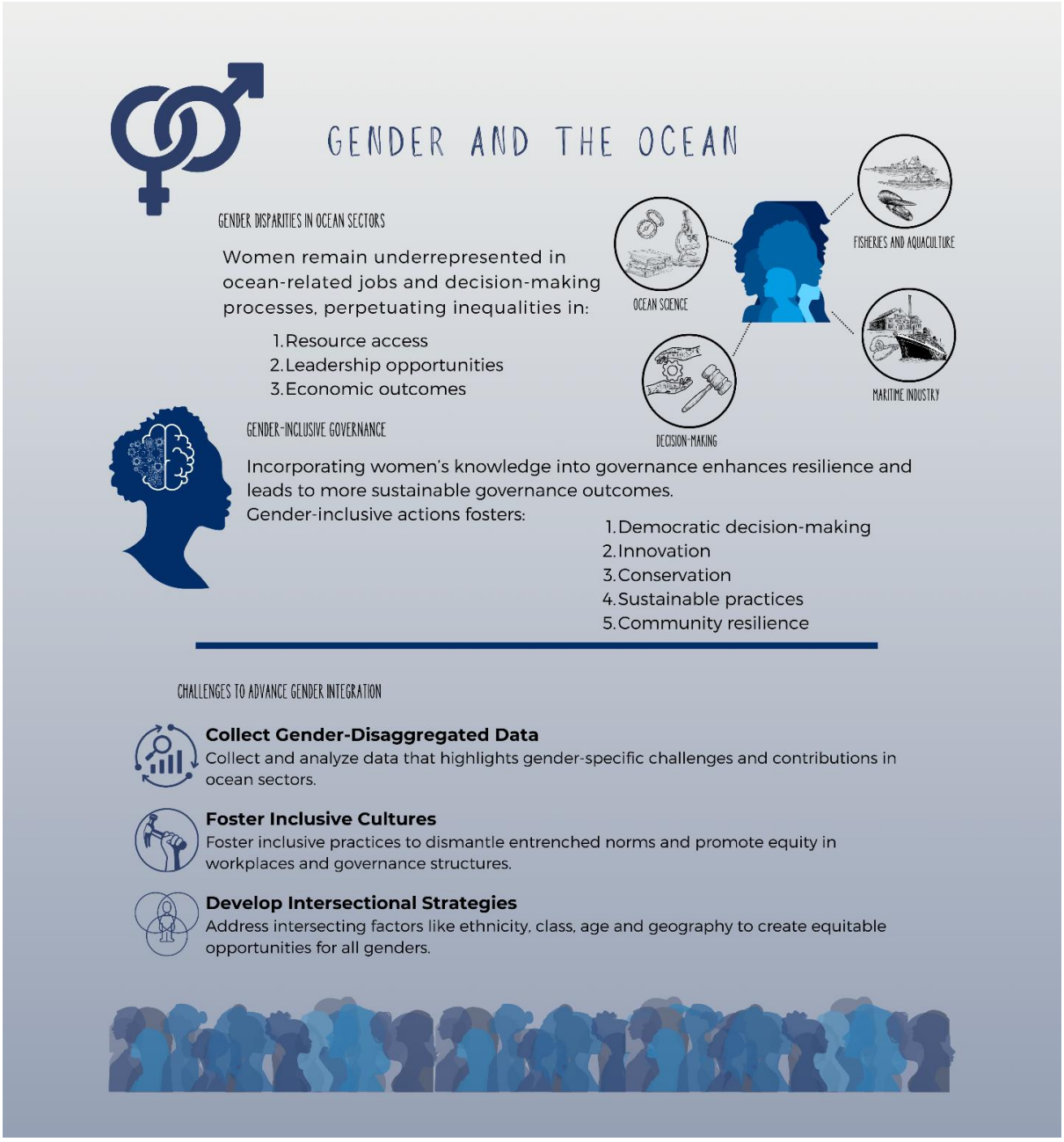
[6] Rivers State University. Port Harcourt. River State

[7] Federal University of Sergipe

Key findings:

- Gender Disparities Persist Across Ocean Sectors: Women remain underrepresented in ocean-related employment and decision-making processes. Traditional roles often restrict their participation in fisheries, aquaculture, maritime industry, and marine sciences, perpetuating inequalities in resource access, leadership opportunities, and economic outcomes (Crosman et al., 2022; Johannesen et al., 2022).
- Importance of Gender-Transformative Governance: Integrating gender perspectives into ocean governance enhances the resilience and effectiveness of conservation and management initiatives. Women's knowledge, particularly in small-scale fisheries and coastal communities, is an underutilized resource that can enrich governance frameworks and promote sustainable outcomes (Andrade et al., 2021; Torre-Castro et al., 2017) (See further at the S5A.C1b on Small-Scale Fishing including Subsistence Fishing).

- Advancements and Gaps in Gender Integration: Milestones such as the 2023 BBNJ Agreement demonstrate progress in recognizing gender in international frameworks. However, systemic challenges, including a lack of gender-disaggregated data and entrenched masculinized cultures, limit the implementation of gender-responsive policies (Kitada & Rodríguez-Chaves, 2024; Hornidge et al., 2023).
- Intersectional Approaches are Critical: Addressing gender issues in ocean governance requires intersectional strategies that consider how factors such as ethnicity, class, and geography intersect with gender. These approaches are vital for tackling systemic barriers and fostering equitable participation in ocean-related activities (Axelrod et al., 2022).
- Benefits of Gender-Transformative Conservation: Case studies show that gender-transformative approaches in marine conservation led to more gender-equitable decision-making and innovative strategies. Promoting women's leadership in ocean science and governance aligns with sustainable practices and strengthens community resilience (Giakoumi et al., 2021; Shellock et al., 2022).



I. Introduction

Gender plays a critical role in shaping ocean-related employment, activities, and governance. However, systemic disparities continue to limit equitable access and representation in these sectors. Women are often underrepresented in leadership positions and decision-making processes, while traditional gender roles restrict their

participation in fisheries, aquaculture, and marine sciences (Crosman et al., 2022; Johannesen et al., 2022). Addressing these inequities is essential for fostering sustainable and inclusive ocean governance (Bennet, 2022).

Achieving the Sustainable Development Goals (SDGs), particularly SDG 5 on gender equality, requires integrating gender considerations into ocean policies and frameworks. A gender-responsive approach not only supports social justice but also enhances the effectiveness of conservation and management initiatives by drawing on women's extensive, yet often underutilized, knowledge of marine ecosystems. This is especially relevant within small-scale fisheries and coastal communities (Andrade et al., 2021; Torre-Castro et al., 2017). Such an approach enriches governance systems, ensuring resilience and sustainability in the face of global challenges.

Despite this recognition, progress remains limited. Systematic collection of gender-disaggregated data is a critical gap that hampers the design of targeted interventions promoting equitable access and participation in ocean sectors (Kitada et al., 2023). Existing research at the gender-ocean nexus has predominantly focused on women's roles, often overlooking the impacts of masculinities and the entrenched masculinized cultures that exclude women and other marginalized groups (Milan & Nye, 2015; Hornidge et al., 2023). Addressing these dimensions is key to dismantling structural barriers and fostering inclusive policies.

Recent advancements, such as the inclusion of gender-responsive language in the 2023 BBNJ (Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement). Agreement, mark significant milestones for international ocean governance. This treaty, the first Law of the Sea instrument to explicitly address gender, acknowledges its cross-cutting importance in sustainable ocean management (Kitada & Rodríguez-Chaves, 2024). Such progress aligns with growing recognition that gender perspectives must be integrated into global frameworks to promote equity and inclusivity across sectors (Chapter 5, Section 5b explores the dimensions of equity further).

The intersection of gender with social, economic, and environmental dimensions further underscores the need for a comprehensive approach. Traditional gender roles have historically influenced interactions with marine environments, from fishing (Mangubahai et al., 2022) and aquaculture (Kruijissen et al., 2018) to governance and research (Crosman et al., 2022; Johannesen et al., 2022). International initiatives by organizations like UNESCO emphasize the need for structural changes to promote gender diversity in marine science and technology, recognizing its importance for fostering innovation and addressing global challenges (James et al., 2024).

This chapter focuses on the role of women within the context of ocean employment and activities, providing an in-depth examination of gender-responsive approaches in ocean governance. By connecting these discussions to the World Ocean Assessment, the chapter underscores the importance of gender-awareness and inclusive policies. Through case studies, it offers actionable insights for embedding gender equality within global ocean governance frameworks.

These three case studies were deliberately selected because each is supported by a prominent international organization that coordinates activities within its respective sphere, exemplifying how structured global collaboration can drive gender-responsive practices. While other sectors—such as offshore oil, gas, renewable energy, tourism, recreation, environmental protection, and coastal management—also play critical roles in the ocean economy, focusing on these cases allows for a concentrated exploration of coordinated international efforts in promoting gender equality.

II. Gender and the Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) of the 2030 Agenda build on the foundation of the Millennium Development Goals (MDGs), which provided a relevant framework for development and achieved significant progress in several areas. Although the MDGs were noted for a limited scope and relatively few indicators that led to uneven progress in some goals, the SDGs seek to complete what they did not achieve (A/RES/70/1). Grounded in frameworks such as the Beijing Declaration and Platform for Action (BPFA) and the Program of Action of the International Conference on Population and Development, the SDGs underscore that ocean and gender disparities often stem from discriminatory laws, beliefs, and practices (Odera & Mulusa, 2020). This foundation manifests in SDG 5, “Achieve gender equality and empower all women and girls,” and in the cross-cutting consideration of gender issues within other(Fukuda-Parr, 2016; Leal Filho et al., 2023). Gender equality is thus recognized as critical for economic, social, and environmental sustainability (United Nations, 2024), directly impacting the 2030 Agenda’s implementation .

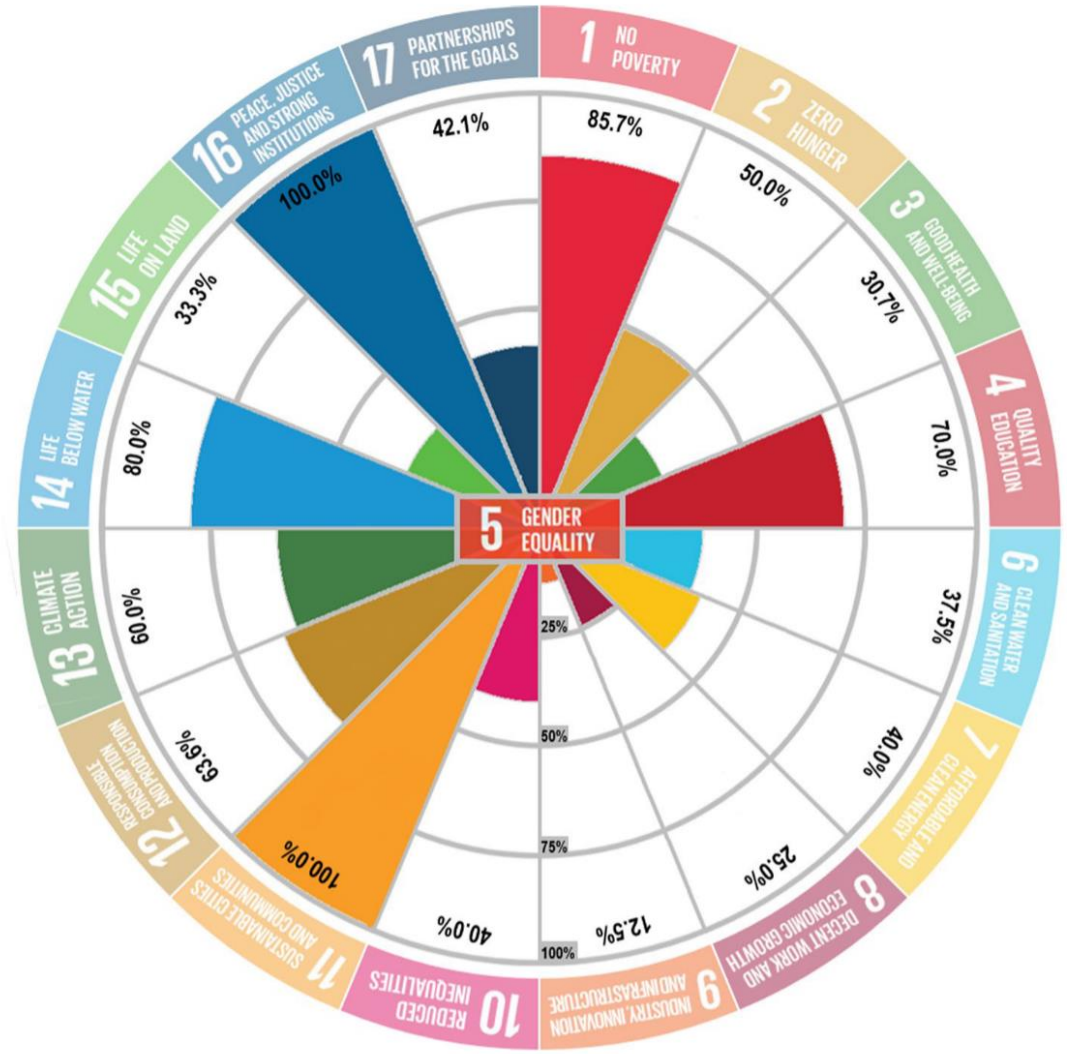


Figure 1. Percentage of gender inequality impact on SDG goals (Leal Filho et al., 2023).

Although SDG 14 does not explicitly address gender, the interdependence of the SDGs demands that gender considerations shape conservation and sustainable use of ocean resources (Breuer et al., 2019; International Council for Science, 2017). Despite limited integration, SDG 14 targets are significantly affected by gender disparities (Leal Filho et al., 2023). Intersecting SDGs 5 and 14 illuminates the importance of integrated approaches that enhance gender equality and advance sustainable ocean management (Singh et al., 2018).

SDG 5's targets address key barriers to gender equality by combating discrimination (5.1), violence (5.2), and harmful practices (5.3), while promoting sexual and reproductive health access (5.6), equal decision-making (5.5), and economic rights (5.a). In contrast, SDG 14 focuses on conserving marine ecosystems and resources, aiming to reduce

pollution (14.1), mitigate ocean acidification (14.3), and restore fish stocks (14.4), among other targets. Fisheries are essential to ocean economies and community resilience. Notably, SDG 14.7 emphasizes economic benefits from marine resources for small-scale fishers, which should explicitly support equitable access for women and other marginalized groups within the ocean economy (Silva et al, 2020).

. Women's involvement in ocean conservation is often underrecognized, despite their unique perspectives and roles in sustainable marine practices (Gissi et al., 2018; Shellock & Maltby, 2023). However, limited representation of women in decision-making jeopardizes progress toward sustainable ocean goals, reinforcing inequalities in resource access and policy influence (Baker-Médard, 2017). For instance, promoting sustainable fisheries requires gender-safe environments both on land and at sea, as well as policies that address women's economic barriers and ensure equal access to markets and marine resources (Becker-Weinberg, 2019).

Empowering women in ocean-related sectors also requires investment in capacity building, technological access, and research opportunities (Fitrianggraeni, 2019; Mahabir-Lee & Rambarath-Parasram, 2019). Engaging women in ocean science bolsters innovation for sustainable marine resource management, especially as women play key roles in community-based conservation and climate resilience initiatives (Loarne-Lemaire et al., 2021; Gicheru et al., 2024). Women working in grassroots organizations, for instance, often lead efforts to reduce marine pollution and educate communities, transforming gender norms and improving urban coastal conditions (Hanson, 2017).

Finally, increasing women's representation in international ocean conservation agreements is essential for fostering gender-responsive policies. Historically, ocean affairs have been male-dominated (Kitada et al., 2015), with slow but growing acknowledgment of women's roles. Expanding women's participation in ocean conservation and management, research, and policy development will not only advance SDG 5 but also accelerate progress in SDG 14, which is one of the SDGs with the lowest implementation rates (Sachs et al., 2024; UNDESA, 2024). Gender-responsive ocean policies and inclusive decision-making processes will be key in moving toward a more equitable and sustainable ocean future.

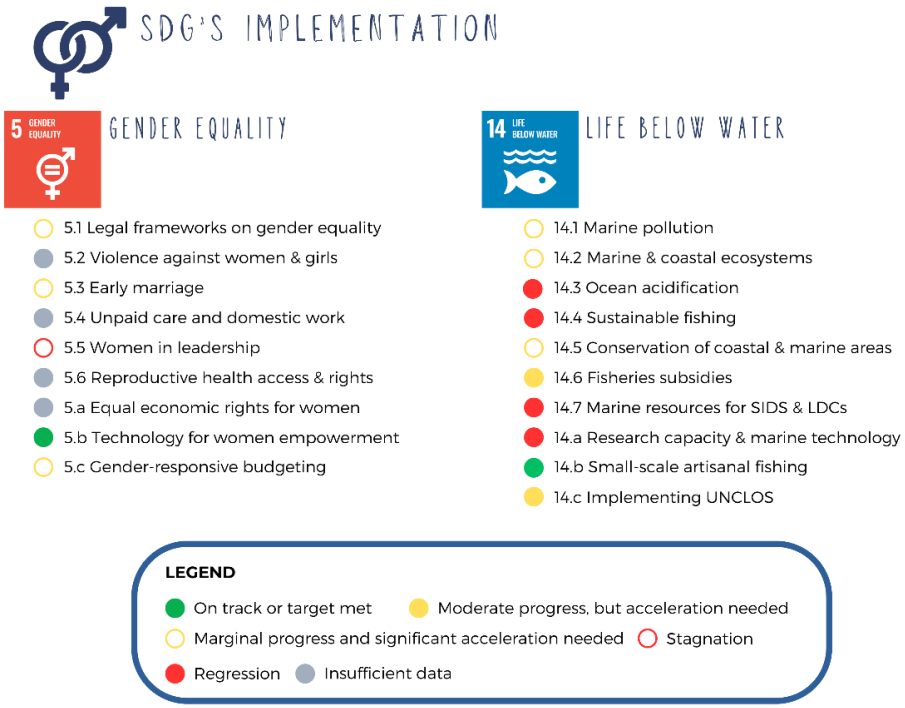


Figure 2: SDG implementation progress (Adapted from UNDESA 2024).

III. Gender Issues in Ocean Science

A. Overview of Existing Gender Disparities in Ocean Science and Governance

Gender equity in ocean science is not only an ethical imperative but also a means to improve the quality, relevance, and impact of the science itself (Nielsen, 2017). As ocean

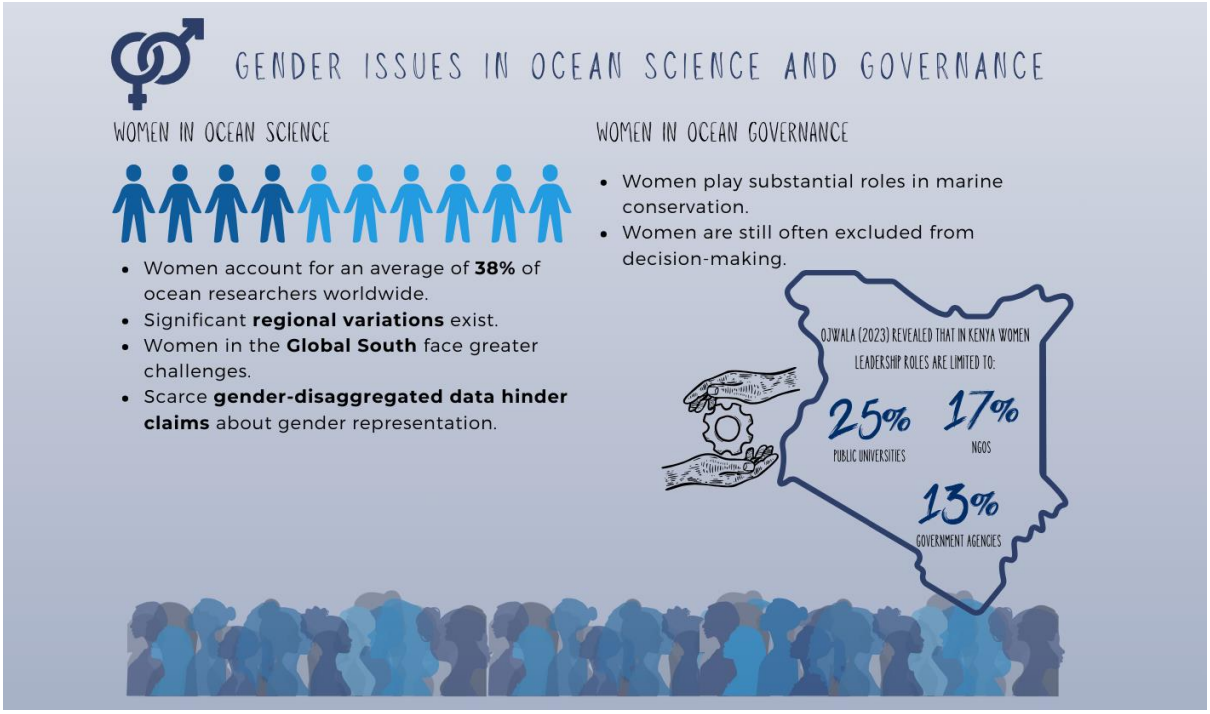
sciences tackle increasingly urgent global challenges, the full participation of diverse talent is required for producing the best possible research and policy advice. While evidence of gendered disparities in science demonstrates considerable progress of improvement overtime, women continue to face discrimination, unequal pay, and access to funding (Shen, 2013). .

Gendered disparities in representation across career stages reflect the persistent gender bias and multiple barriers women face in ocean science (Giakoumi et al., 2021; Brooks & Deniz-Gonzalez, 2021). In many areas, while gender balance has been achieved at the PhD student and recent graduate levels, women remain significantly underrepresented in higher-level academic and leadership positions. This pattern reflects the well-documented "leaky pipeline", a metaphor used to describe the under-representation of women at leadership levels of science and academia (Berryman, 1983; UNESCO, 2015).

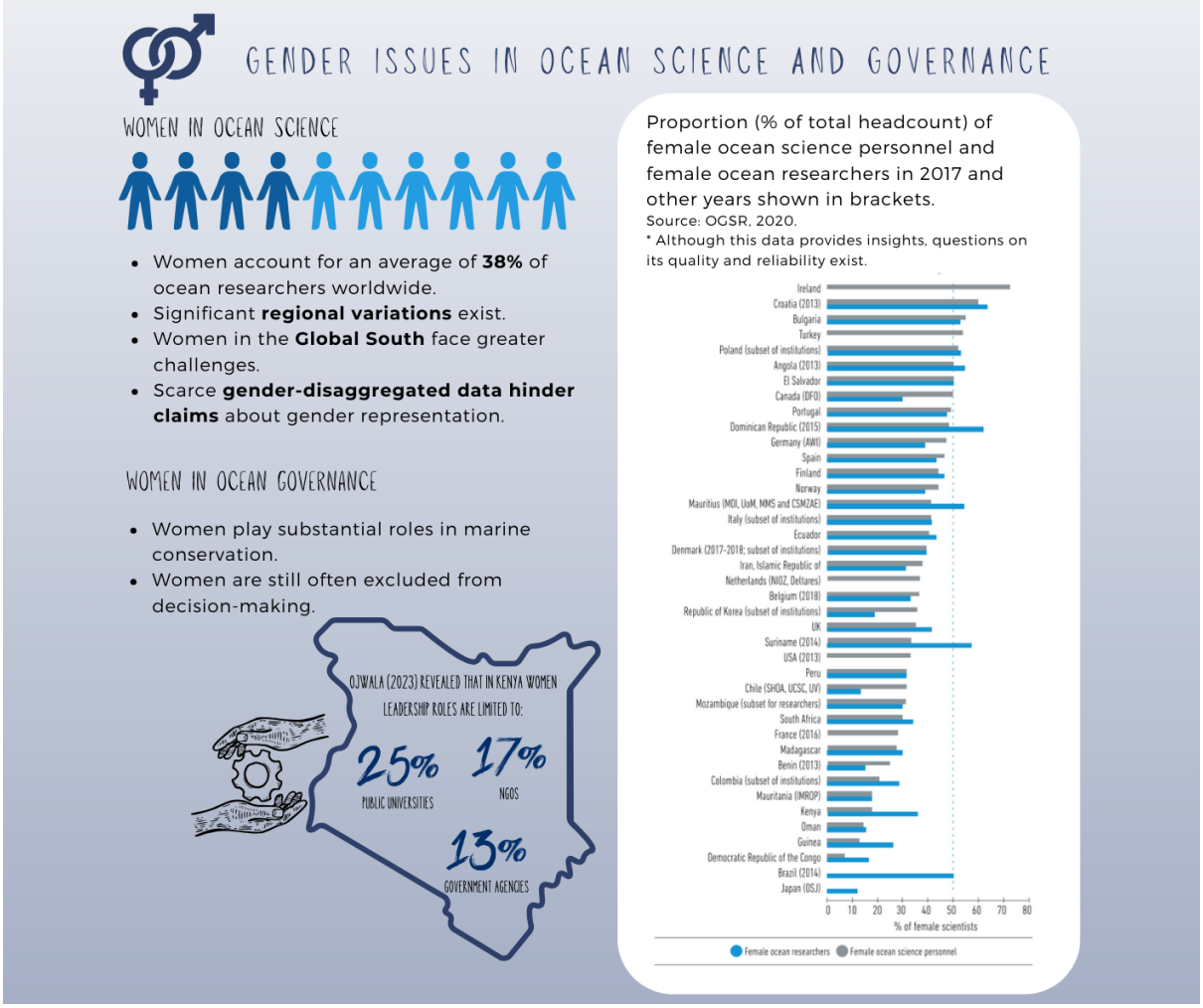
Women face a range of gendered challenges in marine science workplaces, including harassment, stereotyping and unequal distribution of power that require systemic, institutional, and network changes to address in order to create conditions that allow a greater diversity of leaders to advance to leadership roles (Shellock et al., 2022). Family-friendly institutional arrangements and gender neutral parental leave can help mothers and fathers from being penalized in their science career (Powell, 2021).

In ocean science, the best available data reports that women account for an average of 38% of ocean researchers worldwide, with significant regional variations—from 4% in Mauritania to 62% in Croatia (IOC-UNESCO, 2020). While the Global Ocean Science Report provides critical insights, data quality and reliability remain a challenge (Kitada et al., 2023; Ojwala, 2023). Johannesen (2024) highlights the lack of standardized, gender-disaggregated data, making global claims about gender representation difficult to validate.

Despite women's substantial roles in marine conservation and governance, they are often excluded from decision-making (Ojwala et al., 2022). For instance, data from Kenyan ocean science institutions reveal that women hold just 25% of leadership roles in public universities, 17% in NGOs, and 13% in government agencies (Ojwala, 2023). Ensuring gender equality is crucial for achieving the objectives of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), including integrating gender perspectives into ocean policies (IOC-UNESCO, 2020; Sun et al., 2021) (Fig 2).


GENDER ISSUES IN OCEAN SCIENCE AND GOVERNANCE
WOMEN IN OCEAN SCIENCE
Women account for an average of 38% of ocean researchers worldwide.
Significant regional variations exist.
Women in the Global South face greater challenges.
Scarce gender-disaggregated data hinder claims about gender representation.
WOMEN IN OCEAN GOVERNANCE
Women play substantial roles in marine conservation.
Women are still often excluded from decision-making.
OJWALA (2023) REVEALED THAT IN KENYA WOMEN LEADERSHIP ROLES ARE LIMITED TO:
25%
PUBLIC UNIVERSITIES
17%
NGOS
13%
GOVERNMENT AGENCIES

1



B. Challenges Faced by Women in Fieldwork

Fieldwork in ocean science often demands extended periods in remote environments, posing unique challenges for women. Traditional male-biased workplace norms, caregiving obligations, safety concerns, and physical demands related to ship design exacerbate these challenges (Johannesen et al., 2022). Sexual harassment remains pervasive, impacting women's professional and personal lives (St. Clair, 2021). Creating pathways for safe working environments is necessary for greater inclusion of a broader range of social identities in ocean science(Amon et al., 2022).

Implicit biases also perpetuate inequalities, influencing hiring, funding, and publication decisions (Calaza et al., 2021). For example, such biases create divides between knowledge systems, impeding collaborative efforts for ocean sustainability (Hägele & Hornidge, 2024). Addressing these biases is critical for fostering equity and inclusivity in the field (Chapter 5, Section 5b).

C. Initiatives and Policies Promoting Gender Equality in Ocean Science

Gender equality plans offer actionable steps for fostering inclusivity. In 2022, the European Union linked Horizon Europe research funding to gender equality plans, highlighting the importance of diversity in scientific teams. Similarly, the UN Ocean Decade's "Empowering Women for the UN Decade of Ocean Science" program has produced a high-level gender equality plan to guide organizations (Sun et al., 2022; Rodriguez-Chaves et al., 2024). However, evidence from Kenyan ocean science institutions suggests that plans alone are insufficient without systemic implementation (Ojwala et al., 2022; Johannesen, 2025).

Programs like Baltic Gender, Women in Ocean Science (WiOS), UN Ocean Decade's "Empowering Women," IHO's "Empowering Women in Hydrography," and the International Seabed Authority's S.H.E. mentoring program demonstrate regional and international efforts to enhance gender inclusivity. Mentorship programs, representation in outreach initiatives, and policies such as conference quotas and leadership targets contribute to fostering a more balanced ocean science community.

Developing gender-transformative policies not only promotes equal rights for women and men in terms of employment, professional development and working conditions but also ensures equal representation in leadership, decision-making, and research teams. This, in turn, improves resilience and sustainability in ocean governance (Ojwala et al., 2022). In contrast, gender-neutral policies -often termed 'gender-blind' - fail to advance true gender equality, as they assume that women and men face the same challenges, overlooking the unique barriers that hinder inclusivity and equity.

D. Integration of Gender Considerations into Ocean Science

Marine social science has increasingly addressed gender issues, highlighting power dynamics in sea-related practices. However, it largely focuses on gender roles rather than

how dominant systems in science, policy, and society are gendered (Pauwelussen & Lau, 2021). A systematic literature review reveals that Marine social science largely treats gender as an object of study, with limited focus on researcher positionality and knowledge production. Expanding to gender-as-subject and gender-as-epistemology fosters intersectional, reflexive approaches. A gender-as-political-project perspective strengthens ocean equity by addressing structural inequalities, power dynamics, and epistemological biases in marine research (Pauwelussen & Lau, 2021).Gender significantly influences access to and interaction with marine resources. In many regions of the Global South, gender-specific restrictions—such as taboos and traditional practices—affect resource use and management (Jones et al., 2008; Oloko et al., 2024). Gender analysis is needed for improving coastal management and informing marine spatial planning (de la Torre-Castro et al., 2017)Inclusive management strategies enhance socio-ecological outcomes, uphold human rights, and foster equitable governance systems (Bennet et al., 2021).

E. Challenges and Opportunities in Promoting Gender Equality

Promoting gender equity in traditionally male-dominated ocean science is essential for fostering diversity, innovation, and human rights (Shellock et al., 2022). Despite their contributions, women in these fields continue to face systemic barriers, including underrepresentation, isolation, stereotyping, and unsafe working environments (Shellock et al., 2022; Johannesen, 2025). For Black women and other women from minority groups, these challenges are further compounded by financial and structural obstacles that hinder their progress in ocean science programmes, from education through career advancement (Isma et al., 2023; Ojwala, 2024). High tuition costs, limited funding opportunities, limited access to career opportunities and wage disparities create significant roadblocks. A study by Isma et al. (2023) revealed that over 60% of Black women in ocean science in the US identified funding as a critical barrier to achieving their career goals. Additionally, more than 40% of surveyed individuals had to take unpaid internships, while over 90% worked multiple jobs to support themselves due to lower wages for women. These financial constraints combined with systemic discrimination and limited access to resources create an uneven playing field that prevents talented individuals from fully participating in and contributing to ocean science.

Women also hold a mere 13-24% of senior leadership positions in EU research institutions, with very few leading EU research institutes. In publication, women account for only 18-22% of authors in top journals, with a significant gap in senior authorship.

Funding data shows a larger success rate for women in early grants, but their representation drops significantly in advanced funding stages. (Giakoumi et al., 2021)

Addressing these disparities and challenges require international actions such as expanding funding opportunities, creating inclusive mentorship programs and dismantling structural biases. By breaking down these barriers, the ocean science community can harness the full potential of diverse perspectives, ultimately leading to more equitable and innovative solutions for marine challenges. Some effective strategies for advancing gender equality include:

- Establishing in-house gender officer roles to lead and coordinate gender mainstreaming efforts
- Implementing mandatory gender training to raise awareness.
- Increasing women's representation in decision-making forums.
- Enforcing inclusive workplace policies for work-life balance.
- Promoting STEM education for women and girls.
- Collecting gender-disaggregated data to address disparities and monitor progress.
- Providing financial and mentorship programs for women in non-traditional roles

(The Commonwealth Blue Charter, 2024).

The absence of comprehensive gender-disaggregated data hampers efforts to assess and address disparities in ocean science education, employment, and leadership (Ojwala, 2023; Johannesen et al., 2023). Such data is essential to understanding participation and contributions across genders, providing insights into gaps in access to resources and career progression (Ojwala et al., 2022). Policymakers can use these insights to promote inclusivity and equitable governance, ensuring ocean science efforts align with sustainability goals (Gissi et al., 2018).

Addressing data gaps will enable more inclusive decision-making, supporting global progress in women's representation within ocean science and governance frameworks.

As the Ocean Decade nears the halfway mark, UNESCO's Intergovernmental Oceanographic Commission (UNESCO-IOC) initiated the Vision 2030 process to refine the future direction of the Ocean Decade and further strengthen engagement and impact to

2030 and beyond. This process identified the need to 'continue to enhance diversity, inclusivity, and equity in the Ocean Decade, and systematically identify and remove barriers to generational, geographic, and gender diversity' (UNESCO-IOC, 2024, p. 24). An Ocean Decade Gender Working Group has been established to oversee development of a roadmap and action plan for enhancing gender equality in the Ocean Decade.

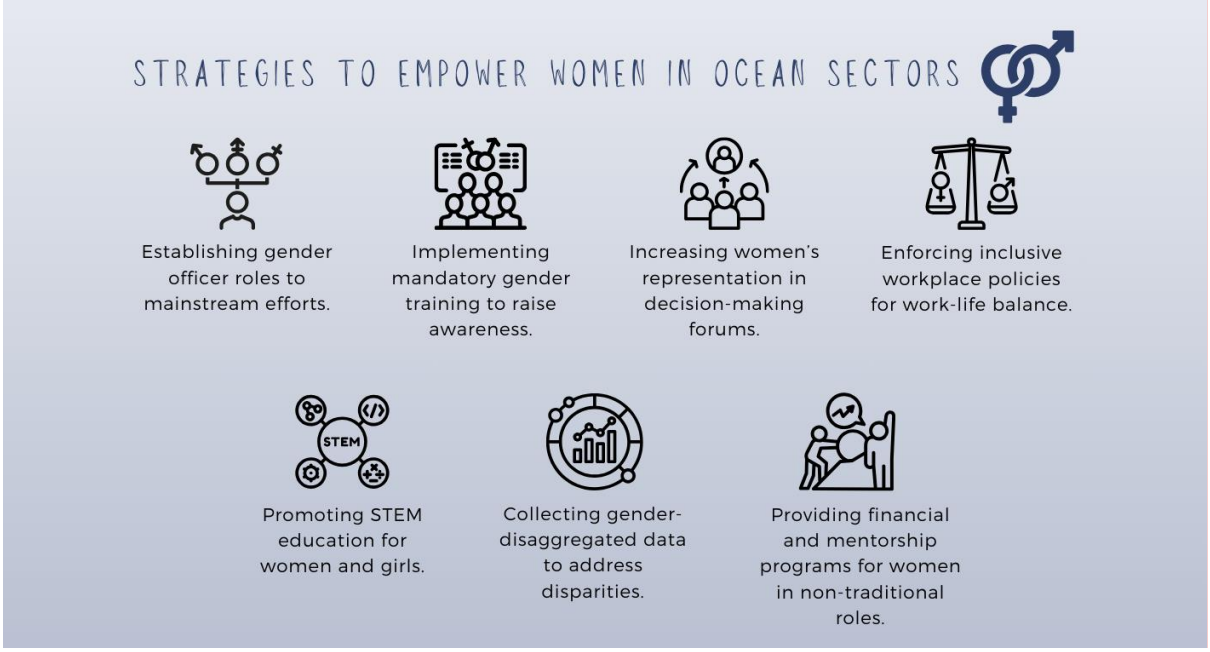


Fig. Source: The Commonwealth Blue Charter, 2024

IV. Incorporating a Gender Lens in Fisheries and Aquaculture

A. Overview of Gender Dynamics in Fisheries and Aquaculture

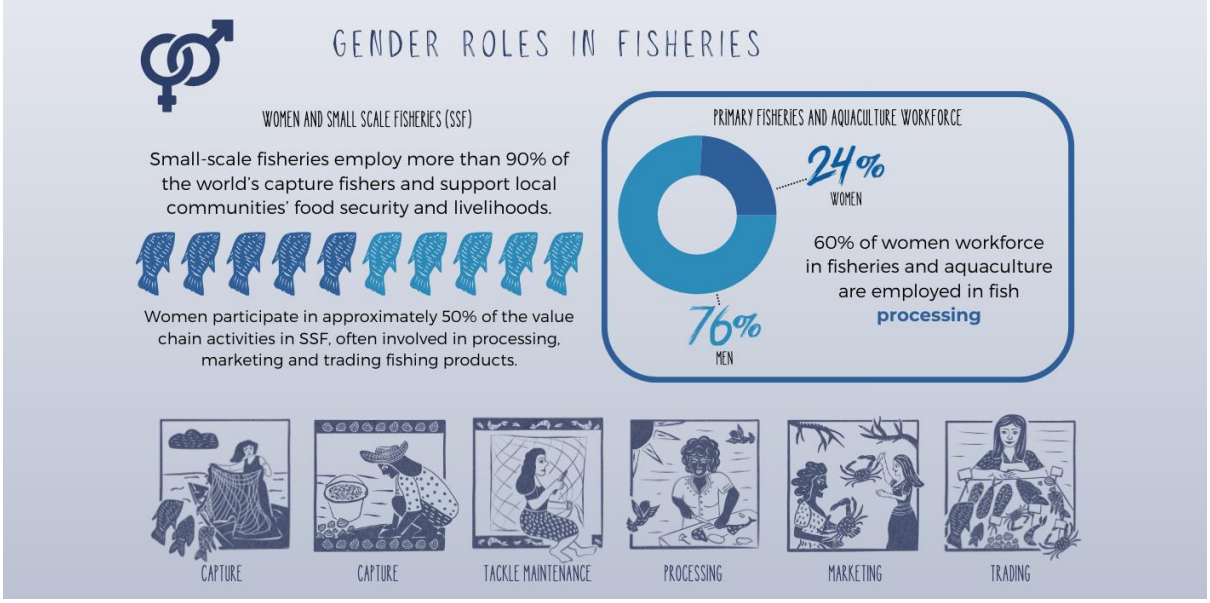
In 2022, approximately 62 million people were employed in the primary sectors of commercial fisheries and aquaculture, with women playing key roles across these "Blue" food sectors by participating in organizations, administration, consulting, and research (FAO, 2024; Frangoudes et al., 2020). These sectors are essential for nutrition, livelihoods, and food security in rural coastal communities (Quimby et al., 2023; Thomas et al., 2021; Weeratunge et al., 2010). Women are active throughout fisheries and aquaculture value chains, particularly in processing, trading, and marketing (Elias et al., 2024; Gopal et al., 2020). However, entrenched beliefs, norms, and regulatory practices often define which activities are "feminized" or "masculinized," reinforcing a rigid gender division of labor

(Kruijssen et al., 2018; Weeratunge et al., 2010). These dynamics highlight that power, equity, and equality within fisheries cannot be fully understood through a gender lens alone; intersecting social dimensions—such as age, class, ethnicity, ability, and marital status—also shape women's roles and access to opportunities (McDougall et al., 2021).

Gender equality is imperative for diversifying seafood value chains and achieving "blue justice" within the sector (McClenachan & Moulton, 2022). However, women's contributions are often underrepresented in data, with limited gender-disaggregated information restricting our understanding of their participation (Merayo, Vakhitova and Carlson, 2024). This lack of documentation marginalizes women and slows the development of gender-sensitive policies in fisheries and aquaculture, perpetuating inequality (Szymkowiak & Rhodes-Reese, 2020; Kruijssen et al., 2018).

B. Representation and Contributions of Women in Fisheries and Aquaculture

Gender roles in fisheries and aquaculture differ globally, influenced by cultural, economic, political, and ecological factors (Adam et al., 2024). Globally, women accounted for 24% of the primary fisheries and aquaculture workforce in 2022, with about 60% employed in fish processing (FAO, 2024). Women's roles are especially prominent in small-scale fisheries (SSF), where they participate in approximately 50% of value chain activities, often in roles related to processing, trading, and marketing (FAO, Duke University & WorldFish, 2023; Weeratunge et al., 2010). In aquaculture, women's involvement in production, processing, and marketing may surpass that in fisheries, contributing significantly to coastal community resilience (Kruijssen et al., 2018; Szaboova et al., 2022) (See further at the S5A.C1b on Small-Scale Fishing including Subsistence Fishing).



FigX:

Despite women's contributions to activities such as net-making, gear repair, and bait acquisition, traditional definitions of "fishing" typically exclude these pre-harvest roles, undervaluing their labor and contributions (FAO, Duke University & WorldFish, 2023). Men are more visible in data collection due to their engagement in offshore, boat-based fishing, while women's inshore activities, like gleaning for shellfish in intertidal zones, are less documented (Thomas et al., 2021; Weeratunge et al., 2010). This exclusion leads to an underestimation of fishing effort and catch volumes, affecting fisheries management decisions on local, national, and international levels (Kleiber et al., 2015).

C. Challenges Faced by Women in Fisheries and Aquaculture

Women in fisheries face challenges that vary across sectors and regions but often include limited recognition, lower wages, and unpaid labor (Elias et al., 2024). Women in SSF processing sectors frequently receive lower or no pay, as their work is perceived as an extension of household duties, such as cooking and cleaning (Merayo, Vakhitova and Carlson, 2024). Meanwhile, men dominate more lucrative fishing sectors, resulting in stark income disparities (Cho, 2024). In aquaculture, women are often relegated to less profitable tasks and receive lower pay for the same work, hindered by traditional gender norms that limit their economic roles (Kruijssen et al., 2018; St. Louis and Oliveira, 2022).

Access to resources remains a significant barrier, with women facing challenges in securing financial support, owning property, and participating in decision-making (Merayo, Vakhitova and Carlson, 2024). Limited access to financial instruments like loans prevents women from investing in essential equipment and land resources, further marginalizing them in fisheries and aquaculture (St. Louis and Oliveira, 2022). Traditional norms, such as those restricting asset inheritance or property ownership, also limit women's involvement and autonomy within these industries (Kruijssen et al., 2018) (Read it further on S5A.C1c Medium and Large-scale Aquaculture).

D. Gender-Specific Impacts of Overfishing and Environmental Changes

Climate-driven changes to marine ecosystems pose severe challenges for aquatic food systems, especially in low- and middle-income coastal areas (Cochrane et al., 2023; Mitra & Barua, 2023). Climate change affects fish availability and trade, disrupts local food security, and exposes coastal communities to heightened vulnerability from extreme weather events, often impacting women disproportionately (Nyasimi and Jakarasi,2024; Barange *et al.*, 2018). With fishing becoming increasingly dangerous, female fishers and

processors bear the brunt of the economic consequences, as their livelihoods depend heavily on fish harvests (Siles, 2019; Riviwanto & Basuki, 2019).

Gendered divisions of labor mean that men and women are exposed to different risks and stressors associated with climate change and overfishing. For example, when extreme weather prevents men from fishing, women who process and sell fish products may lose income sources, destabilizing entire households and communities (Shaffril et al., 2024; Carvalho et al., 2023).Similarly, overexploitation of fish resources, particularly in shallow coastal waters (Ding et al., 2017), affects female workers primarily engaged in the processing and trading sectors (FAO, Duke University & WorldFish, 2023) of low-profit fisheries (McClanahan and Abunge, 2017), resulting in livelihood losses and increased gendered food insecurity. Beyond economic hardship, unsustainable fisheries practices, such as overfishing, may also amplify the risk of sexual violence for female processors and traders (Nyasimi and Jakarasi, 2024)

E. Policies and Initiatives Promoting Gender Equality

Over the past decade, global fisheries policies have increasingly recognized the role of women and emphasized gender equality (Mangubhai & Lawless, 2021). The Voluntary Guidelines for Small-Scale Fisheries (SSF) by the FAO (2015) formally acknowledge the importance of gender mainstreaming for SSF development strategies. The Hidden Harvest initiative (FAO, Duke University & WorldFish, 2023) supports the implementation of SSF Guidelines, aiming to close the gender data gap by highlighting both men's and women's contributions (See further at the S5A.C1b on Small-Scale Fishing including Subsistence Fishing).

Despite these advances, fisheries policies often remain gender-blind in practice, with many practitioners lacking the training and knowledge necessary to implement gender-sensitive strategies (Mangubhai et al., 2022). Even in contexts with advanced fisheries policies, like Norway, the male-dominated ownership of fishing quotas underscores the need for additional gender-aware policies (Gerrard & Kleiber, 2019). Misunderstandings around gender equality also hinder implementation, as seen in Pacific tuna fisheries where perceived progress has not matched on-the-ground realities (Barclay et al., 2021).

In this context, mechanisms for scaling up successful gender-transformative initiatives and ensuring their integration into local governance frameworks would strengthen the link between policy and practice. Connecting female leadership to generational transition in this sector is essential.

F. Successful Examples of Integrating a Gender Lens in Fisheries Management

In many countries, women play a vital role in shellfish industries. For instance, in West Africa, women are integral to the harvesting, processing, and marketing of shellfish in estuarine and mangrove ecosystems (Chuku et al., 2022). The oyster fishery in Ghana's Densu Delta has seen declining populations due to overfishing and habitat loss. In response, USAID's Sustainable Fisheries Management Project (SFMP) partnered with the Development Action Association (DAA) and the Ghana Fisheries Commission to address the issue by establishing the Densu Estuary Women's Oyster Pickers Association (DOPA) (Agbekpornu et al., 2021; Torell et al., 2019).

DOPA's approximately 200 members work to restore oyster habitats and implement sustainable management practices. With training in leadership, oyster ecology, and water quality monitoring, these women have increased their skills, contributing to a more sustainable fishery (Chuku et al., 2022). The project's peer-to-peer learning programs have fostered greater confidence among participants, allowing DOPA's model to serve as a scalable example of community-driven, women-led fisheries co-management (Agbekpornu et al., 2021).

DOPA demonstrates how women's contributions to resource management can be harnessed for effective fisheries governance. By empowering fisherwomen in Ghana, the program has strengthened their roles as stewards of local biodiversity while promoting sustainable livelihoods. Initiatives like DOPA underscore the potential for similar models in other regions, where empowering women through training, leadership development, and community-based management can enhance the sustainability of fisheries and aquaculture (Torell et al., 2019; Women Shellfishers and Food Security Project, 2022).

V. Incorporating a Gender Lens in Maritime Industry

The maritime industry is a capital-intensive business which serves as an economic backbone for many countries. The industry relates to heavy infrastructures of ships and ports where women are under-represented. Amongst 1.9 million seafarers worldwide, women seafarers are estimated as 1.28% (BIMCO & ICS, 2021). In ports, women occupy management or administrative positions but they represent only 17 % in the overall port workforce according to UNCTAD (2022) which investigated 58 port entities in 2021. A survey conducted by the International Maritime Organization (IMO) and the Women's International Shipping & Trading Association (WISTA) revealed that 39% of women who

worked in companies are in mid-management, 28% in technical roles, and 48% in administrative and support roles In maritime authorities, women make up around 20% of the workforce (IMO & WISTA, 2021) (See it further on Section 5A, Chapter 6: Shipping).

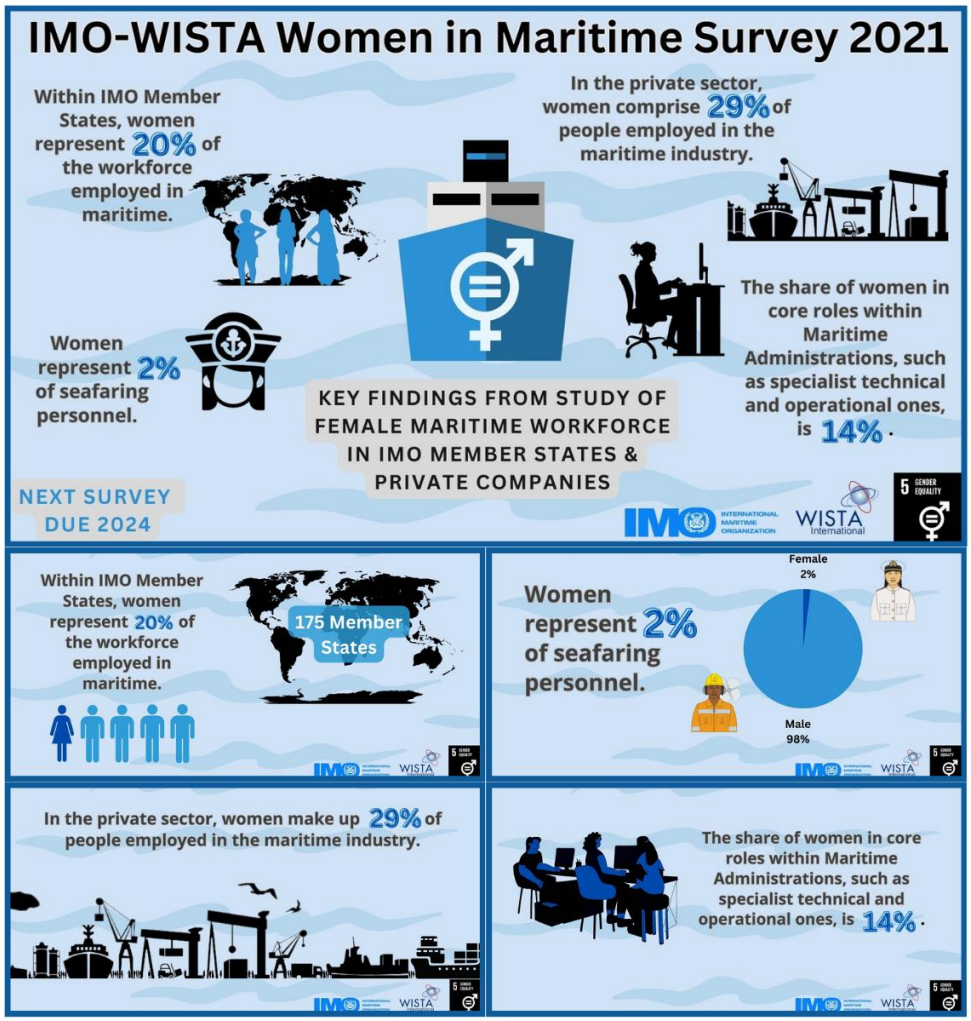


Fig. Women employed in the maritime sector, by subsector. Source: IMO & WISTA, 2021, survey visuals available at https://www.imo.org/ - Access 08 january 2025.

Generally, the maritime industry is characterized with both horizontal and vertical gender segregation, which makes it hard to attract and retain women in the industries (Kitada, 2022; IMO & WISTA, 2021). Work cultures are also reflected by masculine norms and values, such as physical strengths, technical and engineering experiences, and leadership styles. Such work culture is also seen in maritime education and fewer women

study in maritime-related courses, especially technical and engineering subjects. In Europe, the percentage of women enrolled in nautical courses is approximately 13.5 percent as well as in marine engineering at 6.3 per cent on average (Barahona-Fuentes et al., 2020). ~~These figures vary by country,~~While women seafarers have historically been disadvantaged in terms of finding employment and accessing on-board practical training, recent initiatives have the potential to address these inequalities, leading to a gradual increase in their participation in the sector ~~however women seafarers are particularly disadvantaged to find employment and complete practical training on board. This resulted in a marginal increase of women seafarers, compared to the whole seafaring population if business-as-usual continues~~ (WMU, 2023).

Recently, the maritime industry has been sensitized to discuss gender and diversity in relation to occupational safety and health and well-being in the context of the human element. Inspired by the World Maritime Day theme 2019, "Empowering women in the maritime community", the IMO Member States adopted Resolution A.1147, 'Preserving the Legacy of the World Maritime Theme for 2019 and Achieving a Barrier-Free Working Environment for Women in the Maritime Sector' in December 2019 (IMO, 2019). There have been a number of reported and unreported cases of sexual harassment and bullying against female crew (Carballo Piñeiro & Kitada, 2020) and the International Labour Organization (ILO) and IMO held a Joint Tripartite Working Group to identify and address seafarers' issues and the human element in February 2024, which focused on violence and harassment, including sexual harassment, bullying and sexual assault (IMO, 2024). The maritime industry is faced by an urgent need to respond to ensuring a safe working environment. One of the solutions under discussion at IMO is to add mandatory training on violence and harassment as well as psychological safety under the STCW convention. Several IMO Member States also stressed the importance of incorporating the perspectives of other gender minorities, such as LGBTIQ+, into the design of a safe working environment at sea (IMO, 2023) (See it further on Section 5A, Chapter 6: Shipping).

In addition to the human element perspectives, gender equality is recently conceptualized within a just and equitable transition, namely, "just transition". In 2022, Maritime Just Transition Task Force was established among the UN agencies and industry stakeholders with the aim of promoting smarter and greener shipping in a just and equitable manner (Maritime Just Transition Task Force, 2022). Today, gender equality is recognized as the top priority in the industry, but it still has a long way to go to remove all

the barriers against women and other gender identities to achieve diversity and inclusion in the industry (See it further on Section 5A, Chapter 6: Shipping and Chapter 7: Mineral Resources).

VI. Strengthening Science-Based Approaches (1000 words)

Integrating gender perspectives into science-based marine solutions enhances more equitable practices, innovation, participation, and sustainability (Alexander et al., 2021). Several successful initiatives demonstrate how gender-transformative approaches lead to improved research outcomes, reduce inequalities, and strengthen community resilience.

For instance, the Gendered Innovations project highlights case studies that showcase how gender perspectives have contributed to improved outcomes in marine research. These include designing gender-sensitive equipment that enables both men and women to participate effectively in marine fieldwork and developing policies that address gender disparities in research funding and opportunities (Gendered Innovations, 2023). Such examples illustrate that when technology and innovation are designed inclusively, they not only accommodate a broader range of users but also enhance research quality and engagement.

In the Baltic region, the Baltic Gender project has pioneered the Gender Wave tool, which incorporates gender perspectives into marine research and innovation. This tool supports research institutions in analyzing and addressing gender imbalances across scientific disciplines and organizational structures (Baltic Gender, 2020). By fostering gender-aware practices within research, the Gender Wave tool promotes a more equitable research environment and sets a model for other regions seeking to balance gender representation in science.

Collaboration between researchers, policymakers, and local communities is essential for addressing gender disparities in ocean-related activities. Effective partnerships amplify marginalized voices, especially those of women in fishing and extractive industries, ensuring that policies reflect the diverse experiences and needs of these communities.

A notable example is the Network of Women from Extractive and Fishing Communities in Southern Bahia, Brazil. Located in a region heavily impacted by environmental degradation, predatory fishing, and real estate pressures, local communities have mobilized to protect their livelihoods through the Canavieiras Extractive Reserve (RESEX), established in 2006 (Carmo et al., 2016). Recognizing the male

dominance in RESEX management, women fishers and shellfish gatherers formed the Network of Women Shellfish Gatherers and Fishers from Extractive Communities in Southern Bahia in 2009 (Ettinger, 2013; Figueiredo, 2015).

This network aims to empower women, promote gender equity, and advocate for policies that address women's unique challenges in extractive activities. Through the network, women have gained the skills and confidence to participate actively in management discussions, advocate for their rights, and take on leadership roles within their communities (Ettinger et al., 2016). Training sessions and forums organized by the network cover a range of topics, from technical skills to economic autonomy and legal rights, allowing women to build capacities that extend beyond their work in extractive industries (Ettinger, 2013; Carmo et al., 2016).

The network's impact is multifaceted: not only has it enhanced women's economic empowerment, but it has also fostered a sustainable management approach that aligns local traditions with environmental preservation. By engaging in sustainable fishing practices and educating communities on ecosystem protection, the network has contributed to safeguarding biodiversity and promoting long-term food security (Figueiredo, 2015). This community-driven model exemplifies how collective action rooted in gender equality can drive social, economic, and environmental change.

In fisheries and aquaculture, access to gender-trasnformative technology has empowered women to participate in new ways. A powerful example of this is Zanzibar's seaweed farming sector. Initially introduced as a means of economic empowerment for women, seaweed farming in Zanzibar has faced challenges, including declining productivity due to climate change and insufficient access to appropriate technology. In response, the Sea PoWer project introduced tubular net technology for seaweed farming, enabling women to shift their operations to deeper waters. This helps mitigate climate-related declines in coastal yields, enabling more sustainable cultivation (Brugere et al., 2020). This initiative not only provided women with essential skills in boat handling and environmental monitoring, but also created pathways for women's leadership in aquaculture innovation (Brugere et al., 2019; Gopal et al., 2020). Gender-sensitive technological interventions like these transform blue economy sectors by enhancing productivity, expanding livelihood opportunities, and creating a more inclusive industry (See it further on Section 5A, Chapter 6: Shipping).

Gender-transformative technology is essential for advancing ocean science ensuring that innovations are accessible, equitable and beneficial to all genders involved in marine research, management, and conservation. Integrating gender perspectives into technology

development considers the specific needs, experiences and constraints of women and other marginalized groups, thus promoting greater inclusivity, participation and innovation. For instance, area-based management tools like the Western Indian Ocean Symphony support ecosystem-based marine spatial planning, providing data-driven solutions that consider diverse stakeholder needs (Nairobi Convention and SwAM, 2021). Such gender-responsive technologies are needed to empower a wider range of users and enhance contributions of women to ocean scientific research and governance.

Incorporating gender perspectives into science-based approaches for ocean-related sectors like fisheries, aquaculture, and marine conservation leads to more inclusive, sustainable, and effective outcomes (Read it further on S5A.C1c Medium and Large-scale Aquaculture). Success stories from projects like Sea PoWer in Zanzibar and the Women's Network in Southern Bahia demonstrate how gender-sensitive initiatives empower women, enhance resource sustainability, and promote community resilience. Collaborative efforts between researchers, policymakers, and communities are essential to addressing gender disparities in ocean sectors and implementing meaningful change. By integrating gender into ocean science, we build a more inclusive and resilient approach to marine conservation, capable of addressing the diverse challenges of a rapidly changing world.

Ultimately, gender-transformative strategies in science-based solutions pave the way for sustainable development in marine and coastal environments. Gender equity must be central to our efforts, recognizing the invaluable roles that women play in marine stewardship and community resilience. By fostering innovation, collaboration, and gender-sensitive policies, we can work towards a future where marine resources are managed sustainably and equitably for the benefit of all (Chapter 5, Section 5b).

VII. Conclusion

This chapter has explored the role of gender equality in ocean science and governance, highlighting how a gender perspective can enhance the effectiveness, inclusivity, and sustainability of ocean-related activities. The discussion emphasized that the Sustainable Development Goals (SDGs) and recent international agreements, such as the BBNJ (Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement), have marked important strides in addressing gender disparities. A gender lens allows for a more holistic view of marine sectors, acknowledging the unique contributions of women, especially in fisheries, aquaculture, climate adaptation, and marine conservation.

Gender disparities remain significant in these fields, with barriers for women ranging from limited access to leadership positions to systemic biases that undervalue their roles and contributions. Women's roles in marine and coastal communities, often in areas like processing, trading, and local conservation, underscore their importance in the socio-ecological resilience of these areas. Yet, persistent structural challenges limit their involvement in decision-making and leadership. Studies reveal that gender-diverse teams and inclusive governance structures bring a broader range of perspectives and more innovative solutions to marine conservation and governance challenges. Initiatives like the Gendered Innovations project, the Baltic Gender project, and localized efforts such as the Sea PoWer project in Zanzibar and the Women's Network in Southern Bahia, Brazil, illustrate how gender-transformative approaches can lead to more sustainable and impactful marine management and conservation practices.

Promoting gender equality in ocean science and governance is not merely an ethical imperative; it is essential for effective and adaptive marine resource management. As this chapter demonstrates, fostering inclusivity through gender-sensitive policies, training, and research contributes to healthier marine ecosystems and more resilient coastal communities. By integrating women's knowledge and leadership into ocean science, we can address pressing environmental issues with greater nuance and cultural awareness.

A call to action is therefore warranted to expand and deepen gender equality efforts across ocean-related sectors. First, governments and international organizations must prioritize gender equality in policy frameworks, integrating gender-focused objectives into marine conservation and resource management initiatives. Furthermore, funding bodies should provide targeted resources to support gender-sensitive research and training, particularly in regions where gender disparities are most pronounced.

Ocean governance institutions can play a pivotal role by establishing leadership programs and mentorship opportunities for women, particularly those from underrepresented backgrounds, including women of color, Indigenous women, and LGBTQ+ individuals. Gender-disaggregated data collection must also be prioritized, as data gaps remain a major barrier to making visible, and accurately assessing and addressing gender inequalities in these fields. Increasing awareness through gender training, as seen in projects like the UN Ocean Decade's Empowering Women initiative, can help dismantle biases and foster a culture of inclusion and respect within ocean science.

As the field of ocean science and governance continues to evolve, future research must focus on several key areas to ensure that gender equality is fully integrated into marine resource management. One potential area is the intersectionality of gender with

other social factors, such as ethnicity, class, and geography. Future studies can investigate how these intersections affect women's access to resources, decision-making power, and roles in marine sectors, allowing for a more nuanced understanding of the barriers and opportunities within these industries.

Another critical direction is the development and assessment of gender-sensitive technology in marine science. Technological innovations, particularly in remote sensing, marine biology, and climate monitoring, can benefit from inclusive design principles that make them accessible and relevant to diverse user groups. Research can explore how such technology may empower women in ocean-related fields, particularly by reducing physical barriers in activities like data collection and fieldwork.

The impacts of climate change on gender disparities in ocean science and coastal management are also worthy of further study. As climate-induced shifts impact fishery resources, coastal habitats, and marine biodiversity, understanding the gender-specific impacts on livelihoods and resilience can guide adaptive policies that support both ecological and social resilience. Additionally, future research could examine how women in local communities are adapting to climate pressures through community-led conservation initiatives and sustainable resource management, providing valuable insights for scaling these practices globally.

Lastly, expanding research into the economic contributions of women in fisheries, aquaculture, and conservation can bring visibility to their roles and contributions. Quantifying these economic impacts would help correct longstanding undervaluation of women's labor and can encourage policymakers to allocate resources and support programs that enhance women's economic empowerment in marine sectors (Read it further on S5A.C1c Medium and Large-scale Aquaculture).

Promoting gender equality in ocean science and governance is integral to creating more sustainable, resilient, and equitable marine ecosystems. By acknowledging and addressing gender disparities, we strengthen our collective ability to steward marine resources effectively and inclusively. As this chapter has shown, diverse voices and perspectives enrich conservation and governance practices, making them more adaptable and better suited to meet the challenges of a changing world.

VIII. Acknowledgments

We acknowledge the use of OpenAI's ChatGPT to assist in improving the readability and language of this text. All interpretations, data, and conclusions presented herein are solely the responsibility of the authors.

IX. References

Adam, R. et al. (2024) 'Using a sustainable food systems framework to examine gender equality and women's empowerment in aquatic food systems', Frontiers in Sustainable Food Systems, 8. Available at: https://doi.org/10.3389/fsufs.2024.1327798

Agbekpornu, H., Ennin, E.J., Issah, F., Pappoe, A. and Yeboah, R., 2021. Women in West African Mangrove Oyster (Crassostrea Tulipa) Harvesting, Contribution to Food Security and Nutrition in Ghana. Oceanogr Fish Open Access J, 14(1).

Ahmadia, G. N., Cheng, S. H., Andradi-Brown, D. A., Baez, S. K., Barnes, M. D., Bennett, N. J., ... & Wosu, A. (2021). Limited progress in improving gender and geographic representation in coral reef science. *Frontiers in Marine Science, 8*, 731037.

Alongi, D. M. (2008). Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science, 76*(1), 1-13.

Andrade, M. M. D., Xavier, L. Y., Grilli, N. D. M., Oliveira, C. C. D., Andrade, D. A. D., Barreto, G. C., ... & Gonçalves, L. R. (2021). Gender and small-scale fisheries in Brazil: Insights for a sustainable development agenda. *Ocean and Coastal Research, 69*(suppl 1), e21033.

Axelrod, M., Vona, M., Novak Colwell, J., Fakoya, K., Salim, S. S., Webster, D. G., & Torre-Castro, M. de la. (2022). Understanding gender intersectionality for more robust ocean science. *Earth System Governance, 13*, 100148. https://doi.org/10.1016/j.esg.2022.100148

Barahona-Fuentes, C., Castells-Sanabra, M., Ordás, S., & Torralbo, J. (2020). Female figures in maritime education and training institutions between 2009 and 2018: Analysing possible impacts of gender policies. *WMU Journal of Maritime Affairs, 19*(1), 143–158. https://doi.org/10.1007/S13437-019-00190-Y

Barange, M. et al. (2018) Impacts of Climate Change on Fisheries and Aquaculture. Synthesis of Current Knowledge, Adaptation, and Mitigation Options.

Barclay, K. *et al.* (2021) *Pacific Gender Equity and Social Inclusion in Coastal Fisheries and Aquaculture | The Pacific Community*. Available at: https://www.spc.int/resource-centre/publications/pacific-gender-equity-and-social-inclusion-in-coastal-fisheries-and (Accessed: 4 November 2024).

Bennett, N. J. (2022). Mainstreaming equity and justice in the ocean. *Frontiers in Marine Science, 9*, 873572.

Bennett, N. J., Katz, L., Yadao-Evans, W., Ahmadia, G. N., Atkinson, S., Ban, N. C., ... & Wilhelm, A. (2021). Advancing social equity in and through marine conservation. *Frontiers in Marine Science, 8*, 711538.

Berryman Sue E.and Rockefeller Foundation, New York, NY. 1983. Who Will Do Science? Trends, and Their Causes in Minority and Female Representation among Holders of Advanced Degrees in Science and Mathematics. A Special Report. Distributed by ERIC Clearinghouse, Washington, D.C. https://eric.ed.gov/?id=ED245052.

BIMCO & ICS. (2021). *Seafarer Workforce Report: The global supply and demand of seafarers in 2021*. Witherby Publishing Group Ltd.

Brooks, L. A., & Déniz-González, I. (2021). An apercu of the current status of women in ocean science. *Pure and Applied Chemistry, 93*(8), 869-884.

Brugere, C., & Munoz, P. (2019). *Women's participation in the seaweed industry in Zanzibar: Opportunities for empowerment and prosperity*. World Bank.

Brugere, C., Munoz, P., & Pike, K. (2020). Gender-sensitive innovation in seaweed farming: A sustainable solution for climate resilience. *World Development Perspectives, 19*, 100210. https://doi.org/10.1016/j.wdp.2020.100210

Burdett, H. L., Kelling, I., & Carrigan, M. (2022). #TimesUp: tackling gender inequities in marine and fisheries science. *Journal of Fish Biology, 100*(1), 4-9.

Carballo Piñeiro, L., & Kitada, M. (2020). Sexual harassment and women seafarers: The role of laws and policies to ensure occupational safety & health. *Marine Policy, 117*, 103938. https://doi.org/10.1016/j.marpol.2020.103938

Carmo, J. C. do, Pires, M. de M., Jesus Júnior, G. de, Cavalcante, A. L., & Trevizan, S. D. P. (2016). Voice of nature and women in the Canavieiras Extractive Reserve, Bahia, Brazil: Environmental and gender sustainability from an ecofeminist perspective. *Revista Estudos Feministas, 24*(1), 155–180. https://doi.org/10.1590/1805-9584-2016v24n1p155

Cho, M. (2024). Gender equity in small-scale fisheries: Challenges and pathways. *Marine Policy, 145*, 105410.

Chuku, E.O. et al. (2022) 'Spotlighting Women-Led Fisheries Livelihoods Toward Sustainable Coastal Governance: The Estuarine and Mangrove Ecosystem Shellfisheries of West Africa', Frontiers in Marine Science, 9. Available at: https://doi.org/10.3389/fmars.2022.884715.

Cochrane, K. L., Bahri, T., Dabbadie, L., Fernandez-Reguera, D., Kalikoski, D. C., Ma, X., & Vannuccini, S. (2023). The impact of climate change on coastal fisheries and aquaculture.

Crawford, B. et al. (2022) 'The Women Shellfishers and Food Security Project: Multivariate analysis of the theory of change model.'

Crosman, K. M., Allison, E. H., Ota, Y., Cisneros-Montemayor, A. M., Singh, G. G., Swartz, W., ... & Spalding, A. K. (2022). Social equity is key to sustainable ocean governance. *npj Ocean Sustainability, 1*(1), 4.

de Carvalho, D.A., Amaral, S. and Alves, L.M. (2023) 'Climate change adaptation frameworks in fishing communities: A systematic review', Ocean & Coastal Management, 243, p. 106754. Available at: https://doi.org/10.1016/j.ocecoaman.2023.106754.

De la Torre-Castro, M. (2019). Inclusive management through gender consideration in small-scale fisheries: the why and the how. *Frontiers in Marine Science, 6*, 156.

De la Torre-Castro, M., Fröcklin, S., Börjesson, S., Okupnik, J., & Jiddawi, N. S. (2017). Gender analysis for better coastal management–Increasing our understanding of social-ecological seascapes. *Marine Policy, 83*, 62-74.

Ding, Q., Chen, X., Chen, Y., Tian, S., 2017. Estimation of catch losses resulting from overexploitation in the global marine fisheries. Acta Oceanol. Sin. 36, 37–44. https://doi.org/10.1007/s13131-017-1096-x

Elias, M. et al. (2024) 'Towards gender equality in forestry, livestock, fisheries and aquaculture', Global Food Security, 41, p. 100761. Available at: https://doi.org/10.1016/j.gfs.2024.100761.

Ettinger, V. M. T. de M., Jesus Junior, G., Setenta, A. M., & Cavalcante, A. L. (2016). Culture, identity, and gender: Weaving the network of women from extractive and fishing communities in Southern Bahia. *Revista Interdisciplinar De Gestão Social, 4*(3). Retrieved from UFBA.

Ettinger, V. M. T. (2013). Weaving the Network of Women from Extractive and Fishing Communities in Southern Bahia: Recognizing and affirming "being" a woman. *Dissertation presented to the Development and Social Management Program*, School of Administration, Federal University of Bahia, 138pp.

FAO (2015) SSF Guidelines, Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries. Available at: https://www.fao.org/voluntary-guidelines-small-scale-fisheries/en (Accessed: 4 November 2024).

FAO. (2017). *Towards gender-equitable small-scale fisheries governance and development: A handbook*. Biswas N, editor. Rome: Food and Agriculture Organization of the United Nations.

FAO, Duke University and WorldFish (2023) Illuminating Hidden Harvests (IHH), VoluntaryGuidelines. Available at: https://www.fao.org/voluntary-guidelines-small-scale-fisheries/ihh/en (Accessed: 4 November 2024).

FAO. 2024. The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome. https://doi.org/10.4060/cd0683en

Figueiredo, M. A. (2015). Gender and political participation: The experience of the Network of Women Fishers in Southern Bahia. *Revista Ártemis, 20*(2), 171-179. https://doi.org/10.15668/1807-8214/artemis.v20n2p171-179

Frangoudes, K., Gerrard, S. and Said, A. (2020) 'Commentary 6 to the Manifesto for the marine social sciences: gender and the role of women', Maritime Studies, 19(2), pp. 137–138. Available at: https://doi.org/10.1007/s40152-020-00186-y.

Fukuda-Parr, S. (2016). From the Millennium Development Goals to the Sustainable Development Goals: Shifts in purpose, concept, and politics of global goal setting for development. *Gender and Development, 24*(1), 43-52. https://doi.org/10.1080/13552074.2016.1145895

Gerrard, S. and Kleiber, D. (2019) 'Women fishers in Norway: few, but significant', Maritime Studies, 18(3), pp. 259–274. Available at: https://doi.org/10.1007/s40152-019-00151-4

Giakoumi, S., Pita, C., Coll, M., Fraschetti, S., Gissi, E., Katara, I., ... & Micheli, F. (2021). Persistent gender bias in marine science and conservation calls for action to achieve equity. *Biological Conservation, 257*, 109134.

Gissi, E., Portman, M. E., & Hornidge, A. K. (2018). Un-gendering the ocean: Why women matter in ocean governance for sustainability. *Marine Policy, 94*, 215-219.

Gopal, N. et al. (2020) 'Expanding the horizons for women in fisheries and aquaculture', Gender, Technology and Development, 24(1), pp. 1–9. Available at: https://doi.org/10.1080/09718524.2020.1736353.

Harper, S. J., Gurney, G. G., Darling, E., Mangubhai, S., Jupiter, S., Lestari, W. P., ... & Ban, N. C. (2024). Gender differences in the perceived impacts of coastal management and conservation. *npj Ocean Sustainability, 3*(1), 34.

IMO (2019). Preserving the Legacy of the World Maritime Theme for 2019 and Achieving a Barrier-Free Working Environment for Women in the Maritime Sector, Resolution A.1147(31), 31st session of the IMO Assembly.

IMO. (2023). Diversity and inclusivity in the maritime sector. (Submitted by Belgium, Canada, Luxembourg, Denmark, Malta, Netherlands (Kingdom of the), South Africa, and International Transport Workers' Federation (ITF)), TC 73/INF.15.

IMO and ILO. (2024). Report to the IMO Maritime Safety Committee and the ILO Governing Body, The 2nd meeting of the Joint ILO/IMO Tripartite Working Group to Identify and Address Seafarers' Issues and the Human Element, JTWG-SIHE 2/6

IOC-UNESCO. 2020. Global Ocean Science Report 2020–Charting Capacity for Ocean Sustainability. K. Isensee (ed.), Paris, UNESCO Publishing.

Isma, L. M., Bernard, M. L., Layton, J., Santana, R., Wilkins, K. W., & Nembhard, D. (2023). BLACK WOMEN IN OCEAN SCIENCE. Oceanography, 36(4), 56-59.

Johannesen, E., Barz, F., Dankel, D. J., & Kraak, S. B. M. (2023). Gender and early career status: Variables of participation at an international marine science conference. *ICES Journal of Marine Science, 80*(4), 1016-1027.

Johannesen, E., Ojwala, R. A., Rodriguez, M. C., Neat, F., Kitada, M., Buckingham, S., ... & Sun, Z. (2022). The sea change needed for gender equality in ocean-going research. *Marine Technology Society Journal, 56*(3), 18-24.

Johri, S., Carnevale, M., Porter, L., Zivian, A., Kourantidou, M., Meyer, E. L., ... & Skubel, R. A. (2021). Pathways to justice, equity, diversity, and inclusion in marine science and conservation. *Frontiers in Marine Science, 8*, 696180.

Jones, J. P., Andriamarovololona, M. M., & Hockley, N. (2008). The importance of taboos and social norms to conservation in Madagascar. *Conservation Biology, 22*(4), 976-986.

Kitada, M., Johannesen, E., Ojwala, R. A., Buckingham, S., Sun, Z., Rodríguez-Chaves, M., ... & Schofield, C. (2023). Barriers to the collection of gender-disaggregated data in ocean science. *Human Factors in Management and Leadership, 71*.

Kleiber, D., Harris, L.M. and Vincent, A.C.J. (2015) 'Gender and small-scale fisheries: a case for counting women and beyond', *Fish and Fisheries*, 16(4), pp. 547–562. Available at: https://doi.org/10.1111/faf.12075.

Koehler, G. (2016). Tapping the Sustainable Development Goals for progressive gender equity and equality policy?. *Gender & Development, 24*(1), 53-68.

Kruijssen, F., McDougall, C. L., & Van Asseldonk, I. J. (2018). Gender and aquaculture value chains: A review of key issues and implications for research. *Aquaculture, 493*, 328-337.

Lawless, S., Cohen, P. J., Mangubhai, S., Kleiber, D., & Morrison, T. H. (2021). Gender equality is diluted in commitments made to small-scale fisheries. *World Development, 140*, 105348.

Loarne-Lemaire, S., Martineau, C., & Peters, K. (2021). Female innovators in ocean science: Uncovering gender-specific contributions to technology. *Innovation Management Review, 18*(2), 37-51.

Mahabir-Lee, S., & Rambarath-Parasram, S. (2019). Women's economic empowerment in marine science and coastal management. *Women's Studies International Forum, 76*, 102277.

Maneschy, M. C. (2000). Da Casa ao Mar: papéis das mulheres na construção da Pesca. *Proprosta, março/agos*(84/85), 82-91.

Mangubhai, S., Lawless, S., Cowley, A., Mangubhai, J. P., & Williams, M. J. (2022). Progressing gender equality in fisheries by building strategic partnerships with development organisations. *World Development, 158*, 105975.

Mangubhai, S. and Lawless, S. (2021) 'Exploring gender inclusion in small-scale fisheries management and development in Melanesia', Marine Policy, 123, p. 104287. Available at: https://doi.org/10.1016/j.marpol.2020.104287.

Maritime Just Transition Task Force. (2022). *Mapping a Maritime Just Transition for Seafarers: Position paper*. Maritime Just Transition Task Force.

McClanahan, T.R., Abunge, C., 2017. Fish trader's gender and niches in a declining coral reef fishery: implications for sustainability. Ecosyst. Health Sustain. 3, 1353288. https://doi.org/10.1080/20964129.2017.1353288

McClenachan, L. and Moulton, A. (2022) 'Transitions from wild-caught fisheries to shellfish and seaweed aquaculture increase gender equity in Maine', Marine Policy, 146, p. 105312. Available at: https://doi.org/10.1016/j.marpol.2022.105312.

McDougall, C. et al. (2022) 'Gender integration and intersectionality in food systems research for development: A guidance note'. Available at: https://hdl.handle.net/20.500.12348/5286 (Accessed: 4 November 2024)

Merayo, E., Vakhitova, V. and Carlson, A. (2024) *Women in fisheries in the Mediterranean and Black Sea region: roles, challenges and opportunities*. Available at: https://openknowledge.fao.org/items/5672080f-e93e-436f-9968-b43dd8d6c910 (Accessed: 4 November 2024).

Mitra, A. and Barua, P. (2023) *Coping Practices of Women Fisherfolk in Responses to Climate Change at UNESCO Declared World Heritage Site of Sundarbans*, *springerprofessional.de*. Available at: https://www.springerprofessional.de/en/ecological-footprints-of-climate-change/23879964

Nairobi Convention and SwAM (Swedish Agency Marine and Water Management) (2021). Western Indian Ocean Symphony- a tool for ecosystem-based marine spatial planning. Accessed on 7 March 2025 at: https://www.nairobiconvention.org/wio-symphony/.

Nyasimi, M. and Jakarasi, V.N., 2024. Persisting Inequalities: An Intersectional View of Climate Change, Gender and Violence. In The Palgrave Handbook of Violence in Africa (pp. 879-892). Cham: Springer Nature Switzerland.

Nielsen, M. W., Alegria, S., Börjeson, L., Etzkowitz, H., Falk-Krzesinski, H. J., Joshi, A., Leahey, E., Smith-Doerr, L., Woolley, A. W., & Schiebinger, L. (2017). Gender diversity leads to better science. Proceedings of the National Academy of Sciences, 114(8), 1740–1742. https://doi.org/10.1073/pnas.1700616114

Odera, J. A., & Mulusa, J. (2020). SDGs, Gender Equality and Women's Empowerment: What Prospects for Delivery? 95–118. https://doi.org/10.1007/978-3-030-30469-0_6

Ojwala, R. A., Kitada, M., Neat, F., & Buckingham, S. (2022). Effectiveness of gender policies in achieving gender equality in ocean science programmes in public universities in Kenya. Marine Policy, 144, 105237. https://doi.org/10.1016/j.marpol.2022.105237

Ojwala RA (2023). Gender equality in ocean science for sustainable development: Analysis of ocean science institutions in Kenya. WMU Publications: Malmö, Sweden.

Ojwala, R. A. (2024). Unravelling gender and ethnic bias in higher education: students' experiences in access to ocean science education and career opportunities in Kenya. Higher Education, 1-22.

Oloko, A., Harper, S., Fakoya, K., & Sumaila, U. R. (2024). The multi-dimensional perspectives of taboos on gender roles of fisherfolk in the Global South. *Maritime Studies, 23*(1), 1.

Österblom, H., Wabnitz, C. C., Tladi, D., Allison, E. H., Arnaud-Haond, S., Bebbington, J., ... & Selim, S. A. (2023). Towards ocean equity. In *The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy* (pp. 485-521). Cham: Springer International Publishing.

Partelow, S., Schlüter, A., Ban, N. C., Batterbury, S., Bavinck, M., Bennett, N. J., ... & Villasante, S. (2023). Five social science intervention areas for ocean sustainability initiatives. *npj Ocean Sustainability, 2*(1), 24.

Pauwelussen, Annet, & Lau, Sallie. (2023). A Review of Gender Studies and Feminist Theory in and for Marine Social Science (Ocean Nexus Special Report). https://oceannexus.org/specialreports/a-review-of-gender-studies-and-feminist-theory-in-and-for-marine-social-science/

Powell, K. (2021). The parenting penalties faced by scientist mothers. Nature, 595(7868), 611–613. https://doi.org/10.1038/d41586-021-01993-x

Quimby, B. et al. (2023) 'Blue Food Sovereignty Benefits Social-Ecological Resilience: A Case Study of Small-Scale Fisheries Co-Management and Mariculture in Samoa', Human Ecology, 51(2), pp. 279–289. Available at: https://doi.org/10.1007/s10745-023-00401-4

Riviwanto, M. and Basuki, A. (2019) The role of gender as a model of climate change adaptation in fisherman settlement communities - IOPscience. Available at: https://iopscience.iop.org/article/10.1088/1755-1315/314/1/012086 (Accessed: 4 November 2024).

Sachs, J. D., Lafortune, G., & Fuller, G. (2024). The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. Dublin: Dublin University Press. https://doi.org/10.25546/108572

Shaffril, H.A.M., Samah, A.A. and Mazuki, R. (2024) 'A systematic literature review on the adaptation of women in fisheries-based families on climate change impacts', Journal of Environmental Studies and Sciences [Preprint]. Available at: https://doi.org/10.1007/s13412-024-00963-9.

Shellock, R. J., Cvitanovic, C., Mackay, M., McKinnon, M. C., Blythe, J., Kelly, R., ... & Wisz, M. S. (2022). Breaking down barriers: The identification of actions to promote gender equality in interdisciplinary marine research institutions. *One Earth, 5*(6), 687-708.

Shellock, R. J., Cvitanovic, C., McKinnon, M. C., Mackay, M., van Putten, I. E., Blythe, J., ... & Wisz, M. S. (2023). Building leaders for the UN Ocean Science Decade: A guide to supporting early career women researchers within academic marine research institutions. *ICES Journal of Marine Science, 80*(1), 56-75.

Siles, J. et al. (2019) Advancing Gender in The Environment: Gender in Fisheries—A Sea of Opportunities, IUCN. Available at: https://genderandenvironment.org/advancing-gender-in-the-environment-gender-in-fisheries-a-sea-of-opportunities/

Silva, S. T., Andrade, D. A., & Mont'Alverne, T. C. F. (2020). A Invisibilidade Das Mulheres Pescadoras No Brasil: Uma Discussão a Partir Dos Objetivos De Desenvolvimento. *Revista Do Programa de Pós-Graduação Em Direito Da UFC, 40*(1), 143–159.

St. Louis, T.J. and Oliveira, N.M., 2022. Women's contribution to aquaculture's regional development: a literature review. Journal of Applied Aquaculture, 34(2), pp.294-313.

Sun, Z., Kitada, M., & Rodriguez-Chaves, M. (2021). Empowering women in marine science: Lessons from the UN Ocean Decade. *Marine Policy, 130*, 104591.

Szaboova, L., Gustavsson, M. and Turner, R. (2022) 'Recognizing Women's Wellbeing and Contribution to Social Resilience in Fisheries', *Society & Natural Resources*, 35(1), pp. 59–74. Available at: https://doi.org/10.1080/08941920.2021.2022259.

Thomas, A. et al. (2021) 'Why they must be counted: Significant contributions of Fijian women fishers to food security and livelihoods', Ocean & Coastal Management, 205, p. 105571. Available at: https://doi.org/10.1016/j.ocecoaman.2021.105571

Torell, E. et al. (2019) 'Assessing the Impacts of Gender Integration in Ghana's Fisheries Sector', Coastal Management, 47, pp. 1–20. Available at: https://doi.org/10.1080/08920753.2019.1669098.

UNCTAD. (2022). *Review of maritime transport 2022: Navigating stormy waters*. UNCTAD, UN Publication.

United Nations. (2024). Pact For The Future, Global Digital Compact And Declaration On Future Generations.

UNESCO-IOC (2024). Ambition, Action, Impact: The Ocean Decade Pathway to 2030. Consolidated Outcomes of the Vision 2030 Process. UNESCO, Paris. (The Ocean Decade Series, 50).

UNESCO. (2015). UNESCO Science Report: towards 2030. https://unesdoc.unesco.org/ark:/48223/pf0000235406

UNDESA. (2024). SUSTAINABLE DEVELOPMENT GOALS REPORT 2024. UNITED NATIONS Department of Economic and Social Affairs.

Weeratunge, N., Snyder, K. and Choo, P.-S. (2010) 'Gleaner, fisher, trader, processor: Understanding gendered employment in fisheries and aquaculture', Fish and Fisheries, 11, pp. 405–420. Available at: https://doi.org/10.1111/j.1467-2979.2010.00368.x.

Williams, M. J. (2016). How are Fisheries and Aquaculture Institutions Considering Gender Issues? *Asian Fisheries Science, 29*(January 2016), 21-48.

WMU. (2023). *Transport 2040: Impact of Technology on Seafarers - The Future of Work*. World Maritime University. https://doi.org/10.21677/230613

Section 5B
Chapter 7: Pandemics including COVID-19 Impacts

1. Keynote Points

- The COVID-19 pandemic affected marine ecosystems and the people who depend on them all around the world.~~COVID-19 pandemic affected marine ecosystems and the people who depend on them all around the world.~~
- Seafood workers were particularly susceptible to contracting the disease given particular working conditions.~~Seafood workers were particularly susceptible to contracting the disease given particular working conditions.~~
- Lockdowns, and other public health measures, caused immediate drops in seafood demand and tourism worldwide.~~Lockdowns, and other public health measures, caused immediate drops in seafood demand and tourism worldwide.~~
- With decreases in boat traffic and visitors to popular tourist destinations, species were observed several times in uncommon places or higher densities compared to the last few years before the pandemic.
- Cancelled scientific surveys and decreases in fisheries observation resulted in an increase in illegal fishing activities in some areas.
- There are still many unknowns in terms of the direct and indirect effects of the COVID-19 pandemic with more research needed to prepare for future human pandemics.

2. Introduction

Human pandemics are an example of a rare event that can have outsized impacts on marine ecosystems (Bennett and others, 2020a; FAO, 2020; Ross and others, 2021; White and others, 2021). In 2020, the COVID-19 pandemic started to spread around the globe. In 2020 and 2021 alone, there were over 10 million excess deaths related to the disease (World Health Organization, 2022). The pandemic had both immediate and long-lasting impacts on marine ecosystems and those that rely on them, as well as direct health and safety implications for those working in seafood and coastal areas (FAO, 2020; Sorensen and others, 2020). For example, studies showed that seafood workers were particularly susceptible to being infected by COVID-19, given tight working quarters and moist working conditions (White and others, 2022) and not from the food itself as COVID-19 pandemic is being sustained through human-to-human transmission (FAO, 2021). In addition, because of the mandatory use of personal protective equipment such as face masks and gloves, plastic use, and consequently pollution, increased in the early phases of the pandemic, especially before vaccines became widely available (Aragaw, 2020; Chen and others, 2021). Health and safety concerns of seafood workers and plastic pollution are not new or unique to the pandemic, but the event did intensify these and other ongoing issues, such as the marginalization of groups especially vulnerable to COVID-19 impacts.

In addition to these direct impacts, a host of secondary effects developed as lockdowns and other public health measures were put into place (White & Hébert-Dufresne, 2020). This period has been termed the anthropause due to the resulting decrease in anthropogenic activity across both terrestrial and marine ecosystems (Rutz and others, 2020). For example, mobility restrictions affected businesses in coastal areas. Given the normal popularity of seafood restaurants and tourism there (Fig. 1), workers in these sectors were hit particularly hard (Bennett and others, 2020a; Love and others, 2021; Ward-Paige and others, 2020; White and others, 2021). In areas highly dependent on tourism (see ch. 4), livelihoods completely shifted during the pandemic (Abbas and others, 2021). For example, in the Galapagos Islands, essentially all tourism stopped early in the pandemic (Díaz-Sánchez & Obaco, 2021). In the European Union and regions highly dependent on fishing activities, some businesses pivoted to selling seafood directly to consumers (Villasante and others, 2021, 2024). In addition, lingering effects of the pandemic on ocean and coastal communities occurred. For instance, consumer preferences shifted, such as cooking more seafood at home, that continued after the pandemic (Stoll and others, 2021; Villasante and others, 2024).

Taken all together, these pandemic restrictions affected a substantial population. Over 750 million people live in areas that greatly depend on marine resources (Selig and others, 2019), while in the US alone, three million people work in an ocean-dependent business (NOAA, 2024). Further, for 3.3 billion people across the globe, aquatic foods provide at least 20% of their animal protein intake (*The State of World Fisheries and Aquaculture*, 2022). The COVID-19 pandemic provided the opportunity to better understand the importance of community organizations for provision of social security support, particularly during idiosyncratic shocks (*The State of World Fisheries and Aquaculture*, 2022).

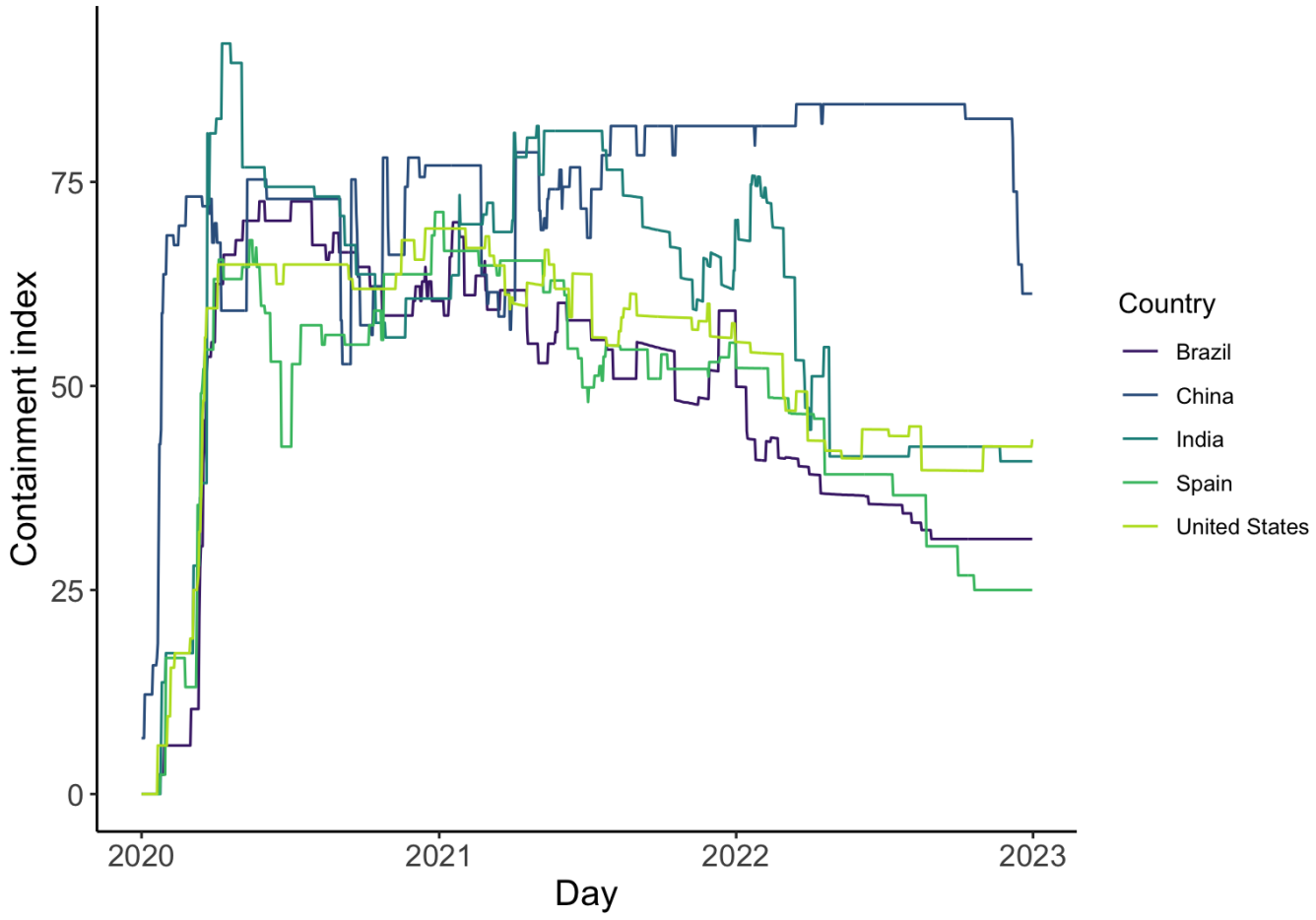


Figure 1. Composite measure of containment based on thirteen policy response indicators, including school closures, workplace closures, travel bans, testing policies, contact tracing, face coverings, and vaccine policies, rescaled to a value from 0 to 100 (100 = strictest). Data from Blavatnik School of Government, University of Oxford (2023).

At the same time, some animal species may have benefited from the reduced human presence, including decreases in tourism and boat traffic (D. J. M. Thomson & Barclay, 2020). Throughout the pandemic, species, such as marine megafauna, were reported inhabiting waters where they were rarely seen in years previous to the event (Rutz and others, 2020). Additionally, the corresponding reduction in underwater noise led to changes in the communication behavior of some animals (Laute and others 2022).

While the COVID-19 pandemic had wide-ranging effects, it is not the first human pandemic to have affected the world's oceans. The 1918–1920 flu pandemic (also called the Spanish flu), killed more than 50 million people worldwide (Martini and others, 2019). The disease spread quickly, especially as the First World War raged on at this time, causing people to move across the globe. Similar to the COVID-19 pandemic, many non-pharmaceutical measures, such as social distancing, went into effect during the 1918-1920 flu pandemic. Because of strong mobility restrictions, some Pacific islands, including American Samoa, remained relatively unscathed by the pandemic (Shanks &

Brundage, 2013). However, coastal communities, including Inuit groups across the Arctic, were hit particularly hard by the flu pandemic (Mamelund and others, 2013). In these communities, workers were concentrated during short fishing windows in the summer (Paskoff & Sattenspiel, 2019). Fishing pressures in many places around the globe also decreased at this time, but this was primarily due to fishing boats being used for wartime activities. Elsewhere, such as Eastern Canada, there were no changes in catch during the 1918-1920 pandemic (Schijns and others, 2021). Similarly, the severe acute respiratory syndrome (SARS) outbreak in 2003, which had nearly a 10% mortality rate, impacted local and regional economies (LeDuc & Barry, 2004). In particular, the growth rate of Chinese ocean-related industries declined drastically during this period, much more so than the Chinese economy at large (Zhao and others, 2014).

Despite these previous pandemics, the unprecedented nature of the COVID-19 pandemic, along with its associated lockdowns, caused gaps in our knowledge, policies, and capacity to emerge early on. For example, new policies had to be written to ensure worker safety and to distribute relief funds to those in the seafood sector in some locations (European Commission, 2020). Early in the pandemic, NOAA fisheries leadership compiled their thoughts on how science and management might have to change for future pandemics, such as during travel restrictions (Link and others, 2021). In addition, data and monitoring gaps occurred in many places during the pandemic. The pandemic created challenges and opportunities, with heterogeneity in impacts among industrial and small-scale sectors, production methods, geographies, value chains, and by gender (Love and others, 2024). Cumulative impacts from climate change and conflicts contributed to pandemic-related hardships.

Here, we provide a literature review from 2020 to 2024 on how the COVID-19 pandemic impacted coastal communities and marine ecosystems in various ways. In addition to highlighting effects specific to human pandemics, we illustrate how this event aggravated existing issues, such as plastic pollution. We note persisting knowledge gaps and how we might manage future pandemics considering marine ecosystems. We also point to other chapters in this assessment that are intricately linked to the COVID-19 pandemic.

3. The impacts of an increase in single-use face masks use within the context of pollution

To slow down COVID-19 transmission, people had to use personal protective equipment (PPE) kits, such as face masks, goggles, and gloves, most of which were single-use materials. The use of single-use face masks was mandatory and common during the pandemic, as they are considered as an effective, and affordable public healthcare measure for containing viral transmissions. For instance, on fishing vessels departing from Namibian ports, fisheries observers and fishing crew were expected to consistently wear face masks while onboard (Erasmus and others, 2022).

However, the marked increase in the manufacture and use of plastics throughout the pandemic led to a significant increase in the illegal disposal of plastic waste into the oceans globally (Shams and others, 2021; Williams & Rangel-Buitrago, 2022). In particular, mismanaging face masks and other PPE has caused various problems (Mallik and others, 2022; Wang and others, 2023), and an

estimated 10 million face masks could have been improperly disposed of and introduced into the environment monthly during the pandemic (WWF, 2020).

Single-use face masks and other PPE not only reduce the aesthetic and recreational value of the environment (see ch. 5a), as seen on Italian beaches (Saliu and others, 2021), but can be easily ingested by fishes, and other organisms, creating an ecological problem (Chen and others, 2021; Jimoh and others, 2023). In addition, wildlife have become entangled in face masks, which can cause immediate mortality or reduce feeding, facilitate predation, and cause infection or wounds, among other effects (Patrício Silva and others, 2021). Face masks are also a source of microplastics containing polystyrene, polypropylene, polyester, or polyethylene (Aragaw, 2020; Chen and others, 2021). It is well-known that microplastic pollution can inhibit growth rates, feeding, and reproduction of marine species while also causing stress, neurotoxicity, and even death (Jimoh and others, 2023).

4. The impact of lockdowns and human activities in the ocean on animal behavior, biodiversity, and presence

The reduction of human presence on and near the ocean — including less shipping traffic by marine traffic, recreational activities, and fishing — changed the behavior of a variety of marine species. These changes were considered mostly positive, including enhanced communication potential and breeding success, re-occupation of urbanized areas, or increases in biodiversity and abundance (Abbas and others, 2021). However, the effects were varied and also included neutral or negative effects for some species, including increased illegal activities and reduced conservation and human assistance (Fournet and others, 2021; Pine and others, 2021).

One of the major effects of the pandemic on the ocean was the reduction of shipping and other anthropogenic activities, which in turn decreased noise pollution. Ambient sound pressure levels were significantly lower in many regions, sometimes even three times quieter (Fournet and others, 2021; Pine and others, 2021). Below 100 Hz, the frequency range often dominated by shipping sound, an average reduction of 1.5 dB was reported in Vancouver, Canada, during the first quarter of 2020 compared to the previous year (D. J. M. Thomson & Barclay, 2020). In other regions, ambient sound pressure levels did not vary significantly, especially if the soundscape was commonly dominated by other sources like biological sounds (e.g. humpback whale songs (Madrigal and others, 2024)) or geophonic sounds (naturally occurring non-biological sounds) (Laute and others, 2022).

Since sound travels quickly and far underwater, marine species often use sound for various life functions, including communication (see ch. 4e). The reduction in noise pollution in many ocean regions led to a change in the communication behavior of some acoustically active species, including increases in call rate, type, or intensity (Duane and others, 2023; Fournet and others, 2021). For instance, a doubling in the number of humpback whale calls (Laute and others, 2022) and an increase in white-beaked dolphin whistles (Reverberi, 2023) were recorded in Iceland when there were fewer whale-watching vessels. In New Zealand, the communication range of fish and dolphins increased by an estimated 65 % (Pine and others, 2021).

Additionally, the reduced number of visitors on shorelines impacted the breeding and nesting behavior of some species. For instance, sea turtle nesting behavior improved, with an increased number of nests and more nesting time, in various countries, including Thailand, Costa Rica, India, and Florida, US (Loh and others, 2022; Quesada-Rodríguez and others, 2021). In contrast, a breeding colony of common murres was disturbed by the 7-fold increase in sea eagle presence due to tourist absence (Hentati-Sundberg and others, 2021). Further, the reduced anthropogenic presence in coastal areas, along with the improved visibility due to clearer water, (Saadat and others, 2020) led to various sightings of animals in uncommon habitats. Similar to reports of wildlife in deserted cities, marine examples of unusual sightings include dolphins in the harbor of Trieste, Italy (Rutz and others, 2020), eagle rays in Dubai Marina (Bar, 2021), dugongs and false killer whales close to the coast in Thailand (Usui and others, 2021), and sea lions in urban centers in Argentina (Usui and others, 2021).Many studies also reported increased biodiversity, including in coral reefs (China and others, 2021; Patterson Edward and others, 2021; Somchuea and others, 2022) and mangroves (Chaudhuri & Bhattacharyya, 2021). The reduced presence of humans, along with less fishing and harvesting, also resulted in higher abundances of fish (Bertucci and others, 2023; Feeney and others, 2022; Johnson and others, 2023; Kough and others, 2022; Lecchini and others, 2021; Olán-González and others, 2022; Olán-González and others, 2023; Patterson Edward and others, 2021; Somchuea and others, 2022; Weng and others, 2023; Yosef and others, 2022), shrimp (Coll and others, 2021), and horseshoe crabs (Degnarain, 2020). These increases were likely a result of short-term changes in habitat use rather than increases in the total population size. However, some negative impacts for marine ecosystems were also reported after the COVID-19 pandemic. Among others, some fish populations may have been exposed to an increase in unregulated fishing activities (Mallik and others, 2022), and the SARS-CoV-2 virus may have also directly impacted marine species due to its potential to infect marine mammals and birds (Mohapatra and others, 2021). For instance, birds and marine mammals like whales, seals, and dolphins can be infected by different coronavirus genera, which they could have contacted through discarded medical waste in the water. Further, dozens to thousands of harbor, Baikal, and common seals, striped dolphins, and harbor porpoises have died of viral pneumonia or measles in the past (Mohapatra and others, 2021).

5. Changes in shipping and port activities and impacts on seafarers and port workers

Facilitating the maritime supply chain was critical during the pandemic. The unprecedented impacts on global trade flows warranted the rapid adaptability of the maritime supply chain, in particular, shipping and port activities (United Nations, 2021). Each stage of the fisheries and aquaculture supply chain was~~is~~ susceptible to being disrupted or stopped by measures arising from COVID-19 restrictions. Only by protecting each stage of the supply chain could~~an~~ the continued availability of fish and fish products be ensured (FAO, 2021). Ports serve as key infrastructure supporting international trade and the global economy, and port workers and seafarers are vital actors in the maritime supply chain. According to the International Labour Organization (ILO), there are 856 international ports and over 2,000 ports globally with variable sizes, services, and abilities (United Nations, 2021, p. 19). The United Nations General Assembly

(UNGA) accounted for approximately 2 million seafarers serving over 98,000 commercial ships and transporting 11 billion tons of seaborne trade in 2019 (United Nations, 2020).

Lockdowns and movement restrictions limited the ability and functioning of seafarers and port workers, which adversely impacted the maritime supply chain. According to the International Maritime Organization (IMO), the COVID-19 pandemic affected seafarers and other maritime professionals through isolated crews, difficulties in repatriation, impacts on working conditions, and labor shortages. For instance, significant challenges occurred for crew change and seafarers' welfare conditions, including their rights to wages, shore leave, sick leave, access to medical care, food supplies, and repatriation (United Nations, 2020). Many seafarers and port workers were stuck onboard ships for months beyond their contracts due to travel restrictions and the lack of clear protocols for crew replacement. In 2020, the IMO estimated that around 400,000 seafarers were still on their ships globally despite their contract expiration due to a lack of repatriation, while another 400,000 were unable to join ships and provide for their families (Gautham, 2021; IMO, 2022)

In addition, in some regions, such as Spain, shortages of port workers due to infections or quarantines resulted in slower port operations and increased delays in loading and unloading ships. Another drawback was the lack of inspectors and administrative staff to renew fishing licenses in third countries due to restrictions (Spanish Fishing Confederation [CEPESCA], 2020). Similarly, fishers were also impacted. For example, in Galicia, Spain, the mental and phyiscal health of fishers was also affected after the first lockdown (March 2020). They were scared of the virus due to the lack of space on board for social distancing among crew members, the scarcity of sanitary material for fishers, and the need to protect family members (Villasante and others 2021).

Travel restrictions and lockdowns from COVID-19 significantly disrupted port operations and, consequently, international trade and commerce. While trade declined globally, impacts varied regionally. For instance, major drops occurred in ship calls in Europe, Oceania, and the Americas, while moderate decreases occurred in Africa, the Far East, and the Gulf regions (UNCTAD, 2022b). UNCTAD reported an 8.7% contraction of ship calls globally in the first half of 2020 compared to a year earlier (UNCTAD, 2022b).

To ease trade, the maritime supply chain needed to ensure swift and safe cargo handling, which entailed regulatory, governance, and operational adjustments for ports, port workers, and seafarers. Port workers and seafarers were given the status of "essential workers" or "key workers" in various countries (UNCTAD, 2022b). However, the severity of the measures varied by country (UNCTAD, 2022b). In 2020, a specific resolution was adopted at the 75th Session of the United Nations General Assembly (UNGA) urging Member States to designate seafarers and other maritime personnel as "key workers" (United Nations, 2020). In agreement with the IMO's Maritime Safety Committee during its 102nd session, this resolution also encouraged travel and ship crew change protocols to ensure safety during the COVID-19 pandemic. This intent was further bolstered by the resolution adopted by the 32nd Session of the IMO Assembly, which not only urged designating seafarers as "key workers" to "facilitate shore leave and safe and unhindered movement across borders" but also sought to prioritize vaccination of seafarers and provide them with immediate medical care access and medical evacuation in cases of urgency (IMO, 2022).

The IMO, in coordination with organizations like the ILO, the International Transport Workers' Federation, and the International Chamber of Shipping, established a Seafarer Crisis Action Team (SCAT) to monitor developments, coordinate efforts, communicate with stakeholders, and provide focused support for seafarers in urgent cases, especially crew changes, repatriation, medical access, and abandonment (United Nations, 2020, and ch. 6). The IMO reports that SCAT dealt with over 500 cases involving thousands of individual seafarers to date, along with cases continuously being reported (IMO, 2022).

6. The impacts on ocean sciences and observing

The impact of COVID-19 on global scientific production can be measured in different ways. According to (Gao and others, 2021), "researchers in the bench sciences, female scientists, and those with young children experienced significant declines in research time and other publication-based metrics, according to data collected before the summer of 2020," and none of this is different in ocean sciences. (Jiang and others, 2022) pointed out that the amount of attention paid to the ocean during the pandemic was nearly negligible despite its prominent functions for human well-being.

Due to the lockdown and movement restrictions, many fieldwork and research missions were temporarily suspended. This particularly impacted those involving in situ data collection, such as expeditions and surveys on research vessels and laboratory experiments (IOC-UNESCO, 2020). Several studies confirmed that due to the cancellation of numerous research cruises and the disruption of ship-based observations , year-long gaps in time series data exist, which are irreversible and permanent (Boyer and others, 2023; Link and others, 2021). In turn, this disrupts trends and introduces a 'dark' period that researchers cannot fill. For example, Viglione (2020) demonstrated how weather forecasts and climate records have COVID-19 associated gaps that cannot be filled. For some counties, data collection was not completely discontinued, but data quantity was reduced (Boyer and others, 2023; Erasmus and others, 2022). Boyer and others (2023) also demonstrated that ship days at sea for the U.S. National Oceanographic and Atmospheric Administration's (NOAA) research declined significantly in 2020 and the first quarter of 2021, reflecting the impacts of COVID-19 on ocean sciences and observation. Furthermore, workgroups to discuss data were poorly attended, and certain consultations, such as Environmental Impact Assessment consultations, were limited. Thus, reports and projects were mostly finalized with limited input from stakeholders (Link and others, 2021).

However, short-term ocean observations were not interrupted, nor were autonomous observations (Boyer and others, 2023). In addition, during the pandemic, research seeking to understand the impacts of COVID-19 on maritime supply chains, port logistics, and global maritime transportation arose (Boyer and others, 2023). Many researchers redirected their studies, often discontinuing ongoing research due to the context. However, Visbeck, (2020) stressed that given the diversity of research and areas related to ocean sciences, not all sectors of the ocean sciences community had the same level of access, abilities, choices, and resilience.

International travel, essential for scientific collaborations and global research network meetings, was severely limited by COVID-19. The same went for innovative collaborations with civil society and the private sector, both holding significant potential for advancing real-time ocean observation and stewardship (Enevoldsen and others, 2024). This affected collaborative projects between countries and institutions on maritime and ocean affairs since conferences, workshops, and joint expeditions were postponed, cancelled, or held virtually.

The pandemic particularly impacted early-career researchers (ECRs) and early-career ocean professionals (ECOPs) (Schadeberg and others, 2022). In terms of education and research, postgraduate courses and training programs in maritime and ocean sciences were also affected. Doctoral and master's students, who depended on data collection or participation in expeditions, faced delays in completing their projects. This particularly affected applied research, which required field research or face-to-face international cooperation.

In terms of funding, many governments and funding agencies redirected research resources to studies related to health and fighting the pandemic. As a result, other sciences, including ocean and maritime sciences, saw a drop in funding for projects not directly related to COVID-19. The same applied to the decrease in new grants, scholarships, and funding for long-term projects and the reorientation of research (Schadeberg and others, 2022). This decline was impactful since states devote only 1.7% of their research budgets on average to ocean sciences (0.03% to 11.8%, depending on the country), much less than they spend on other major scientific fields (IOC-UNESCO, 2020).

Despite this, the intersection between the COVID-19 pandemic, which began in 2020, and the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), also known as the Decade of the Ocean, offers a number of important links for ocean sciences (United Nations, 2024). Indeed, the pandemic brought the need to think about global resilience and sustainability to the forefront; these themes are also central to the Ocean Decade agenda.

In addition, the perception of the links between the ocean and public health increased. A central theme of the Ocean Decade, issues such as marine pollution, biodiversity loss, and climate change — all affecting ocean health — have come to be seen as essential for long-term human well-being. At the same time, virtual initiatives and international collaboration were strengthened, opening up new opportunities for inclusive global dialogues on the ocean. Further, this allowed the participation of developing countries and scientists who might not have been able to attend face-to-face events. Additionally, virtual conferences benefit from lower costs, time savings, increased flexibility and accessibility, and reduced carbon emissions (Guetter and others, 2022). Finally, many researchers were able to accurately predict the impacts of COVID-19 on scientific research, meaning this expertise could be used to better cope with and prepare for future crises (Hobday and others, 2024).

7. The decrease in compliance and observing and the associated increase in illegal activities

COVID-19 affected the effectiveness of fisheries observers in monitoring, controlling, surveilling, and collecting fisheries data (Erasmus and others, 2022). It was challenging to deploy fisheries observers, especially given their health and safety (Erasmus and others, 2022; Kearns, 2020). Some

countries, such as Namibia, had a significant reduction in observed fishing trips in 2020 compared to 2019 and 2021 (Erasmus and others, 2022). On the other hand, some countries, such as Canada, "pulled" fisheries observers from all vessels completely (~~J.~~ Thomson, 2020). This reduction in observer coverage meant some vessels had no observers and essentially no law enforcement or data collection. The absence of observers on board fishing vessels is a driver for illegal, unreported, and unregulated (IUU) fishing activities (Erasmus and others, 2022). Levels of monitoring and enforcement of fishing activities need to be maintained to ensure management control measures are enforced and IUU fishing activities do not increase. The most common impact on monitoring, control, and surveillance~~MCS~~ activities being reported is the disruption to at-sea observer programmes (FAO, 2021). Furthermore, because data collected by fisheries observers are used as inputs into stock assessment models, this lack could have affected the evaluation of fish stocks.

The COVID-19 pandemic led to a reportedly rise in illegal activities relating to the fisheries sector and the protection of the marine environment. A lack of monitoring and enforcement and the increased needs of impoverished people may have led to increased ~~illegal, unreported, and unregulated (~~IUU~~)~~ fishing activities (Mallik and others, 2022).

In some regions, monitoring and enforcement mechanisms were severely impeded. For example, some of the Regional Fisheries Management Organisations (RFMOs) suspended observer coverage onboard fishing vessels in areas they manage (Indian Ocean Tuna Commission (IOTC) Secretariat, 2020; WCPFC CHAIR, 2020). At the domestic level, states took varying measures, some of which positively impacted monitoring and enforcement procedures, while others impeded them.

In terms of positive impacts, campaigns were carried out in Belize to increase awareness of laws and to request the public's cooperation in reporting IUU fishing activities (UNCTAD, 2022c). In Malaysia, border security was considered a priority, and an increase in coordination between enforcement authorities was noted (Phua and others, 2021). In other regions, monitoring and enforcement remained the same, but the negative impact of the pandemic on livelihoods led to increased infringement of fisheries laws. These illegal activities included fishing in no-take zones, the use of destructive fishing gear, and even mangrove deforestation along coastlines (Phua and others, 2021).

Additionally, a significant decrease in monitoring and enforcement efforts was also reported in several countries, often due to reallocating resources to other matters of national importance, such as public health and decreased economic productivity. This led to an intensification of recreational and commercial fishing in some areas, with an increase in illegal fishing activities and cases of vessels fishing nearer to the coast (Bates and others, 2021; Bennett and others, 2020b).

Wildlife conservation laws were also not respected, for example, juvenile species in the Bahamas conch fisheries were illegally fished (Bates and others, 2021). Marine protected areas (MPAs) are usually afforded a higher level of legal protection, yet in some countries law enforcement became less of a priority, leading to an increase in illegal fishing in these areas (King and others, 2022; Phua and others, 2021). Based on the Automatic Identification System (AIS) data, in the Chagos MPA, the number of suspected illegal fishing vessels per month in 2022 increased by 19 times compared to the period from 2010 to 2020.

However, authorities could not board the vessels due to COVID restrictions and this led to a reduction in convictions (Collins and others, 2023). Thus, an absence of fishing-related convictions

during that period may not equate to a reduction in offenses — rather, it could represent an absence of detection and enforcement. Likewise, the decrease in fisheries data during the pandemic and its lack of accuracy due to reduced observer coverage and monitoring means no complete picture of related illegal activities at sea exists. Transshipment by fishing vessels is regulated by states and RFMOs. However, transshipment records during the pandemic differed from previous years, and it was inferred that fishing companies might not have reported their activities "*knowing of the poor monitoring of the activity at the time due to the pandemic*" (Ministry of Fisheries and Trade of Tuvalu, 2023).

An increase in AIS disabling events was also recorded during the pandemic, for example, on Spanish purse seiners and longliners in the Indian Ocean (Engel & Hobson, 2023). Under international law, AIS has important functions where it is prescribed: improving the safety and efficiency of navigation, enhancing the safety of life at sea, and protecting the marine environment (IMO, 2015). Disabling AIS, which is illegal in cases where the system is prescribed, increases the risks of collisions while also decreasing the transparency and effectiveness of monitoring and enforcement. However, AIS laws are generally not enforced in the fisheries sector (Bunwaree, 2023).

Finally, in terms of human rights and labor laws, fishing vessel crews were mistreated in some instances (Schwenzfeier & Hofford, 2023).

8. The impact on trade and supply chains

The impacts of the COVID-19 pandemic on maritime trade — one of the most important sectors of the ocean economy — significantly affected the global economy (Liu and others, 2023; Xu and others, 2021). Due to the nature of the pandemic and the closure of national borders, the maritime industry was one of the most affected sectors (Liu and others, 2023; Xu and others, 2021). However, the COVID-19 pandemic had dueling impacts on maritime trade; first, it significantly reduced the global economy in the short term, while the export of many anti-epidemic materials also stimulated maritime trade growth.

From a regional perspective, the pandemic immediately impacted the Asia-Pacific region. China's export routes were particularly hit, especially in the first quarter of 2020, when lockdowns affected production and supply chains. Nonetheless, this also affected shipping routes around the world. Container traffic in European ports was reduced due to the economic slowdown and mobility restrictions, with ship calls dropping by 10.2% (according to data from the European Maritime Safety Agency (EMSA, 2024)). Across the major ports in Europe, the countries most severely affected at the start of the pandemic, such as Italy and Spain, suffered from the restrictions imposed by the pandemic, with reduced traffic and port capacity, as well as disruptions to internal logistics. In the Americas, countries with a high dependence on imports and exports, such as Brazil and Mexico, suffered from delays and a reduced volume of transported goods. In the case of the United States, major ports such as Los Angeles and Long Beach faced congestion due to the high demand for imports following the recovery in trade. At the same time, they faced a shortage of port workers and containers.

In terms of the volume and profile of cargo handled, the reduction in global trade led to factory closures and quarantines, resulting in a significant drop in the volume of maritime cargo. According to (Millefiori and others, 2021), reduced shipping activity generally occurred from March to June 2020, when the most severe restrictions were in force. Mobility varied between −13.77% and −5.62 for container ships, −3.32% and +2.28 for dry bulk, −9.27% and −0.22 for wet bulk, and −42.77% and −19.57 for passenger traffic. In the second half of 2020, maritime trade began to recover with an increase in demand for medical products and protective equipment, along with a leap in e-commerce — greatly altering the dynamics of this industry. The imbalance between demand and port capacity led to terminal congestion and delays in the delivery of goods. In general, nodes and links in the global shipping container network have been severely damaged due to the impact of COVID-19 (Li and others, 2024).

During the pandemic, there were~~The~~ temporary closures of ports, ~~lower~~ reduced demand for energy and raw materials, unavailability of ships, and a lack of available ~~containers led to significant increases in freight costs around the world~~containers (Khan and others, 2022). In response to the pressure on maritime transport, different kinds of emergency policies were enacted, with many countries adopting measures to guarantee the functioning of ports and essential cargo operations. In some cases, manning regulations and port operations were temporarily relaxed to facilitate the movement of goods and maritime workers.

Some companies and countries began to reevaluate their supply chains to reduce dependence on certain ports and routes. At the same time, the pandemic accelerated the adoption of digital technologies and automation in ports to improve efficiency and deal with future crises. It also impacted the consumption profile of certain segments with online shopping and e-commerce. (UNCTAD, 2022a) sums up some elements that were crucial to navigating the COVID-19 disruption across maritime transport and logistics, such as making use of international recommendations and directives, being prepared and having protocols, supporting workers and personnel, and facilitating and prioritizing the flow of essential goods (Villasante and others, 2021, 2024). For example, in fish markets, supermarkets, and fishmongers, telephone and online sales progressively dominated, triggering home delivery, while direct sales also recovered over time during the pandemic. The retail commerce sector made a great effort to promote online sales and home delivery to facilitate the consumption of fresh fish products (Villasante and others, 2021, 2024).

However, some studies also showed that COVID-19 generated new windows of opportunity for some countries and/or actors. For example, in the European Union, Carpenter and others (2023) found that the economic impact of COVID-19 on the fisheries sector was smaller than initially expected, and overall profits remained positive. This was in part due to low fuel prices, which reduced operating costs, and the early response from governments to support the sector. Nielsen and others (2023) combined surveys from industry representatives and official data to conclude that, on average, COVID-19 negatively impacted income. Overall, it seems clear that individual supply chains and firms, and possibly industries, experienced significant negative impacts of COVID-19, but that in aggregate, this was mostly made up by other supply chains and firms who experienced new opportunities (Nielsen and others 2023). The fact that there were none or only moderate impacts on quantity and price for the sectors where we have data suggests that, in total, the EU aquaculture industry and the markets it serves were highly resilient through the first stage of the pandemic (Nielsen and others 2023).

9. Outlook

There has been an immense amount of interest and research related to the impacts of COVID-19 on the world's oceans (a Google Scholar search in Oct 2024 revealed over 160,000 results using "COVID-19" and "ocean"). However, the full scope of the pandemic's effects on the oceans and those that rely on them will never be fully known. Data gaps occurred during the pandemic, and some datasets (e.g., seafood worker demographics) were not collected regularly before, during, or after the pandemic. In addition, further research is needed to examine if some of the reported changes (e.g. for biodiversity or species behavior) were long-lasting or disappeared after the end of lockdown measures. These gaps and missed opportunities highlight the importance of continuing and establishing more long-term monitoring programs to capture the effects of rare events, especially in under-resourced locations. Importantly, more work is needed to assess the long-term effects of the pandemic and what lessons can be learned for future human pandemics and other extreme events.

10. Key remaining knowledge gaps

Insufficient long-term data exist on the effects of reduced human activity on marine ecosystems during the pandemic. In addition, we have a limited understanding of how shifts in consumer preferences for seafood (e.g., home cooking) will affect the seafood industry in the long term. Further, there is inadequate data on the ecological impacts of increased plastic waste, particularly single-use masks and PPE, on marine species and habitats. We also lack comprehensive studies on how the pandemic's restrictions on scientific research expeditions affected the long-term monitoring of ocean systems. Gaps exist in our understanding of how pandemic-driven shifts in ~~illegal, unreported, and unregulated (~~IUU~~)~~ fishing have impacted fish stocks and marine ecosystems. Moreover, we lack knowledge on which effects of the COVID-19 pandemic were unique or may inform future large-scale disruptions, like other global pandemics. Finally, the long-term impacts of reduced anthropogenic noise on marine species communication and behavior are unclear.

11. Key remaining capacity-building gaps

We need improved policies and protocols to protect seafood workers from future pandemics, particularly in crowded or moist working environments. Increased knowledge of the demographics of those working in seafood is also necessary. We should also strengthen global monitoring and enforcement mechanisms to prevent increases in illegal activities (e.g., IUU fishing) during crises disrupting surveillance. Another area of improvement is enhancing the capacity for rapid adaptation in fisheries management, such as remote or automated monitoring systems, to mitigate gaps in observer programs. Further, developing sustainable, low-plastic alternatives for PPE would reduce pollution in marine environments. We should also increase investment in robust technologies and tools for autonomous ocean monitoring that could be used during disruptions to traditional research methods. Finally, a greater focus on resilience planning within the seafood

supply chain to handle future pandemics would ensure an equitable distribution of relief funds and safety protocols.

Conclusions

The COVID-19 pandemic profoundly impacted marine ecosystems, and those who rely on them, worldwide. The large amounts of plastics manufactured and used throughout the pandemic increased the illegal disposal of plastic waste into the oceans globally — causing marine and microplastic pollution. However, the decrease in anthropogenic activity also altered the behavior of marine species, for instance, leading to increased breeding and calling activity. Port operations were also severely impacted, slowing international trade and commerce, while seafood workers were at particular risk of contracting the disease. Further, there were drops in seafood demand and tourism in coastal areas. Scientific research and fisheries observations were also hindered, leading to an increase in illegal fishing activities in some areas. As a result, strengthening policies and addressing research gaps is needed to handle future pandemics with more resiliency.

Acknowledgements

Generative artificial intelligence was used for brainstorming, finding references, and improving readability of the text.

References

Abbas, and others. Exploring the impact of COVID-19 on tourism: Transformational potential and implications for a sustainable recovery of the travel and leisure industry. Current Research in Behavioral Sciences, 2, 100033. https://doi.org/10.1016/j.crbeha.2021.100033. 2021.

Aragaw and T. A. Surgical face masks as a potential source for microplastic pollution in the COVID-19 scenario. Marine Pollution Bulletin, 159, 111517. https://doi.org/10.1016/j.marpolbul.2020.111517. 2020.

Bar and H. COVID-19 lockdown: Animal life, ecosystem and atmospheric environment. Environment, Development and Sustainability, 23(6), 8161–8178. https://doi.org/10.1007/s10668-020-01002-7. 2021.

Bates, and others. Global COVID-19 lockdown highlights humans as both threats and custodians of the environment. Biological Conservation, 263, 109175. https://doi.org/10.1016/j.biocon.2021.109175. 2021.

Bennett, N. J., Finkbeiner, E. M., Ban, N. C., Belhabib, D., Jupiter, S. D., Kittinger, J. N., Mangubhai, S., Scholtens, J., Gill, D., & Christie, P. (2020a). The COVID-19 Pandemic, Small-Scale Fisheries and Coastal Fishing Communities. Coastal Management, 1–11. https://doi.org/10.1080/08920753.2020.1766937

Bertucci, and others. Effects of COVID-19 lockdown on the observed density of coral reef fish along coastal habitats of Moorea, French Polynesia. Regional Environmental Change, 23(1), 16. https://doi.org/10.1007/s10113-022-02011-0. 2023.

Boyer, and others. Effects of the Pandemic on Observing the Global Ocean. Bulletin of the American Meteorological Society, 104(2), E389–E410. https://doi.org/10.1175/BAMS-D-21-0210.1. 2023.

Bunwaree. THE ILLEGALITY OF FISHING VESSELS 'GOING DARK' AND METHODS OF DETERRENCE. International and Comparative Law Quarterly, 72(1), 179–211. https://doi.org/10.1017/S0020589322000525. 2023.

Chaudhuri, and others. Impact of Covid-19 lockdown on the socioenvironmental scenario of Indian Sundarban. In Environmental Resilience and Transformation in Times of COVID-19 (pp. 25–36). Elsevier. https://doi.org/10.1016/B978-0-323-85512-9.00032-2. 2021.

Chen, and others. Used disposable face masks are significant sources of microplastics to environment. Environmental Pollution, 285, 117485. https://doi.org/10.1016/j.envpol.2021.117485. 2021.

China, and others. Reduced human activity in shallow reefs during the COVID-19 pandemic increases fish evenness. Biological Conservation, 257, 109103. https://doi.org/10.1016/j.biocon.2021.109103. 2021.

Coll, and others. Ecological and economic effects of COVID-19 in marine fisheries from the Northwestern Mediterranean Sea. Biological Conservation, 255, 108997. https://doi.org/10.1016/j.biocon.2021.108997. 2021.

Collins, and others. Changes in illegal fishing dynamics in a large-scale MPA during COVID-19. Current Biology, 33(16), R851–R852. https://doi.org/10.1016/j.cub.2023.05.076. 2023.

Degnarain, N. (2020, May 16). Six Places Where Oceans, Rivers And Marine Life Have Rebounded During The Coronavirus Pandemic. Forbes. https://www.forbes.com/sites/nishandegnarain/2020/05/16/six-places-where-oceans-rivers-and-marine-life-have-rebounded-during-the-coronavirus-pandemic/?sh=43d597f63fb0

Díaz-Sánchez, and others. The effects of Coronavirus (COVID-19) on expected tourism revenues for natural preservation. The case of the Galapagos Islands. Journal of Policy Research in Tourism, Leisure and Events, 13(2), 285–289. https://doi.org/10.1080/19407963.2020.1813149. 2021.

Duane, and others. The Effect of COVID-19 Shutdowns on Hawaiian Coral Reef Soundscapes. OCEANS 2023 - Limerick, 1–6. https://doi.org/10.1109/OCEANSLimerick52467.2023.10244572. 2023.

EMSA. European Maritime Safety Agency Newsroom. https://emsa.europa.eu/newsroom/item/4407-covid19.html. 2024.

Enevoldsen, and others. State of the Ocean Report 2024. UNESCO-IOC. https://doi.org/10.25607/4WBG-D349. 2024.

Engel, and others. AIS UTILISATION IN ICCAT BY EUROPEAN FLAGGED FISHING VESSELS (23–010; p. 39). Ocean Mind. https://static1.squarespace.com/static/645662d9155d6a5bec4b27e8/t/648d895f6ca0e13bf82a3f44/1686997351332/23-010-AIS-utilization-in-ICCAT-by-European-flagged-fishing-vessels-between-2018-2021a.pdf. 2023.

Erasmus, and others. Impacts of COVID-19 on at-sea data collection and regulatory activities and fisheries catches off Namibia. Regional Studies in Marine Science, 55, 102519. https://doi.org/10.1016/j.rsma.2022.102519. 2022.

European Commission. Proposal for a COUNCIL REGULATION on the Establishment Of A European Instrument For Temporary Support To Mitigate Unemployment Risks In An Emergency (SURE) Following the COVID-19 Outbreak. COM/2020/139 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1587138033761&uri=CELEX%3A52020PC0139. 2020.

FAO. How is COVID-19 affecting the fisheries and aquaculture food systems. FAO. https://doi.org/10.4060/ca8637en. 2020.

FAO. The impact of COVID-19 on fisheries and aquaculture food systems, possible responses. https://doi.org/10.4060/cb2537en. 2021.

Feeney, and others. COVID-19 lockdown highlights impact of recreational activities on the behaviour of coral reef fishes. Royal Society Open Science, 9(11), 220047. https://doi.org/10.1098/rsos.220047. 2022.

Food and Agriculture Organization of the United Nations. (2020, April 7). Migrant workers and the COVID-19 pandemic |Policy Support and Governance| Food and Agriculture Organization of the United Nations. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1270461/

Fournet, and others. The impact of the “Anthropause” on the communication and acoustic habitat of Southeast Alaskan humpback whales. The Journal of the Acoustical Society of America, 149(4_Supplement), A136–A136. https://doi.org/10.1121/10.0005328. 2021.

Gao, and others. Potentially long-lasting effects of the pandemic on scientists. Nature Communications, 12(1), 6188. https://doi.org/10.1038/s41467-021-26428-z. 2021.

Gautham, P. (2021, January 6). ‘An unwanted prison sentence’ for seafarers stuck at home and stranded at sea. UN News. https://news.un.org/en/story/2021/01/1081482

Guetter, and others. In-person vs. virtual conferences: Lessons learned and how to take advantage of the best of both worlds. The American Journal of Surgery, 224(5), 1334–1336. https://doi.org/10.1016/j.amjsurg.2022.07.016. 2022.

Hentati-Sundberg, and others. COVID-19 lockdown reveals tourists as seabird guardians. Biological Conservation, 254, 108950. https://doi.org/10.1016/j.biocon.2021.108950. 2021.

Hobday, and others. Predicting and assessing the impacts of COVID-19 disruption on marine science and sectors in Australia. Reviews in Fish Biology and Fisheries. https://doi.org/10.1007/s11160-024-09899-3. 2024.

IMO. REVISED GUIDELINES FOR THE ONBOARD OPERATIONAL USE OF SHIPBORNE AUTOMATIC IDENTIFICATION SYSTEMS (AIS). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.1106(29).pdf. 2015.

IMO. COMPREHENSIVE ACTION TO ADDRESS SEAFARERS' CHALLENGES DURING THE COVID-19 PANDEMIC (Assembly Resolution A.1160(32) Agenda Item 12; p. 3). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.1160(32).pdf. 2022.

Indian Ocean Tuna Commission (IOTC) Secretariat. (2020, March 19). IOTC CIRCULAR 2020-14 TEMPORARY SUSPENSION OF OBSERVER DEPLOYMENTS UNDER THE IOTC REGIONAL OBSERVER PROGRAMME. Food and Agriculture Organization of the United Nations. https://iotc.org/sites/default/files/documents/2020/03/Circular_2020-14_-_Suspension_of_observer_deployments_under_ROPE.pdf

IOC-UNESCO. Global ocean science report 2020: Charting capacity for ocean sustainability, executive summary (IOC Policy Series, 2020-1, p. 25). Intergovernmental Oceanographic Commission. 2020.

Jiang, and others. Global impacts of COVID-19 on sustainable ocean development. The Innovation, 3(4), 100250. https://doi.org/10.1016/j.xinn.2022.100250. 2022.

Jimoh, and others. Impact of face mask microplastics pollution on the aquatic environment and aquaculture organisms. Environmental Pollution, 317, 120769. https://doi.org/10.1016/j.envpol.2022.120769. 2023.

Johnson, and others. Insights from the 2-year-long human confinement experiment in Grand Cayman reveal the resilience of coral reef fish communities. Scientific Reports, 13(1), 21806. https://doi.org/10.1038/s41598-023-49221-y. 2023.

Kearns, M. (2020, July 1). COVID-19 prompts NOAA to extend fisheries observer waiver for the US Greater Atlantic region. SeafoodSource. https://www.seafoodsource.com/news/supply-trade/covid-19-prompts-noaa-to-extend-fisheries-observer-waiver-for-the-us-greater-atlantic-region

Khan, and others. The dynamic interaction between COVID-19 and shipping freight rates: A quantile on quantile analysis. European Transport Research Review, 14(1), 43. https://doi.org/10.1186/s12544-022-00566-x. 2022.

King, and others. Marine reserves and resilience in the era of COVID-19. Marine Policy, 141, 105093. https://doi.org/10.1016/j.marpol.2022.105093. 2022.

Kough, and others. Anthropause shows differential influence of tourism and a no-take reserve on the abundance and size of two fished species. Aquatic Conservation: Marine and Freshwater Ecosystems, 32(10), 1693–1709. https://doi.org/10.1002/aqc.3856. 2022.

Laute, and others. Impact of whale-watching vessels on humpback whale calling behavior on an Icelandic foraging ground during the Covid-19 pandemic. Marine Ecology Progress Series, 701, 159–173. https://doi.org/10.3354/meps14202. 2022.

Lecchini, and others. Effects of COVID-19 pandemic restrictions on coral reef fishes at eco-tourism sites in Bora-Bora, French Polynesia. Marine Environmental Research, 170, 105451. https://doi.org/10.1016/j.marenvres.2021.105451. 2021.

LeDuc, and others. SARS, the First Pandemic of the 21st Century1. Emerging Infectious Diseases, 10(11), e26–e26. https://doi.org/10.3201/eid1011.040797_02. 2004.

Li, and others. Data-driven research on the impact of COVID-19 on the global container shipping network. Ocean & Coastal Management, 248, 106969. https://doi.org/10.1016/j.ocecoaman.2023.106969. 2024.

Link, and others. A NOAA Fisheries science perspective on the conditions during and after COVID-19: Challenges, observations, and some possible solutions, or why the future is upon us. Canadian Journal of Fisheries and Aquatic Sciences, 78(1), 1–12. https://doi.org/10.1139/cjfas-2020-0346. 2021.

Liu, and others. Enablers for maritime supply chain resilience during pandemic: An integrated MCDM approach. Transportation Research Part A: Policy and Practice, 175, 103777. https://doi.org/10.1016/j.tra.2023.103777. 2023.

Loh, and others. Positive global environmental impacts of the COVID-19 pandemic lockdown: A review. GeoJournal, 87(5), 4425–4437. https://doi.org/10.1007/s10708-021-10475-6. 2022.

Love, and others. Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. Global Food Security, 28, 100494. https://doi.org/10.1016/j.gfs.2021.100494. 2021.

Love, and others. A Scoping Review of Aquatic Food Systems during the COVID-19 Pandemic. Reviews in Fisheries Science & Aquaculture, 32(2), 189–210. https://doi.org/10.1080/23308249.2023.2231096. 2024.

Madrigal, and others. Comparing the underwater soundscape of the Hawaiian Islands Humpback Whale National Marine Sanctuary and potential influences of the COVID-19 pandemic. Frontiers in Marine Science, 11, 1342454. https://doi.org/10.3389/fmars.2024.1342454. 2024.

Mallik, and others. Impact of COVID-19 lockdown on aquatic environment and fishing community: Boon or bane? Marine Policy, 141, 105088. https://doi.org/10.1016/j.marpol.2022.105088. 2022.

Mamelund, and others. Influenza-Associated Mortality during the 1918–1919 Influenza Pandemic in Alaska and Labrador: A Comparison. Social Science History, 37(2), 177–229. 2013.

Martini, and others. The Spanish Influenza Pandemic: A lesson from the history 100 years after 1918. Journal of Preventive Medicine and Hygiene, Vol 60, E64 Pages. https://doi.org/10.15167/2421-4248/JPMH2019.60.1.1205. 2019.

Millefiori, and others. COVID-19 impact on global maritime mobility (11(1); Scientific Reports). https://www.nature.com/articles/s41598-021-97461-7. 2021.

Ministry of Fisheries and Trade of Tuvalu. Tuvalu Fisheries Annual Report 2022 (p. 61). Tuvalu Fisheries Department Ministry of Fisheries and Trade Government of Tuvalu. https://tuvalufisheries.tv/wp-content/uploads/2023/08/TFD-AR-2022_final-draft14Jul2023.pdf. 2023.

Mohapatra, and others. Negative and positive environmental perspective of COVID-19: Air, water, wastewater, forest, and noise quality. Egyptian Journal of Basic and Applied Sciences, 8(1), 364–384. https://doi.org/10.1080/2314808X.2021.1973182. 2021.

NOAA. Our World Ocean Provides [Infographic]. https://oceanservice.noaa.gov/facts/why-care-about-ocean.html. 2024.

Olán-González, and others. COVID-19 lockdown reveals fish density may be much higher in marine reserves. Ecology. https://doi.org/10.1101/2022.05.17.492376. 2022.

Olán-González, and others. Ecotourism impacts on reef fishes in a marine reserve during the COVID -19 era. Frontiers in Ecology and the Environment, 21(7), 317–323. https://doi.org/10.1002/fee.2657. 2023.

Paskoff, and others. Sex- and age-based differences in mortality during the 1918 influenza pandemic on the island of Newfoundland. American Journal of Human Biology, 31(1), e23198. https://doi.org/10.1002/ajhb.23198. 2019.

Patrício Silva, and others. Risks of Covid-19 face masks to wildlife: Present and future research needs. Science of The Total Environment, 792, 148505. https://doi.org/10.1016/j.scitotenv.2021.148505. 2021.

Patterson Edward, and others. COVID-19 lockdown improved the health of coastal environment and enhanced the population of reef-fish. Marine Pollution Bulletin, 165, 112124. https://doi.org/10.1016/j.marpolbul.2021.112124. 2021.

Phua, and others. Marine protected and conserved areas in the time of COVID. PARKS, 27, 85–102. https://doi.org/10.2305/IUCN.CH.2021.PARKS-27-SICP.en. 2021.

Pine, and others. A Gulf in lockdown: How an enforced ban on recreational vessels increased dolphin and fish communication ranges. Global Change Biology, 27(19), 4839–4848. https://doi.org/10.1111/gcb.15798. 2021.

Quesada-Rodríguez, and others. Impact of 2020 COVID-19 lockdown on environmental education and leatherback sea turtle (Dermochelys coriacea) nesting monitoring in Pacuare Reserve, Costa Rica. Biological Conservation, 255, 108981. https://doi.org/10.1016/j.biocon.2021.108981. 2021.

Reverberi and M. The non-silent world: Acoustic responses of white-beaked dolphins (Lagenorhynchus albirostris) to changes in maritime traffic: A case study during the covid-19 anthropause in Skjálfandi Bay, Iceland [Maters Dissertation, University of Akureyri]. http://hdl.handle.net/1946/45856. 2023.

Ross, W., Jacobs, Dr. N., & Oliver, C. (2021, January). NOAA Fisheries Updated Impact Assessment of the COVID-19 Crisis on the U.S. Commercial Seafood and Recreational For-Hire/Charter Industries: National Snapshot, January-July 2020. NOAA Fisheries. https://media.fisheries.noaa.gov/2021-02/Updated-COVID-19-Impact-Assessment-webready.pdf

Rutz, and others. COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. Nature Ecology & Evolution, 4(9), 1156–1159. https://doi.org/10.1038/s41559-020-1237-z. 2020.

Saadat, and others. Environmental perspective of COVID-19. Science of The Total Environment, 728, 138870. https://doi.org/10.1016/j.scitotenv.2020.138870. 2020.

Saliu, F., Veronelli, M., Raguso, C., Barana, D., Galli, P., & Lasagni, M. (2021, July). https://linkinghub.elsevier.com/retrieve/pii/S2666765721000132

Schadeberg, and others. Productivity, pressure, and new perspectives: Impacts of the COVID-19 pandemic on marine early-career researchers. ICES Journal of Marine Science, 79(8), 2298–2310. https://doi.org/10.1093/icesjms/fsac167. 2022.

Schijns, and others. Five centuries of cod catches in Eastern Canada. ICES Journal of Marine Science, 78(8), 2675–2683. https://doi.org/10.1093/icesjms/fsab153. 2021.

Schwenzfeier, and others. Behind the MSC Blue Tick: Illegal Fisheries, Marine Pollution, High Grading and Blowouts—Further Infringements in MSC-Certified Tuna Fisheries of the Western and Central Pacific Ocean (p. 46). Shark Guardian. 2023.

Selig, and others. Mapping global human dependence on marine ecosystems. Conservation Letters, 12(2), e12617. https://doi.org/10.1111/conl.12617. 2019.

Shams, and others. Plastic pollution during COVID-19: Plastic waste directives and its long-term impact on the environment. Environmental Advances, 5, 100119. https://doi.org/10.1016/j.envadv.2021.100119. 2021.

Shanks, and others. Pacific islands which escaped the 1918–1919 influenza pandemic and their subsequent mortality experiences. Epidemiology and Infection, 141(2), 353–356. https://doi.org/10.1017/S0950268812000866. 2013.

Somchuea, and others. Marine Resource Recovery Following the COVID-19 Event in Southern Thailand. Civil Engineering Journal, 8(11), 2521–2536. https://doi.org/10.28991/CEJ-2022-08-11-011. 2022.

Sorensen, and others. From Bad to Worse: The Impact on COVID-19 on Commercial Fisheries Workers. Taylor & Francis Group, 4. https://doi.org/10.1080/1059924X.2020.1815617. 2020.

Stoll, and others. Alternative Seafood Networks During COVID-19: Implications for Resilience and Sustainability. Frontiers in Sustainable Food Systems, 5, 614368. https://doi.org/10.3389/fsufs.2021.614368. 2021.

The State of World Fisheries and Aquaculture 2022. FAO. https://doi.org/10.4060/cc0461en. 2022.

Thomson, and others. Real-time observations of the impact of COVID-19 on underwater noise. The Journal of the Acoustical Society of America, 147(5), 3390–3396. https://doi.org/10.1121/10.0001271. 2020.

Thomson, J. (2020, April 8). Fisheries and Oceans Canada pulls at-sea observers from fishing boats due to coronavirus pandemic. The Narwhal.

UNCTAD. (2022a). COVID-19 AND MARITIME TRANSPORT NAVIGATING THE CRISIS AND LESSONS LEARNED (COVID 19 Response, p. 99). https://unctad.org/system/files/official-document/tcsdtlinf2022d1_en.pdf

UNCTAD. (2022b). Emerging strategies for ports during the pandemic (Policy Brief 93; p. 4). United Nations. https://unctad.org/system/files/official-document/presspb2022d1_en.pdf

UNCTAD (Ed.). (2022c). Impact and implications of COVID-19 for the ocean economy and trade strategy: Case studies from Barbados, Belize and Costa Rica. United Nations.

United Nations. International cooperation to address challenges faced by seafarers as a result of the COVID-19 pandemic to support global supply chains (Agenda item 128 (a); UNGA 75th Assembly, p. 3). https://documents.un.org/doc/undoc/ltd/n20/332/14/pdf/n2033214.pdf. 2020.

United Nations. COVID-19 and Maritime Transport: Impact and Responses (Series No 15; Transport and Trade Facilitation Series, p. 74). United Nations Conference on Trade and Development. https://unctad.org/system/files/official-document/dtltlb2021d1_en.pdf. 2021.

United Nations. UN Report: Ocean Decade Vision 2030 White Papers. https://oceandecade.org/publications/ocean-decade-vision-2030-white-papers/. 2024.

Usui, and others. Impacts of the COVID-19 pandemic on mammals at tourism destinations: A systematic review. Mammal Review, 51(4), 492–507. https://doi.org/10.1111/mam.12245. 2021.

Viglione, G. (2020, April 13). How COVID-19 could ruin weather forecasts and climate records. Nature, 580, 440–441.

Villasante, and others. Impacts of the COVID-19 pandemic on the Spanish seafood sector. Marine Policy, 169, 106293. https://doi.org/10.1016/j.marpol.2024.106293. 2024.

Villasante, and others. Rapid Assessment of the COVID-19 Impacts on the Galician (NW Spain) Seafood Sector. Frontiers in Marine Science, 8, 737395. https://doi.org/10.3389/fmars.2021.737395. 2021.

Visbeck, M. (2020, June). Ocean Science During the Corona Virus Pandemic CHALLENGES AND OPPORTUNITIES. The Oceanographic Society. https://tos.org/oceanography/assets/docs/33-2_visbeck.pdf

Wang, and others. Global face mask pollution: Threats to the environment and wildlife, and potential solutions. Science of The Total Environment, 887, 164055. https://doi.org/10.1016/j.scitotenv.2023.164055. 2023.

Ward-Paige, and others. A framework for mapping and monitoring human-ocean interactions in near real-time during COVID-19 and beyond [Preprint]. Open Science Framework. https://doi.org/10.31219/osf.io/sxnu5. 2020.

WCPFC CHAIR. (2020, April 8). Commission Decision in response to COVID-19 regarding suspension of requirement for purse seine observer coverage until 31 May 2020. Western and Central Pacific FIsheries Commission. https://www.wcpfc.int/doc/circ-2020-24/commission-decision-response-covid-19-regarding-suspension-requirement-purse-seine

Weng, and others. Decreased tourism during the COVID-19 pandemic positively affects reef fish in a high use marine protected area. PLOS ONE, 18(4), e0283683. https://doi.org/10.1371/journal.pone.0283683. 2023.

White, and others. Early effects of COVID-19 on US fisheries and seafood consumption. Fish and Fisheries, 22(1), 232–239. https://doi.org/10.1111/faf.12525. 2021.

White, and others. State-level variation of initial COVID-19 dynamics in the United States: The role of local government interventions. PLoSONE, 14. https://doi.org/10.1371/journal.pone.0240648. 2020.

White, and others. The direct and indirect effects of a global pandemic on US fishers and seafood workers. PeerJ, 10, e13007. https://doi.org/10.7717/peerj.13007. 2022.

Williams, and others. The past, present, and future of plastic pollution. Marine Pollution Bulletin, 176, 113429. https://doi.org/10.1016/j.marpolbul.2022.113429. 2022.

World Health Organization. Global excess deaths associated with COVID-19, January 2020—December 2021. https://www.who.int/data/stories/global-excess-deaths-associated-with-covid-19-january-2020-december-2021. 2022.

WWF. Nello smaltimento di macherine e guanti serve resposabilità. World Wide Fund for Nature. https://www.wwf.it/scuole/?53500%2FNello-smaltimento-di-mascherine-e-guanti-serve-responsabilita. 2020.

Xu, and others. Estimating the effect of COVID-19 epidemic on shipping trade: An empirical analysis using panel data. Marine Policy, 133, 104768. https://doi.org/10.1016/j.marpol.2021.104768. 2021.

Yosef, and others. Anthropopause positively influenced Red Sea Clownfish (Amphiprion bicinctus) populations but not the host sea anemone (Actiniaria spp.) in Eilat, Israel. Marine Policy, 145, 105280. https://doi.org/10.1016/j.marpol.2022.105280. 2022.

Zhao, and others. Defining and quantifying China's ocean economy. Marine Policy, 43, 164–173. https://doi.org/10.1016/j.marpol.2013.05.008. 2014.

Section 5B

Chapter 8: Indigenous Peoples ~~Peoples~~, Traditional ~~Owner~~ and Local Community Knowledge~~s~~ (ITLK)

Coordinating author: Paul Mboya Tuda
Co-authors (alphabetic order): Shelley Denny, Sherry Pictou, Winifereti U, Nainoca
Co-Lead: Ian Butler, Jörn Schmidt

1. Keynotes

- Indigenous Peoples, Traditional and Local community Knowledges (ITLK) are increasingly being acknowledged as a valuable complement knowledge systems and ocean governance models.
- Scientific and governance systems frequently conceptualize ITLK as only land-based and also assume ITLK must be "integrated" or validated by non-Indigenous methodologies, which can lead to power imbalances and a loss of ITLK's cultural integrity.
- Effective knowledge systems are challenged by a persistent failure to recognize or engage with diverse world views, including Indigenous Peoples' ways of knowing.
- Ocean governance models that incorporate ITLK are more likely to achieve comprehensive well-being outcomes including by maintaining cultural heritage, fostering community resilience and offering generational insight into marine ecosystems and their sustainable use.
- Achieving a sustainable future necessitates specific actions such as promoting ITLK leadership in decision-making, ensuring inclusive and equitable participation, aligning objectives, and legally recognizing and empowering these communities as equal stakeholders.
- Examples of mutually respectful and effective collaboration, where ITLK and scientific knowledge have been woven together to generate context specific insights and more inclusive outcomes, have been documented.
- Future WOAs should aim to improve the weaving of ITLK alongside conventional scientific knowledge and uphold the protection of Indigenous Peoples, Traditional and Local community values and rights.

Indigenous Peoples, Traditional Owner and Local community Knowledges (ITLK) areis increasingly being acknowledged as a source of a valuable complement to conventional scientific knowledge.

- Regional workshops by UNDOALOS aimed to understand key global issues surrounding ITLK for the respectful inclusion in WOA IIIeinformation complementary to non-indigenous or conventional scientific information

- Regional workshops by UNDOALOS aimed to understand key global issues surrounding ITLK for the respectful inclusion in WOA IIIRegional workshops by UNDOALOS aimed to understand key global issues surrounding ITLK for better integration in future WOAs ITLK plays a vital role in supporting ocean governance, maintaining cultural heritage, and fostering community resilience.

ITLK contributes to ocean governance, maintaining cultural heritage, fostering community resilience and offering generational insight into marine ecosystems and their sustainable use.

Effective knowledge systems are challenged by a persistent failure to recognize or engage with diverse world views, including indigenous ways of knowing.

The challenges of working with ITLK include the persistence of non-indigenous ways of knowing and the failure to recognize or engage with diverse world views and knowledge systems

- The challenges of working with ITLK include the persistence of non-indigenous ways of knowing and the failure to recognize or engage with diverse world views and knowledge systemsThe challenges of working with ITLK include the persistence of non-indigenous ways of knowing and the failure to consider Indigenous values and different worldviews.

There are documented eExamples of mutually respectful and effectiverespectful collaboration, where ITLK and scientific knowledge have been woven together to generate context specific insights and more inclusive outcomes, where ITLK and scientific knowledge have been woven together to generate context specific insights and more inclusive outcomes, have been documented.

Effective inclusion of ITLK as cross-cutting issue in regional workshops has been demonstrated as a valuable tool.

~~Future WOAs will aim to improve the weaving of ITLK alongside conventional scientific knowledge and uphold the protection of Indigenous rights, in line with the UN Declaration on the Rights of Indigenous Peoples (UNDRIP).~~

~~Future WOAs will aim to improve the weaving of ITLK alongside conventional scientific knowledge, and uphold the protection of Indigenous rights, by their incorporation in regional workshops, in line with the UN Declaration on the Rights of Indigenous Peoples (UNDRIP).~~

- ~~There are successful examples of Indigenous and non-indigenous knowledge co-existing, being used to mutual benefit and supported by appropriate methods.~~

~~Future WOAs should adopt prioritizean approaches that better weaves and respects Indigenous Peoples' Knowledge and Local Community Knowledge ITLK alongside conventional scientific knowledge.Future WOAs will aim to improve the weaving of ITLK alongside conventional scientific knowledge and uphold the protection of Indigenous rights, in line with the UN Declaration on the Rights of Indigenous Peoples (UNDRIP).~~

~~Future WOAs should adopt an approach that better integrates and respects ITLK alongside non-Indigenous knowledge~~

2. Introduction

Indigenous Peoples, Traditional and Local Communities possess knowledge systems developed through generations of intimate interaction with their surrounding environment, often referred to as Traditional Ecological Knowledge (TEK) (Strand and others, 2024). These knowledge systems are based on lived experiences, cultural practices and long-term observations, which are transmitted across generations through oral traditions and cultural practices ~~which are passed down through generation and are communicated via oral traditions and cultural practices~~ (Magni, 2017; Pictou, 2023). The methods of transmission —through stories, ceremonies, and customary practices —are as important as the knowledge itself (Magni, 2017; Ogar and others, 2020). As a result, these knowledge systems are highly place-based and context-specific, capturing the complex relationships among people, species, and ecosystems~~reflecting the diverse relationships between people, species, and ecosystems~~ (Jessen and others, 2022; Strand and others, 2024).

Although this chapter uses the terminology recognized by the United Nations, using the terms "Indigenous Peoples" and "Local Communities", it should be noted that other terms may be used in national contexts. In Australia, the term 'Traditional Owner' specifically refers to Aboriginal and Torres Strait Islander peoples with cultural, spiritual, or historical ties to particular land and sea areas ~~In Australia, for example, the term traditional owner is used specifically to refer to Aboriginal and Torres Strait Islander peoples who have cultural, spiritual or historical ownership of specific areas of land or sea~~(Davies and others, 2020). However, to be consistent with international law and the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), the term is not used throughout this chapter.

When discussing ITLK, it is important to emphasize that ITLK is a dynamic and evolving knowledge system, weaving~~integrating~~ Indigenous Peoples' expertise with contemporary observations and lived experiences ~~ITLK is not limited to historical or static information, but is a dynamic and evolving system that integrates Indigenous knowledge with current observations and experiences~~ (Bay and others, 2023; Friedlander & Gaymer, 2021). ITLK is deeply rooted in the relationship between Indigenous Peoples, traditional and local communities and their environment and is a reflection of how communities engage with, manage, and sustain natural resources, while adapting to emerging challenges ~~n expression of how the communities interact with, use and manage natural resources, and strengthen their resilience in the face of new and complex circumstances~~ (Rist and others, 2019; Tilot and others, 2021). The adaptability of ITLK makes it essential for biodiversity conservation, environmental sustainability, and marine resource management ~~This dynamic nature of ITLK makes it particularly relevant and valuable for biodiversity conservation, environmental sustainability, and ocean conservation efforts~~ (Allison and others, 2023; Kitolelei and others, 2022; Ogar and others, 2020).

Recent publications by Strand and others, (2024) and Allison and others, (2023) highlight the growing and critical recognition of the role of ITLK in sustainable ocean management. This recognition extends to several key areas such as developing more inclusive and equitable ocean plans, improving protection of marine biodiversity, enhancing ecosystem resilience and fostering more holistic approaches to ocean governance that consider socio-ecological systems (Barianaki and others, 2024; Frid and others, 2023; Ogar and others, 2020). This view is also supported by a recent publication by the Food and Agriculture Organization of the United Nations (FAO) on the governance of small-scale fisheries, which highlights how Indigenous Peoples knowledge systems contribute not only to environmental sustainability but also to inclusive management and knowledge-sharing within socio-ecological systems (Berkes and Franz, 2025). This holistic approach often incorporates spiritual and cultural values, emphasizing the interconnectedness between people and the sea (Rist and others, 2019; Tilot and others, 2021). Thus, governance structures including~~tegrating~~ ITLK are more likely to represent multiple facets of well-being (Allison and others, 2023; Magni, 2017), because they consider the

interconnectedness of social, economic, environmental, and cultural aspects of life, prioritize community interests, promote sustainable practices, preserve cultural identity, and demonstrate adaptability in the face of changing circumstances.

As the world faces compounded environmental crises, there is growing recognition that ITLK can provide insights for sustainable resource management and biodiversity conservation. This has led to the incorporation of ITLK into global processes and assessments such as the Global Assessment Report on Biodiversity and Ecosystem Services (Balvanera and others, 2022; IPBES, 2019), reports by the Intergovernmental Panel on Climate Change (IPCC) (Ford and others, 2016) and contributions to the Convention on Biological Diversity (CBD)(Parks and Tsioumani, 2023). Similarly, the World Ocean Assessment (WOA) process, which was established by the ~~a~~ UN General Assembly resolution in 2004 and is currently in the third cycle (WOA III) has also recognized the need to meaningfully include and engage with ~~integrate~~ ITLK throughout its assessment to capture a more holistic understanding of the state of the marine environment and inform sustainable ocean governance. Moreover, recent global initiatives such as the UN Decade of Ocean Science for Sustainable Development (2021-2030) and the Biodiversity Beyond National Borders (BBN) Agreement explicitly recognize the importance of ITLK in promoting ocean sustainability (UNESCO-IOC, 2021; United Nations, 2023). These frameworks emphasize the need for culturally appropriate participation, knowledge-sharing and equal participation - principles in line with the UN Declaration on the Rights of Indigenous Peoples.

The first cycle of the WOA, conducted from 2010-2014, focused on producing the first global integrative marine assessment (UNDOALOS, 2017). However, it did not explicitly incorporate ITLK. In the lead up to the second cycle, initiated in 2016, an assessment was conducted, which identified gaps in previous assessments, including the lack of representation of diverse knowledge systems such as ITLK. Based on this, the second cycle was tasked with producing technical abstracts that could better summarize information for policymakers. However, the inclusion of ~~But~~ ITLK in past assessment ~~integration~~ was still limited. It was in the scoping and planning for the third cycle, starting in 2021, that the explicit recognition of ITLK emerged as a priority. The shift toward greater inclusion was driven by feedback from WOA regional workshops, which highlighted the need to acknowledge and weave together ITLK within the WOA process~~integrate Indigenous Peoples' knowledge, Traditional Owners' knowledge, and local community practices into the WOA~~. This was seen as a major gap in previous World Ocean Assessments, as highlighted through feedback received during the WOA regional workshop process.

As a result, the outline for the WOA III was developed to include a dedicated chapter on ITLK. To inform the chapter development, the organizers have also conducted focused regional

workshops and solicited case studies from stakeholders, with the goal of documenting ~~capturing~~ diverse ITLK experiences and insights. While this represents progress, more work is needed to fully empower the inclusion of ITLK in the WOA and future assessment processes. The participants in regional workshops, including the ITLK representatives, see this dedicated ITLK chapter as an important first step towards establishing a stronger partnership between ITLK holders and the conventional scientific community in assessing the state of the world's oceans. They emphasized the need to go beyond tokenistic inclusion and truly weave ITLK into the WOA process and outputs as equal and essential contributions.~~integrate ITLK as an equal and essential component of the WOA process and outputs.~~

3. Acknowledging the value and application of Indigenous Peoples' Knowledge(s)

Many worldwide ancient Indigenous Peoples' creation or origin stories from around the world center on life beginning with or in relation to the ocean, the sea or water. Similarly, centuries old archaeological shell midden sites (Rick, 2024) and petroglyphs or rock art—including those of whales or whale hunting— exist across the globe, marking Indigenous Peoples' knowledge and knowledge transformations and human relationships with both land and water (Charette and others, 2021). According to the Ocean Human Rights Platform, there are "27 million [I]ndigenous people in nearly 2,000 communities across 87 countries" living in coastal areas (Fears, 2016). There are also sea-nomadic or mobile Indigenous Peoples' societies, such as the **Bajau** and **Moken** peoples of Southeast Asia, whose deep maritime knowledge and mobility are central to their identities and ways of life. These communities, often referred to as "sea peoples," maintain rich traditions of marine stewardship, including sustainable fishing, freediving, and ocean navigation (Boni and others, 2024). More importantly, there are countless Indigenous Peoples increasingly becoming displaced from their ancestral oceanic sources of food and livelihood (Crosman and others, 2022). Knowing their "lives, food, and livelihoods depend on the health of ocean resources, Indigenous ~~[~~P~~]~~eoples have, through millennia, developed social-ecological systems of marine resources management that rely on cultural traditions as well as an intimate dynamic and long-term knowledge of the environment" (Vierros and others, 2020:119; Also see Johannes, 1978; Johannes and others, 2000).

The importance of ~~Indigenous knowledges~~ITLK for protecting and conserving biodiversity and addressing climate change is becoming increasingly recognized in the international fora, such as Conference of the Parties to the Convention on Biological Diversity (COP), International Union for Conservation of Nature=(IUCN), United Nations Permanent Forum on Indigenous Issues

(UNPFII), and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES.) Recently, the importance of Indigenous Peoples' knowledge for ocean sustainability is highlighted in a series of "blue papers" commissioned by the *High Level Panel for a Sustainable Ocean Economy* (HLPSOE) (Strand et al.), which calls for the "co-production" of ocean plans with Indigenous Peoples (2024). Many challenges remain, especially in applying the *UN Declaration on the Rights of Indigenous Peoples* and fundamental Human Rights in international decision-making spheres, and application of the new Biodiversity Beyond National Jurisdiction agreement(BBNJ), which are made up of various fragmented legal frameworks (Bodansky, 2024; Vierros and others, 2020; Chirop et al. 2019) in processes regarding deep sea mining (Morgera, 2024) and for achieving the SDG 14 – Life Below Water, itself (Haas, 2023).

A main barrier for addressing this challenge lies within how non-Indigenous knowledge, conventional scientific method and governance systems: 1) often treat the ocean as being separate from the land; 2) conceptualize Indigenous People as being only land based, and; 3) assume that Indigenous Peoples' Knowledges need to be "integrated" or validated by non-Iindigenous Peoples' knowledge or conventional scientific methodologies. (Crosman and others, 2022; Jones and others, 2024; Strand and others, 2024). As stated by Enyew, Poto, and Tsiouvalaj (2021:213):

> This land-sea dichotomy contravenes the holistic vision of Indigenous peoples, and ignores the fact that activities conducted on land may affect the rights of local communities and Indigenous [P]eoples related to their traditional use of marine spaces and resources. The *Law of the Sea* also principally follows a zonal division of the ocean space, where each maritime zone is subject to different levels of State sovereignty and jurisdiction, and governed by distinct regulatory mechanisms. This zonal approach and the associated logic of State sovereignty does not follow Indigenous boundaries and has various consequences on Indigenous peoples.

For some Indigenous Peoples, not only are land and water interconnected but also so are all life forms. This interconnectedness is embedded in Indigenous Peoples' principles of mutual reciprocity in their land and water-based practices for food and livelihood and for ensuring intergenerational ecological and human lifespans (Crosman and others, 2022; Enyew and others, 2021; Pictou, 2023; Somiah, 2022; Von Der Porten and others, 2019). Many Indigenous Peoples assert that the concepts of life, energy and spirituality are synonymous. All of them are intertwined and embedded in the territory and, therefore, cannot be addressed separately. At the core of existence, there is no division between water, plants, animals, and even human beings. For that reason, when talking about life, spirituality, water and territory, we cannot discuss them in silos (Martinez-Cruz and others, 2024).

It is also important to note that Indigenous Peoples' relational worldviews and practices derive from a vast array of diverse global contexts and are not static or frozen in time nor space. Indigenous Peoples can also be mobile and transitionary between and across various scales of diverse lands and waters formulating local, national and international diplomacies and protocols (Ambers and George, 2024; Borrows, 2016; Crosman and others, 2022).

These concepts of harmonization and fluid internationalism are synonymous with "Two-Eyed Seeing", which applies the strengths of both Indigenous and non-Indigenous Peoples worldviews (M'sit No'kmaq 2021; Ocean Networks Canada 2022) or embraces multiple knowledge systems and "diverse ways of knowing" (Strand and others, 2024), without discrediting the diversity of approaches.

4. Approaches and guiding principles for applying ITLK

Approaches and guiding principles of working with ITKL are less documented than the challenges of working with ITLK. But there is increasing recognition of the value and role of Indigenous Peoples, local knowledge, and the need for knowledge co-creation to enhance ocean governance (Strand and others., 2022). Recent examples of emerging frameworks include co-production approaches grounded in Indigenous Peoples' research protocols and priorities, such as those developed in Arctic research (Yua and others, 2022) and in diverse community contexts (Rathwell and others, 2025). It is also important to note that many Indigenous Peoples ~~Nations~~ have local protocols and knowledge-sharing principles that may not be publicly available. This growing field is reflected in partnership models that bring together disparate worldviews (Indigenous and non-Indigenous Peoples) ~~This is evident in partnership models of bringing together disparate worldviews (Indigenous and non-Indigenous)~~ in cross-cultural collaboration to challenge the status quo, such as ethical space (of engagement) (Ermine, 2007) and knowledge co-creation as Two-Eyed Seeing (Bartlett and others, 2012; Marshall and others, 2021; Reid and others, 2021).

Understanding ITLK involves understanding that distinct worldviews are not pan-Indigenous. These worldviews do, however, share common values inherent to Indigenous P~~p~~eoples. Key values include relatedness, respect, and reciprocity existing as a 'package' underpinning Indigenous Peoples' way of life. Relatedness, as connection to the physical and spiritual realms, also, referred to as kinship, is maintained through respectful relationships with other people and species that are reinforced by cultural practices. Reciprocity is required to maintain respectful relationship. It is the responsibility and obligation as stewards to maintain balance and harmony to the natural and spiritual realms (Artelle and others, 2018; McMillan and Prosper, 2016; Whyte, 2013).

Even when one is aware of the differences between Indigenous and non-Indigenous peoples' knowledge systems, working within the context of ITLK poses several challenges, especially if knowledge holders and those who seek such knowledge are unaware of distinct differences, or lack training in the inter and transdisciplinary approaches (Fernández-Llamazares and others, 2021; Ens and others, 2012). Some scholars have even cautioned against "integrating" ITLK because it: prioritizes the non-Indigenous ways of knowing, fails to consider Indigenous Peoples' values and worldviews, lacks a shared understanding of ITLK as well as the understanding of the benefit of knowledge pluralism valued and used by Indigenous peoples (Bingham and others, 2021; Latulippe, 2015).

Despite these barriers, there are examples of successful ways in which Indigenous and non-Indigenous peoples' knowledge and understandings have been respectfully bridged (Alexander and others, 2019)~~integrated~~. For example, of the use of qualitative data derived from social science methods in quantitative models (Ban and others, 2017; Lam and others, 2019), as well as using Bayesian Belief Networks (BBNs) - qualitative and quantitative indicators developed from participatory workshops as a tool to bridge IK and scientific knowledge (e.g. Slave River Delta, Canada; Lam and others, 2019). In this regard, the IPBES Values Assessment, (Termansen and others, 2022), draws attention to the practices that are consistent with the values of I~~i~~ndigenous Peoples and local communities. It stresses the importance of recognizing plural values of nature, relational, spiritual, and cultural and supports valuation processes that are co-developed, context-specific, and respectful of knowledge sovereignty.

Similarly, qualitative data derived from interviews with Indigenous fishers who relied on a specific food source to provide a catch rate, informed by their past experiences, was used to determine declines in catch rates using simulations (Ban and others, 2017). Another recent example by Gryba and others, (2025), demonstrates the use of ITLK as a sole data source in developing habitat selection models, reinforcing the value of ITLK in quantitative ecological research. Thus, there is opportunity to use Indigenous Peoples' knowledge acquired through social science methods in quantitative-based modeling.

5. WOA III scoping work: regional workshops and case study

In an effort to understand the scope of ITLK and the global range of issues related to ITLK so that it could be better incorporated into the WOA, UNDOALOS undertook a series of regional workshops and examined one case study as part of the scoping process for WOA III.

5.1 Regional workshops

Regional workshops were held in Brazil, Jamaica, Seychelles, Portugal, and the United States. Each workshop brought representatives from Indigenous P~~p~~eoples, Traditional Owners, local

community members, and experts and practitioners working in ocean-related institutions (Figure 1). The scoping process focused on identifying regional needs, reviewing existing information, and considering perspectives on what should be included in the assessment to be most useful for policymakers.

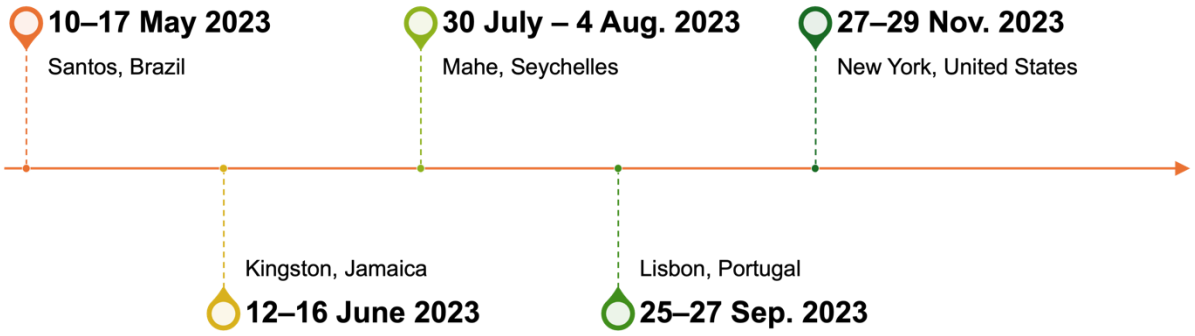


Figure 2~~1~~. Timeline of regional workshops held in Brazil, Jamaica, Seychelles, Portugal, and the United States, gathering diverse stakeholders to identify regional needs and perspectives for an ocean-related assessment to inform WOA III

To allow for comparison across regions, workshop deliberations were centered on five key questions:

1. How might Indigenous Peoples, Traditional Owners, and local community knowledge assist in understanding the economic and social drivers that produce changes observed in the ocean?
2. What are the current consequences of ongoing changes in the ocean for Indigenous, Traditional Owners, local community social systems, and cultural security?
3. What do future projections and outlooks for the ocean look like across societal and cultural groups and people?
4. What actions could be taken to achieve a sustainable future that will position all components of society, including Indigenous Peoples, Traditional Owners, and local communities, as equal agents in taking such actions?
5. Which socio-economic factors will have the greatest influence on the contributions that societal and cultural groups, including Indigenous Peoples, Traditional Owner and local communities, can make to achieving a sustainable future?

For help summarize the regional contributions, workshop notes were analyzed using a grounded theory approach. The participants' responses were coded across the five main

questions, identifying common themes and keywords. The terms most used in all workshop texts were identified to generate a word cloud (Figure 2). The figure highlights the most common concepts arising from the discussions around ~~the integration of~~ ITLK in the areas of ocean governance, cultural heritage and community resilience.

Figure ~~32~~. Word cloud highlighting the most frequently mentioned concepts derived from responses during regional workshops on Indigenous, Traditional Owner, and local community knowledge discussion~~integration~~.

The word cloud (Figure 2) is not intended to be conclusive or to capture the full diversity of ITLK, but rather to serve as a tool to summarize key views and ideas raised in the regional workshops - especially those of traditional and local communities and ocean-related experts. The word cloud as such provides a broad overview of the views shared by the participants in the regional workshops. The most common terms - knowledge, traditional, ~~i~~indigenous, local, communities, groups, and impacts - reflect the central role of culturally rooted, place-based knowledge systems in interpreting ocean change and contributing to an equitable governance.

The repeated occurrence of terms such as understanding, change, social, process and sustainable underlines the dynamic and interdisciplinary nature of ITLK in relation to both environmental and social change. Words like recognition, culture, rights, governance, access and inclusion all speak to the call of participants to better ~~integrate and~~ respect ITLK holders as equal partners in ocean governance processes. Insights from regional workshops reveal the vital role that ITLK plays in supporting ocean governance, maintaining cultural heritage, and fostering community resilience particularly in light of the ongoing changes in the ocean (Figure 3).

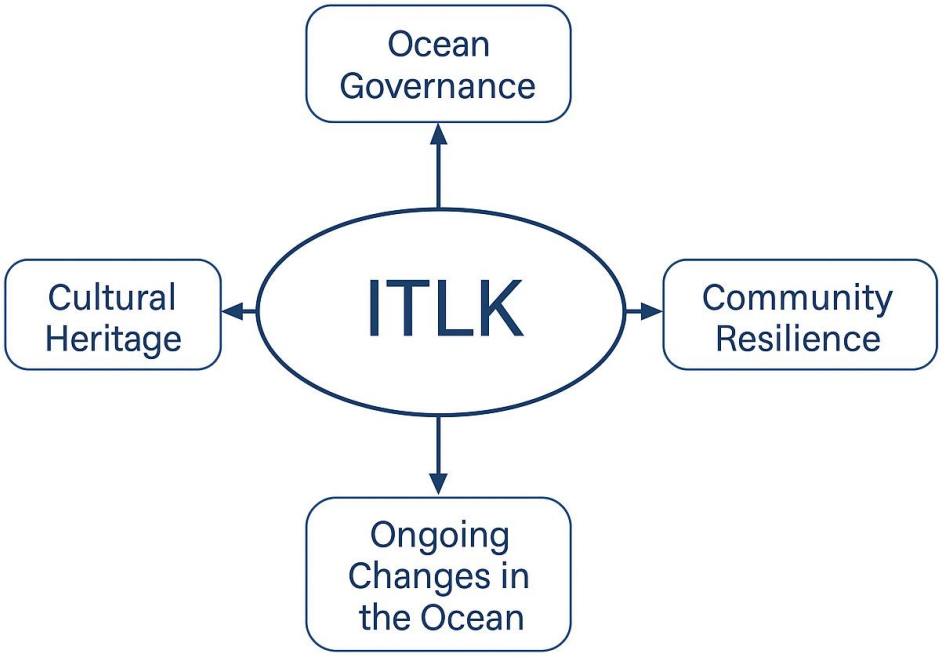


Figure ~~4~~3 Conceptual diagram illustrating key relationships derived from regional workshop responses, showing how ITLK contributes to ocean governance, cultural heritage, and community resilience in the context of ongoing ocean change

Given its long-standing historical use and the years invested in protecting and passing it down from one generation to the next, ITLK provides valuable, culturally authoritative, and context-specific insights for managing coastal and marine resources. Amid the current changes in the ocean, ITLK offers a lens for understanding the economic and social drivers behind these changes. In addition, Indigenous ~~communities~~ Peoples have a wealth of knowledge about ocean-related changes that can be used to calibrate scientific forecasts (Kaiser and others, 2019). Indigenous Peoples are aware of how to define, understand and use natural resources in a sustainable manner. They are also key players and have different perspectives to understand the crises and challenges and how to overcome them.

Many Indigenous Peoples possess valuable knowledge that contributes to the management of coastal resources and resource use pattern. Therefore, the effects of ongoing ocean change on these communities cannot be fully understood without incorporating an ITLK perspective. This is because the impacts of ocean changes extend beyond the biological realm – they disrupt the Indigenous Peoples ways of life, disrupt their social systems and erode their cultural identity, and exacerbate their vulnerability to

environmental and economic pressures. For instance, The loss of a biological species is not only a significant ecological loss but also leads to the loss of cultural identity.

This loss of cultural identity is exemplified by the direct experiences of Indigenous and local communities. As one participant noted, *'Climate change impacts fish stocks, affecting local activities and cultural heritage,'* illustrating how the decline of key species disrupts not only livelihoods but also "Loss of traditional knowledge and cultural identity." Additionally, *'Threats to sacred sites and cultural traditions'* highlight how environmental degradation can lead to a loss of species and spaces critical to community identity. Despite these impacts, *'Loss of traditional knowledge and cultural identity'* is an aspect often overlooked in scientific assessments, highlighting the need for a more encompassing frameworks that account for not only the ecological aspects but also cultural and spiritual impacts as well as of ecological changes.

The cultural assets of most Indigenous Peoples, Traditional Owners and local communities are closely tied to the natural environment. Significant changes in these environments, can undermine their cultural security. due to this close connection, they are especially vulnerable to both environmental and economic changes. Climate change-induced displacement, loss of livelihoods, and food and water insecurity were among the most prevalent issues that emerged from the discussions. Economic changes such as growing blue economies increase the probability of climate injustice, exacerbating the "Marginalization and weakening of societal coping mechanisms." Addressing these vulnerabilities requires adaptive strategies, informed planning, and inclusivity in governance and decision-making processes. As one participant noted, 'Inclusive and equitable participation in decision-making processes' is essential for ensuring that the voices of Indigenous and local communities are heard. Examples include co-management frameworks and Community-Based Fisheries Management (CBFM), which provide platforms for equitable participation.

Future projections and outlooks are different across societal and cultural groups, varying greatly between Indigenous Peoples and non-Indigenous ~~communities~~ Peoples due to 'their different worldviews, ways of knowing, and knowledge systems'. There will be regional variations in the effects, such as temperature changes and sea level rise, so certain communities or groups with different socioeconomic levels and groups will be impacted differently than others. Unfortunately, if 'business as usual' scenarios are implemented, the future outlook will only become bleaker, inequality will inevitably increase, and this will vary depending on the state of the economy and access to the ocean and its resources.

For Indigenous Peoples, with difficult access to income alternatives and technologies, the cost of living will be higher in the future, and they will be forced to transform their lives (e.g. move to higher ground or find new ways to earn an income, which is less dependent on the ocean). Therefore, assessments of climate change impacts and adaptation strategies should bring on board diverse perspectives to truly reflect the realities on the grounds.

Achieving this, requires implementing "targeted actions that position all components of society", including Indigenous Peoples, Traditional Owners, and local communities, as equal stakeholders. These actions include *'promoting Indigenous leadership in decision-making roles'* and embedding *'inclusive and equitable participation in decision-making processes.'* It is essential to *'align government objectives with Indigenous community goals'* while enforcing *'policies that protect Indigenous communities' rights.'* Strengthening partnerships is vital, as highlighted by the call for *'capacity building through partnerships'* and the need to *'develop bottom-up governance approaches'* that prioritize local agency. Additionally, incorporating traditional knowledge into formal systems through *'transdisciplinary approaches'* and integrating it into *'environmental impact assessments'* ensures these communities' contributions are recognized and valued. In the end Indigenous, Traditional Owners and Local communities are the ones with the best interests of their localities at heart, whether developmental or otherwise and so what they think and say about their local areas is a cultural and legal right that holds so much weight.

The socio-economic factors that will have the greatest impact on the social and cultural groups to achieving a sustainable future include recognition, empowerment and inclusive governance. "Legal recognition that empowers these communities" represents a starting point. This ensures that their rights and territories are respected and included into broader governance frameworks. Furthermore, embedding "inclusive deliberative advisory processes in marine resource management systems" promotes equal participation and collaboration. In addition, "promoting Indigenous [P]eoples, Traditional Owners and local communities in leadership positions" improves their ability to influence decision-making processes. Aligning government objectives with those of these communities, such as *'balancing government need to create employment with ecosystem capacity,'* ensures policies are both sustainable and equitable. Empowerment through *'ensuring participation at rules and decision-making processes at multiple levels'* and securing *'tenure rights of communities'* strengthens their capacity to contribute effectively. Finally, advancing *'social justice, equality, and equity across groups'* is essential to address historical inequalities and build a future where all communities can thrive and no one is left behind."

5.2 Case study: Fijian Indigenous methodologies and frameworks - Mana the Mud Lobster

Indigenous Fijian society and their kinship system use sayings and idioms for teaching and instructions. There is deep sense of interconnectedness in the Indigenous world, in Fiji for instance, where every Indigenous Person has a totemic plant and animal (fish, bird or terrestrial animal). Garibaldi and Turner (2004), defines 'cultural keystone species' or totems as "the culturally salient species that shape in a major way the cultural identity of a people, as reflected in the fundamental roles these species have in diet, materials, medicine, and/or spiritual practices". Interconnectedness in the Fijian world is represented by totemism, as expressed by Tuwere, (2002)." The totems represent among other things the interdependence of land, sea or river, and sky in the world of Fijians. They are usually a trilogy of linked ika (fish); kau (trees); and manumanu (bird, animal or insect)". These totems (such as the mud lobster above) can be used as a metaphor to represent the framework in community planning and even academic writing, such as in a thesis or methodology such as the Kakala research framework by Professor Konai Thaman (Johansson-Fua, 2023; Thaman, 1997). Kakala is an example of a Pacific method of teaching and learning by Thaman (1997). It was intended to encourage Pacific students to articulate theories from their perspectives and to recognize Pacific world views in their thinking and learning (Thaman, 1997).

In collaborating with IPLC it is good practice to communicate in the local language and translate any printed material into the local language.

In the Fijian Rewa Strategic Development Plan (SDP), the Mud Lobster (Mana in Fijian) (*Thalassina anomala*) (Figure 3) is used as a metaphor in its framework – in terms of the physiology and the essence of the Mana. For instance (as per diagram) "Physiologically" the eight legs (pereopod) of the Mud lobster represents the eight Priority areas of the SDP whilst for the "Essence", ecologically speaking, the Mud Lobsters are recognized as the "Friends of the Mangroves" as its burrowing is important for the recycling of nutrients in the mangrove ecosystem. This resonates with the Indigenous people of Rewa as they live in the Rewa Delta surrounded by mangroves. This metaphor underscores the use of the SDP, the deep connection between cultural values, ecological understanding and sustainability in fostering brings development. It also supports contextualization, relevance and sense of ownership by the Indigenous user and audience and helps to minimize the 'lost in translation' when foreign or 'outside' concepts and values are applied. It also helps facilitate rekindling identity and reviving ITLK.

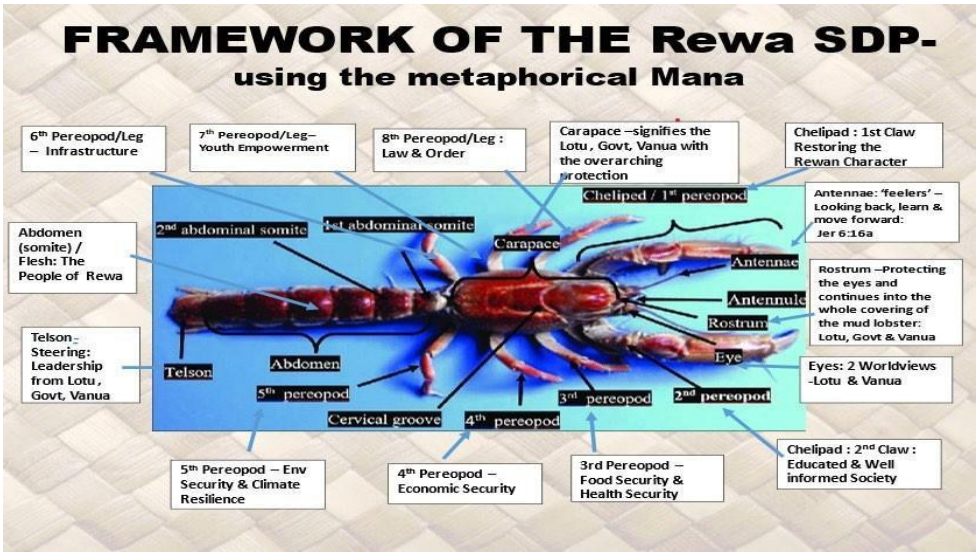


Figure 3. Framework of the Rewa Strategic Development Plan (SDP) employing the metaphorical 'Mana the Mud Lobster' ('Mana' in Fijian), illustrating Indigenous methodologies and frameworks for weaving~~integrating~~ cultural values and ecological understanding into sustainable development strategies.

6. Conclusion and future outlook

ITLK systems have their own unique worldviews, epistemologies and ways of understanding the environment. Although ITLK is increasingly recognized globally, many attempts to integrate ITLK into non-Indigenous or scientific frameworks often result in power imbalances because ITLK is treated as data to be integrated into existing management structures, rather than as a knowledge system in its own right. This approach can result in undermining the integrity and autonomy of these knowledge systems to where ITLK loses its cultural context and becomes oversimplified to fit existing narratives (Shackeroff and Campbell, 2007).

In the context of the World Ocean Assessment (WOA), it is suggested that the ongoing process and future assessments should adopt an approach that better weaves ~~integrates~~ and respects ITLK alongside non-traditional knowledge. This follows the global trend to better recognize and engage with ITLK to support better environmental and social management outcomes. The WOA should aim to cover diverse, regional Indigenous Peoples' issues.

There are many sections and chapters of the WOA where ITLK overlaps with current content and/or where ITLK content may be included ~~integrated~~ in future WOA cycles as reflected in fig. 4. Incorporating ITLK in these sections would help ensure future WOA truly center ITLK as an essential contributor to sustainable ocean management, fostering more inclusive and effective environmental stewardship.

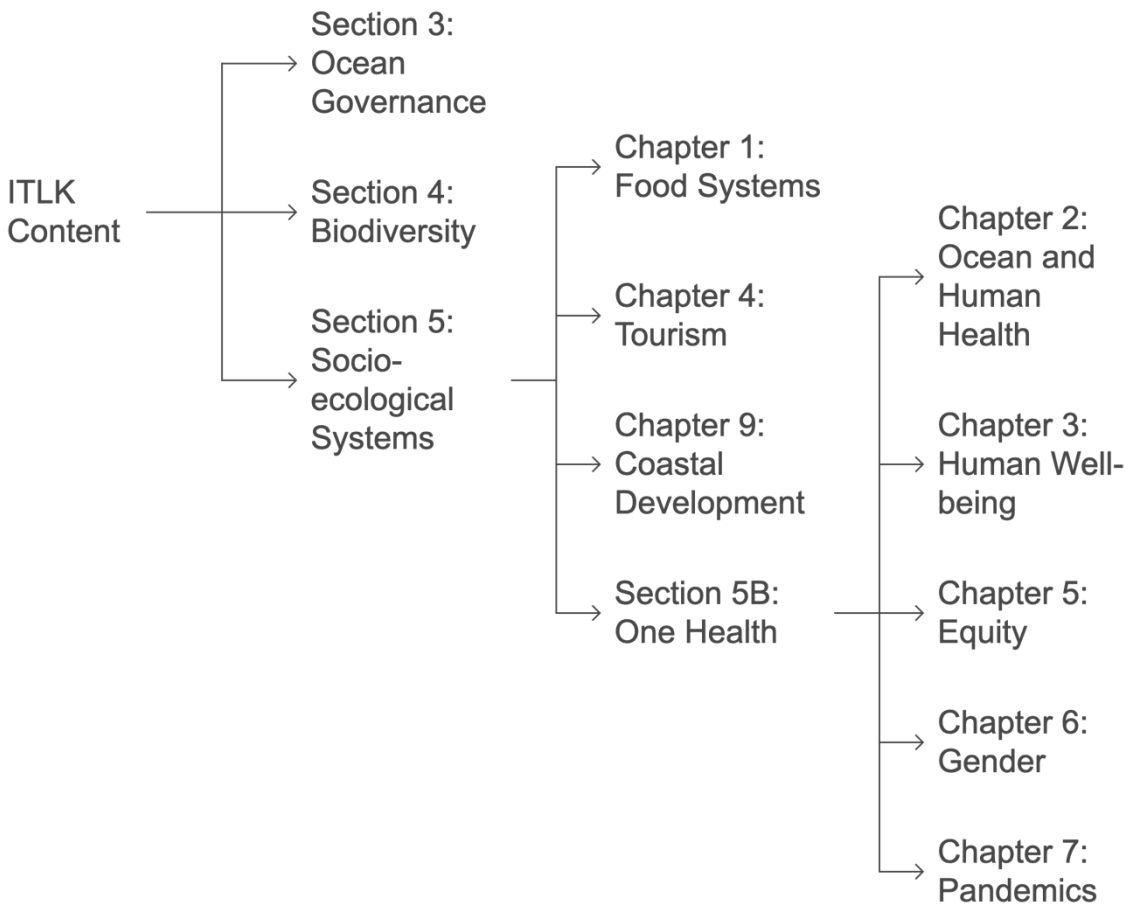


Figure 5~~4~~. Sections and chapters of the WOA where ITLK overlaps with current content or may be includ~~integrat~~ed in future cycles.

8. Acknowledgement

The writers would like to acknowledge that some AI assisted software (Connected paper, Elicit) were used to assist with literature searches. Text support software (Grammarly, Paperpal and Co-pilot) were used to help with editing.

9. References

Alexander, Steven M., and others. Bridging Indigenous and science-based knowledge in coastal and marine research, monitoring, and management in Canada. Environmental Evidence, vol. 8, art. 36, 2019. https://doi.org/10.1186/s13750-019-0181-3

Allison, Edward H., and others. "The human relationship with our ocean planet", in The Blue Compendium, Jane Lubchenco and Peter M. Haugan, eds. Cham: Springer, 2023.

Ambers, A. and R. George yacaaʔał. Fluid internationalisms: the ocean as a source and forum of Indigenous international law. Borders in Globalization Review, vol. 5, No. 1, pp. 21–25, 2024.

Artelle, Kyle A., and others. Values-led management: the guidance of place-based values in environmental relationships of the past, present, and future. Ecology and Society, vol. 23, No. 3, 2018.

Balvanera, Patricia, and others. Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn: IPBES, 2022.

Ban, Natalie C., and others. Indigenous knowledge as data for modern fishery management: a case study of Dungeness crab in Pacific Canada. Ecosystem Health and Sustainability, vol. 3, No. 8, 2017.

Barianaki, Eleni, and others. How to incorporate cultural values and heritage in maritime spatial planning: a systematic review. Heritage, vol. 7, No. 1, pp. 380–411, 2024.

Bartlett, Cheryl, and others. Two-Eyed Seeing and other lessons learned within a co-learning journey of bringing together Indigenous and mainstream knowledges and ways of knowing. Journal of Environmental Studies and Sciences, vol. 4, pp. 331–340, 2012.

Bay, Line K., and others. Management approaches to conserve Australia's marine ecosystem under climate change. Science, vol. 381, No. 6658, pp. 631–636, 2023.

Berkes, Fikret, and Nicole Franz. Governing for Transformation Towards Sustainable Small-Scale Fisheries. Rome: FAO, 2025.

Bingham, Jacob A., and others. Knowledge pluralism in First Nations' salmon management. Frontiers in Marine Science, vol. 8, 2021.

Bodansky, Daniel. Four treaties in one: the Biodiversity Beyond National Jurisdiction Agreement. American Journal of International Law, vol. 118, No. 2, pp. 299–323, 2024.

Boni, Yosua, and others. Preserving coastal and marine resources: the existence of local wisdom among the Bajau Tribe. Journal of Global Innovations in Agricultural Sciences, pp. 663–671, 2024.

Borrows, John. Freedom and Indigenous Constitutionalism. Toronto: University of Toronto Press, 2016.

Charette, Christian, Georges Nash and Alain Mazel, eds. Indigenous Heritage and Rock Art: Worldwide Research in Memory of Daniel Arsenault. Oxford: Archaeopress, 2021.

Crosman, Kristen M., and others. Social equity is key to sustainable ocean governance. npj Ocean Sustainability, vol. 1, No. 1, art. 4, 2022.

Davies, Hayley N., and others. Mapping the marine environment through a cross-cultural collaboration. Frontiers in Marine Science, vol. 7, art. 716, 2020.

Ens, Elizabeth J., and others. Australian approaches for managing 'country' using Indigenous and non-Indigenous knowledge. Ecological Management & Restoration, vol. 13, No. 1, pp. 100–107, 2012.

Enyew, Elias N., and others. Beyond borders and states: modelling ocean connectivity according to Indigenous cosmovisions. Arctic Review on Law and Politics, vol. 12, pp. 207–221, 2021.

Ermine, Willie. The ethical space of engagement. Indigenous Law Journal, vol. 6, pp. 193–210, 2007.

Fears, Darryl. Indigenous peoples of the world's coastlines are losing their fisheries—and their way of life. The Washington Post, 2 December 2016.

www.washingtonpost.com/news/energy-environment/wp/2016/12/02/coastal-native-people-who-need-fish-the-most-are-losing-them/.

Formatted UN-Style Bibliography (Full List – Part 2)

Fernández-Llamazares, Álvaro, and others. Scientists' warning to humanity on threats to Indigenous and local knowledge systems. Journal of Ethnobiology, vol. 41, No. 2, pp. 144–169, 2023.

Ford, James D., and others. Including Indigenous knowledge and experience in IPCC assessment reports. Nature Climate Change, vol. 6, No. 4, pp. 349–353, 2016.

Frid, Alejandro, and others. Re-imagining the precautionary approach to make collaborative fisheries management inclusive of Indigenous Knowledge Systems. Fish and Fisheries, vol. 24, No. 6, pp. 940–958, 2023.

Friedlander, Alan M., and Carlos F. Gaymer. Progress, opportunities and challenges for marine conservation in the Pacific Islands. Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 31, No. 2, pp. 221–231, 2021.

Garibaldi, Ann, and Nancy Turner. Cultural keystone species. Ecology and Society, vol. 9, No. 3, 2004.

Haas, Benjamin. Achieving SDG 14 in an equitable and just way. International Environmental Agreements: Politics, Law and Economics, vol. 23, No. 2, pp. 199–205, 2023.

IPBES (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds.). IPBES Secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6522522

IPBES. (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES Secretariat, Bonn, Germany.
https://doi.org/10.5281/zenodo.3831673Version 1. Bonn: IPBES, 2019.

~~Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Global Assessment Report on Biodiversity and Ecosystem Services of the~~

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Version 1. Bonn: IPBES, 2019.

Jessen, Tyler D., and others. Contributions of Indigenous knowledge to ecological and evolutionary understanding. Frontiers in Ecology and the Environment, vol. 20, No. 2, pp. 93–101, 2022.

Johansson-Fua, Seu'ula. "Kakala research framework", in Varieties of Qualitative Research Methods: Selected Contextual Perspectives, J. M. Okoko, S. Tunison and K. D. Walker, eds. (Cham: Springer International Publishing, 2023), pp. 275–280.

Jones, Bethany L. H., and others. New directions for Indigenous and local knowledge research and application in fisheries science: lessons from a systematic review. Fish and Fisheries, vol. 25, No. 4, pp. 647–671, 2024.

Kaiser, Brooks A., and others. The importance of connected ocean monitoring knowledge systems and communities. Frontiers in Marine Science, vol. 6, art. 309, 2019.

Kitolelei, Seini, and others. Fisherwomen's Indigenous and local knowledge—the hidden gems for the management of marine and freshwater resources in Fiji. Frontiers in Marine Science, vol. 9, art. 991253, 2022.

Lam, Mimi E., and others. Value- and ecosystem-based management approach—and Pacific herring fishery conflict. Marine Ecology Progress Series, vols. 617–618, pp. 341–364, 2019.

Latulippe, Nicole. Situating the work. AlterNative: An International Journal of Indigenous Peoples, vol. 11, No. 2, pp. 117–121, 2015.

Magni, Giorgia. Indigenous knowledge and implications for the sustainable development agenda. European Journal of Education, vol. 52, No. 4, pp. 437–447, 2017.

Marshall, Albert, and others. "Awakening the sleeping giant": Re-Indigenization principles for transforming biodiversity conservation in Canada and beyond. FACETS, vol. 6, pp. 839–869, 2021.

Martinez-Cruz, Teresa E., and others. Water is more than a resource: Indigenous Peoples and the right to water. Social Sciences & Humanities Open, vol. 10, art. 100978, 2024.

McMillan, Lorna J., and Karlee Prosper. Remobilizing netukulimk: Indigenous cultural and spiritual connections with resource stewardship and fisheries management in

Atlantic Canada. Reviews in Fish Biology and Fisheries, vol. 26, No. 4, pp. 629–647, 2016.

Morgera, Elisa. Participation of Indigenous Peoples in decision making over deep-seabed mining. AJIL Unbound, vol. 118, pp. 93–97, 2024.

Formatted UN-Style Bibliography (Full List – Part 3)

Ogar, Esther, and others. Science must embrace Traditional and Indigenous knowledge to solve our biodiversity crisis. One Earth, vol. 3, No. 2, pp. 162–165, 2020.

Parks, Louisa, and Elsa Tsioumani. Transforming biodiversity governance? Indigenous Peoples' contributions to the Convention on Biological Diversity. Biological Conservation, vol. 280, art. 109933, 2023.

Pictou, Sherry. Reconciliation or Apiksitaultimik? Indigenous relationality for conservation. 2023.

Rathwell, Kaitlyn J., and others. A Growing Tree metaphor: identifying and reflecting on 26 Action Items for ethical bridging of Indigenous and Western knowledge systems in biodiversity research

and monitoring. Ecology and Society, vol. 30, art. 30, 2025. https://doi.org/10.5751/ES-15946-300230

Reid, Andrea Amanda J., and others~~Reid, Amanda J., and others~~. "Two-Eyed Seeing": an Indigenous framework to transform fisheries research and management. Fish and Fisheries, vol. 22, No. 2, pp. 243–261, 2021.

Rick, Torben C. Shell midden archaeology: current trends and future directions. Journal of Archaeological Research, vol. 32, No. 3, pp. 309–366, 2024.

Rist, Phil, and others. Indigenous protected areas in Sea Country: Indigenous-driven collaborative marine protected areas in Australia. Aquatic Conservation: Marine and Freshwater Ecosystems, vol. 29, Suppl. 2, pp. 138–151, 2019.

Shackeroff, Jenna M., and Lisa M. Campbell. Traditional ecological knowledge in conservation research. Conservation and Society, vol. 5, No. 3, pp. 343–360, 2007.

Somiah, Vanessa. The sea is Indigenous "land" too. Sojourn: Journal of Social Issues in Southeast Asia, vol. 37, No. 1, pp. 85–112, 2022.

Strand, Meryl, and others. Co-producing sustainable ocean plans with Indigenous and traditional knowledge holders. Washington, D.C.: World Resources Institute, 2024.

Strand, Meryl, and others. Reimagining ocean stewardship: arts-based methods to 'hear' and 'see' Indigenous and local knowledge in ocean management. Frontiers in Marine Science, vol. 9, 2022.

Termansen, M., Jacobs, S., Mwampamba, T.H., Ahn, S., Castro, A., Dendoncker, N., Ghazi, H., Gundimeda, H., Huambachano, M., Lee, H., Mukherjee, N., Nemogá, G.R., Palomo, I., Pandit, R.,
Schaafsma, M., Ngouhouo, J., Choi, A., Filyushkina, A., Hernández-Blanco, M., Contreras, V., & González-Jiménez, D. (2022). Chapter 3: The potential of valuation. In P. Balvanera, U. Pascual, M.
Christie, B. Baptiste, & D. González-Jiménez (Eds.), Methodological Assessment Report on the Diverse

Thaman, Konai Helu. Kakala: a Pacific concept of teaching and learning. Paper presented at the Australian College of Education National Conference, Cairns, 1997.

Tilot, Virginie, and others. Traditional dimensions of seabed resource management in the context of deep sea mining in the Pacific: learning from the socio-ecological

interconnectivity between island communities and the ocean realm. Frontiers in Marine Science, vol. 8, art. 637938, 2021.

Tuwere, Ilaitia S. Vanua: Towards a Fijian Theology of Place. Suva: Institute of Pacific Studies, University of the South Pacific, 2002.

UNESCO Intergovernmental Oceanographic Commission (IOC). The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) Implementation Plan. Ocean Decade Series, No. 20(64). Paris: UNESCO, 2021.

United Nations Division for Ocean Affairs and the Law of the Sea (UNDOALOS), ed. The First Global Integrated Marine Assessment: World Ocean Assessment I, 1st ed. Cambridge: Cambridge University Press, 2017.

United Nations. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement). New York: United Nations, 2023.

Vierros, Marjo K., and others. Considering Indigenous Peoples and local communities in governance of the global ocean commons. Marine Policy, vol. 119, art. 104039, 2020.

Von der Porten, Suzanne, and others. The role of Indigenous resurgence in marine conservation. Coastal Management, vol. 47, No. 6, pp. 527–547, 2019.

Whyte, Kyle Powys. On the role of traditional ecological knowledge as a collaborative concept: a philosophical study. Ecological Processes, vol. 2, No. 1, pp. 1–12, 2013.

Wong, Carmen Connie, and others~~Wong, Connie, and others~~. Towards reconciliation: 10 Calls to Action to natural scientists working in Canada. FACETS, vol. 5, No. 1, pp. 769–783, 2020.

Yua, Eva, and others. A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, vol. 27, art. 34, 2022.