Impacts of disasters on forests, in particular forest fires

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In accordance with the decision of the fifteenth session of the UN Forum on Forests (UNFF15), the UNFF secretariat will organize a high-level round table during the sixteenth session of the Forum (UNFF16) to discuss major forest-related developments. Disasters and forest fires have been identified in the UN Strategic Plan for Forests (UNSPF) and its Global Forest Goals (GFGs) as one of the indicative thematic areas for action. Target 4 of GFG1 also includes a reference to disasters. In light of the magnitude and continued occurrences of disasters and their impacts on forests and taking into account the thematic areas identified in the UNSPF, this consultancy paper is prepared to support the discussions during the UNFF16 high-level round table on major forest-related developments.

Executive summary

These past few years, 24/7 media coverage of catastrophic forest fires in Australia, Brazil, and USA, among others, has captured widespread attention. Causes and consequences underlying these disasters differ vastly from a location to another. The objective of this background study is to provide a general view of the impacts of disasters on forests, with particular focus on the impacts of fire.

Natural disturbances are an integral part of forest ecology, allowing rejuvenation, nutrient cycling, as well as biodiversity. Forest disturbances can be abiotic (e.g., droughts), biological (e.g., bark beetle), and human-made (e.g., deforestation). Fire is particular case, at the crossroad of natural and human influences, whose potential for disaster is a source of growing concern all over the world.

Fire is a natural phenomenon that has contributed to shaping the biosphere for the past 400 million years. Starting 300,000 years ago, humankind began to use fire for landscape engineering, causing new ecological adaptations, fostering biodiversity, and improving livelihood. Currently, global fire activity burns around 400 million hectares of land every year; nearly two third of this area is burned in the savanna ecosystems of Africa, Australia, and South America. Boreal, Mediterranean, and tropical forests experienced most of fire activity outside of savanna and grassland ecosystems.

Nowadays, human activities are responsible for most fire activity—up to 99% in some regions. Yet, global area burned has been decreasing for several decades, and the location of fire activity has shifted where large-scale human pressure has caused major environmental changes, with disastrous consequences. Wildfire events classified as disasters represented 3.5% of recorded disasters between 1998 and 2017, and though there is no clear data to show the increase in fatalities and losses as a trend, there is a net sharp rise in suppression costs. This rise results from the multiplication of values at risk located in fire-prone landscapes. Forest fires also bring environmental disasters and losses to ecosystems, including by preventing vital ecosystem services and benefits to society, such as drinking water.

Ongoing climate change and other environmental issues linked to globalized human activities will make fire disasters more likely; definitive numbers, however, are impossible to provide given the complex feedbacks existing between fire, climate, and human footprint. Nonetheless, there is a general scientific agreement that many regions will experience more fire-conducive climate, leading to drier and warmer weather conditions—a trend visible already; harsher climate conditions will also make post-fire forest regeneration more difficult, threatening communities depending on forests for their livelihood. Expanding human footprint will also bring more ignitions, thereby enhancing fire activity and increasing community vulnerability.

For the past two decades, Integrated Fire Management, or IFM, has been advanced as the most efficient and logical path towards fire disaster risk reduction. IFM essentially aims at a focused-shift from suppression to prevention, preparedness, and post-disaster recovery; a goal whose success heavily relies on working with local communities. Based on the IFM framework, several major recommendations to reducing fire disaster risks can be made: learning to live with local fire conditions; reducing the vulnerability of highly valued resources and assets; acknowledging traditional fire knowledge; adopting a responsible, science-informed, proactive fire strategy; promoting good governance; promoting capacity building for local communities; promoting collaboration and knowledge sharing; promoting long-term monitoring and data collection; promoting new technologies and innovative approaches to fire risk management.

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1. Terminology

1.1. General ecology terms

- **Biodiversity:** biological diversity, which means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems [1].
- **Ecosystem services:** the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth [2].
- **Forest:** land area of more than 0.5 ha, with a tree canopy cover of more than 10%, which is not primarily under agricultural or other specific non-forest land use. In the case of young forests or regions where tree growth is climatically suppressed, the trees should be capable of reaching a height of 5 m in situ, and of meeting the canopy cover requirement [1].
- **Forest ecosystem:** dynamic complex of plant, animal and micro-organism communities and their abiotic environment interacting as a functional unit, where trees are a key component of the system. Humans, with their cultural, economic and environmental needs are an integral part of many forest ecosystems [1].
- **Peatland:** a type of freshwater wetland that form from the accumulation and burial of plant detritus under cool and/or wet climates. Peat soils are mostly made of undecayed organic matter that can be several meters thick. Peatlands currently only cover 3% of the global land surface yet are the largest natural terrestrial carbon sink [3].

1.2. Forest disturbance terms

- **Deforestation:** the long-term or permanent conversion of forest to other land uses, such as agriculture, pasture, water reservoirs, infrastructure and urban areas. Deforestation is responsible for one-fifth of total GHG emissions globally; it also has detrimental impacts on other natural resources such as water and biodiversity, as well as on local livelihoods and national economies [4].
- **Degradation:** the reduction of the capacity of a forest to provide goods and services. This can be caused by a natural or a man-made disturbance, or a product of the two. Absence of corrective measures countering degradation can lead to total and perpetual loss of goods and services provided by forested lands [4].
- **Disturbance:** an event or force, of nonbiological or biological origin, that brings about mortality to organisms and changes in their spatial patterning in the ecosystems they inhabit. Disturbance plays a significant role in shaping the structure of individual populations and the character of whole ecosystems. It is often characterized by its intensity, its frequency, its size, and its scale, among other aspects [5].
- **Drought:** complex phenomena triggered by the absence of water over a long period of time, which can adversely impact vegetation, animals and people. Meteorological droughts happen when precipitation is insufficient; hydrological drought refers to the low amount of water in a hydrological system; agricultural drought refers to crop damages linked to long-term water shortages; and socio-economic drought refers to the shortage of commodities due to drought [6].
- **Pest:** any organism (e.g., fungi, insect, virus) occurring in unsustainable numbers that can threaten the health and vigour of a forest, its biodiversity, and the many social, cultural and economic goods

and services it provides. Pests can be native, with natural outbreaks occurring periodically; they can also be alien when introduced from outside of a given ecosystem. Both native and alien pests can become invasive when they extend beyond their known usual range, due for instance to climate change [7].

- **Windthrow:** uprooting and steam breakage caused by wind, which often leads to trees' death. This common forest disturbance can range from a windfall affecting a small tree stand to an entire forest blown down during extreme weather events such as cyclones [8].

1.3. Fire-focused terms

- **Community-Based Fire Management (CBFiM):** Fire management approach based on the strategy to include local communities in the proper application of land-use fires (managed beneficial fires for controlling weeds, reducing the impact of pests and diseases, generating income from non-timber forest products, creating forage and hunting, etc.), wildfire prevention, and in preparedness and suppression of wildfires [9].
- **Fire:** product of a chemical reaction called combustion, an oxidation process triggered by the association of a fuel, a heat source, and oxygen, which releases energy, various gases (e.g., carbon dioxide, carbon monoxide, methane), organic matter, and water. In an ecological context, fire is often described as the opposite reaction to photosynthesis. This definition excludes the use of fire for domestic purposes [10].
- **Fire ecology:** study of the interactions between fire (natural or anthropogenic) and the ecosystems in which they happen, and how these interactions evolve over time. The adaptation of natural organisms to the repeated passage of fire, from fire-resistance to fire-dependence, is a core topic of fire ecology [11].
- **Fire regime:** main characteristics of fire activity for a given location, which can be reduced to the following essential parameters: seasonality, size, frequency, severity, type (e.g., ground or crown fire), cause (i.e., human vs natural). These characteristics are influenced by a number of natural and human factors (see pyrogeography) [12].
- **Prescribed burning:** planned and controlled fire ignited in low fire danger conditions and used to meet management objectives, often for fuel load reduction and/or for ecological purposes. It is an umbrella term that is applied in different geographic and operational contexts, which can lead to confusion, in particular with traditional burning practices [13].
- **Pyrogeography:** ensemble of natural and anthropogenic factors that drive patterns of fire activity through time and space. Natural factors can be biotic, such as vegetation types, or abiotic, such as topography and climate, whereas anthropogenic factors mainly relate to land use and land conversion, as well as political, social, and economic practices that regulate the use and spread of fire. Pyrogeography and fire regime are the two sides of the fire activity coin [14].
- **Pyrodiversity:** habitat mosaic created by fire activity, either within the perimeter of one fire or as the product of historical fire activity over a stretch of land. It is generally accepted that "pyrodiversity begets biodiversity", thereby underlying the role of fire in the history and maintaining of life. Pyrodiversity varies by fire regime and pyrogeographic contexts [15].
- **Traditional burning:** usually small-scale burning techniques traditionally used by local human groups for hundreds to thousands of years for various purposes such as game management, hazard reduction, food source enhancement, and spiritual purpose. Traditional burning encompasses various types of cultural and aboriginal burning practices identified around the world. This type of burning is

increasingly seen as a sustainable and efficient way of maintaining ecosystem services and pyrodiversity while reducing wildfire risk [16].

- **Wildland-urban interface (WUI):** umbrella term referring to areas where human-made infrastructures and assets (e.g., houses, water treatment plant, roads, farmland) are in contact or intermix with vegetated areas prone to wildfire [17].

1.4. Miscellaneous

- **Anthropocene:** Unofficial yet popular term designating the current epoch, characterized by the general and measurable destabilisation of the Earth's bio-geo-chemical cycles caused by global and unsustainable human activity. The Anthropocene is now often illustrated through the concept of "planetary boundaries", or the limits to which global human activity can extend without compromising its own existence. At the moment, five of the nine boundaries have been crossed [18].
- **Co-management:** science-based, holistic approach aiming at the sharing of authority, responsibility, and benefits between government, local communities, and other private and public actors involved in the management of risk, with the ultimate goal of reducing stakeholders' vulnerability. Co-management is at the core of successful, integrated fire management [19].
- **Cultural landscape:** landscapes that have been affected, influenced, or shaped by human involvement within its natural environment. Cultural landscapes often reflect specific techniques of sustainable land-use, considering the characteristics and limits of the natural environment they are established in, and a specific spiritual relation to nature [20].
- **Disaster:** A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts. There is thus no such thing as a "natural" disaster. The effect of the disaster can be immediate and localized, but is often widespread and could last for a long period of time [21].
- **Forest Landscape Restoration:** process of restoring the ecological functionality of degraded and deforested landscapes while enhancing the well-being of people who coexist with these places [22].
- **Governance:** Governance represents the norms, values and rules of the game through which public affairs are managed in a manner that is transparent, participatory, inclusive and responsive. In a broad sense, governance is about the culture and institutional environment in which citizens and stakeholders interact among themselves and participate in public affairs [23].
- **Hazard:** A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, anthropogenic or socio-natural in origin. Natural hazards are predominantly associated with natural processes and phenomena. Anthropogenic hazards, or human-induced hazards, are induced entirely or predominantly by human activities and choices [21].
- **NATECH:** Natural hazards leading to technological disasters. UNISDR defines NATECH as joint disasters that combine natural and technological hazards (e.g., chemical spill) and that feature very complex consequences owing to amplifying effects between the two types of hazard [24].
- **Risk:** The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of combined hazard and vulnerability [21].
- **Vulnerability:** The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the

impacts of hazards. Vulnerability is understood as the combination of exposure (to hazard), resistance (e.g., physical, social), and resilience ("capacity to bounce back", also called coping capacity) [25].

2. Introduction: Forests, societies, and disasters

2.1. The nourishing forests

2.1.1. Environmental importance of forests

Forests cover over 30% of the world's landmass, with an estimated count of nearly 3 trillion trees [26,27]; this number however is subject to debate, as forests definitions vary widely [28]. According to the Food and Agricultural Organization of the United Nations (FAO), about 45 % of forests are found under tropical climate, followed by the boreal, the temperate, and subtropical climate domains, together accounting for the largest reservoir of terrestrial biodiversity.

Forests, in their largest definition(s), provide a wide range of ecosystem services and benefits that are critical to the livelihood of communities, urban and rural, rich and poor, and from local to global scales [27,29]. These services are categorized as provisioning (e.g., timber, fuel wood, and other Non-Timber Forest Products), regulating (e.g., carbon storage, water availability and quality), cultural (e.g., landscape vista, sacred land), and supporting (e.g., soil formation, plant growth) (figure 1) [29–31]. For instance, it is estimated that nearly 75% of humanity's water supply come from forests. Globally, ecosystem services provided by forests are conservatively estimated around USD $9.4 trillion [32].

Forest biodiversity is not an ecosystem service *per se* but rather an essential ecological factor contributing to healthy forest functioning, and thus to the generation of ecosystem services [33]. Forest structural diversity, such as vertical and horizontal heterogeneity and the density of large trees, is another important factor leading to ecosystem services supply [34].

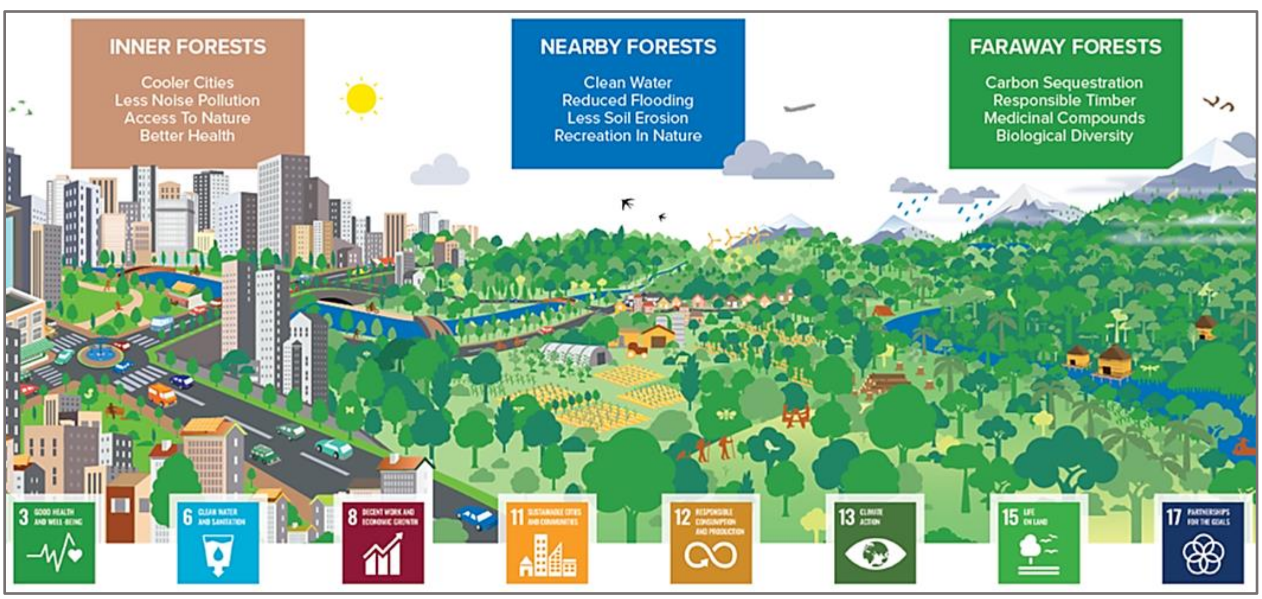

Figure 1: Importance of healthy forests in supporting urban areas and the achievement of the Sustainable Development Goals. (Credit: World Resources Institute - https://wriorg.s3.amazonaws.com/s3fs-public/3-scales-infographic.png)

Global environmental change—in particular climate change and human footprint expansion—has led to pervasive changes to forest health, causing negative impacts on people's livelihood [35]. Nearly half of the global forest cover shows detectable signs of human action, with a concerning increasing trend regarding the degradation of primary forests [26,36,37]. Deforestation due to agriculture remains the largest cause of forest degradation.

Despite a net decrease in annual forest cover loss—from 7.8 million hectares per year in the 1990s to 4.7 million hectares per year during 2010–2020 [4]—the future is worrisome as international targets set for forest protection—such as the Bonn Challenge—seem too far from reach. It is concerning as reports of declining forest health are numerous; there is widespread danger to shifting from forest to permanent non-forested ecosystems, causing a decrease in ecosystem services supply [38,39].

2.1.2. Social and economic importance of forests

Forests support the livelihood of numerous communities around the world. It is estimated that 750 million people live in forests, that 13.2 million people across the world have a job in the forest sector, and another 41 million have a job that is related to the sector. Globally, between 1 billion and 2.6 billion people—including more than 2,000 indigenous cultures—depend directly or indirectly on forests for their livelihoods, medicine, fuel, food, and shelter [40,41]. In Congo, for instance, 40 million people depend directly on forests for subsistence.

There is evidence that forest degradation is linked to poverty [42], particularly in areas showing inadequate land tenure systems coupled to economic pressures from the global market economy. The result is often seen as rampant illegal and unsustainable deforestation to grow cash crops, to create pastureland, and to access underground resources. There is now widespread acknowledgement that reversing the effects of global environmental change, as well as reaching the SDGs go hand-in-hand with forest conservation, protection, restoration, and sustainable exploitation [26,43].

2.2. Forest disturbances leading to disasters: an overview

Disturbances are an integral part of forest ecology, allowing rejuvenation, nutrient cycling, and maintaining biodiversity [44,45]; thus, ecosystems have co-evolved with a given disturbance regime that they adapted to. These disturbances can, occasionally, reach a magnitude triggering disasters when they impact highly-valued resources and assets (e.g., timber, water, human communities living in forested areas, etc).

Disasters can be direct with a rapid onset, such as a forest fire burning into valuable timber and through forest communities, or indirect, with a slow onset, such as long-term droughts that might eventually impact the capacity of upstream forests to supply water to downstream communities. Ongoing climate change, as an amplifier of hydro-climatic hazards, is now rapidly changing forest disturbance regimes in areas of high demand for ecosystem services, thereby increasing the likelihood of disasters [38,46].

We briefly present several agents of forest disturbances that can lead to disasters, namely: abiotic, biological, and human-made. These disturbances often overlap, especially now in the Anthropocene where human footprint widely affects natural processes [47]. A typical example relates to the introduction of exotic species, a human-made disturbance, which can lead to a biologic disaster if this species happens to be invasive and detrimental to local forest ecosystems by changing their fire regime.

2.2.1. Abiotic origin

Abiotic disturbances are caused by non-living phenomena—or, hereafter, hazards: storms, wildfires, cyclones, droughts, floods, etc. Those can be short-lived with local impacts (e.g., a storm), or years-long with continental impacts (e.g., drought). While global accounts (e.g., statistics, maps) of the impacts of

fire on forests exist from multiple sources, those are incomplete or missing for other hydroclimatic events such as droughts, storms, and floods.

Fires affect nearly 100 million hectares of forests every year on average, equivalent to 3% of global forest area, while all other abiotic disturbances impact less than 0.5% of forest areas[1] [27]. Droughts can happen everywhere and impact local forests to various degrees, from shortening tree lifespan to potential large-scale tree die-off [48], as illustrated recently in California[2]. The effect of floods on trees may be mostly limited to riparian areas [49] and most of the literature rather focuses on the buffering effect of forests on flood occurrence and magnitude. Extreme winds in forested environments—from localized storms to cyclones— cause a wide range of negative impacts depending on tree species, stand structure, and stand age, the worst being windthrows (figure 2a) [8,50]. Cold waves, heavy snowfall, and ice are also damaging to forests: ice and snow accumulation can break branches, bend trees, and cause trees to break (figure 2b), while low temperatures can damage tissues and cause widespread mortality. Generally speaking, overall impacts of abiotic disturbance to forested landscape remain variable, and the magnitude of forest damages and time for forest to recover will depend on forest structure and species, as well as local climate conditions [51].

When abiotic hazards happen over a large area, the recovery phase can take time and exposes forests to other disturbances, such as fire [52]. Many ecosystems services and benefits can suffer from the absence of forest cover and potential long-term decline in forest health: water quality, timber production, recreational opportunities, biodiversity, to name a few [51,53,54]. In France in 1999, two winter storms impacted almost 10,000 km² of forests (estimated 140 million cubic meters of wood), for total estimated costs over €100 billion in damages. The 2008 China ice storm damaged 21 million hectares of natural forests and plantations, destroying 340 million cubic meters of timber [55].

Figure 2: (a) Windthrow caused by the 1999 Klaus storm in South Western France. (credit: David Le Deodic https://images.sudouest.fr/2017/11/28/5a13f20066a4bdfd6e16302b/default/1000/une-triste-vision-de.jpg); (b) Damage in northern Arkansas from the 2009 ice storm (Credit: iWitness Weather/patpie, https://weather.com/storms/winter/news/top-10-worst-ice-storms-20131205)

Large abiotic hazards remain rather rare generally but cause enduring legacies in forested landscapes [56]. In a context of global environmental change, where extreme hydro-climatic events might happen more often, global analyses and data collection related to forest damages caused by abiotic disturbances and post-disaster recovery will benefit from more research [51].

[1] This latter statistic is based on a limited reporting of disturbances from 37 countries, accounting for 33% of global forest cover. See FAO Global Forest Assessment 2020.

[2] https://www.universityofcalifornia.edu/news/massive-forest-die-sierra-nevada-caused-multiyear-drought

2.2.2. Biological origin

Biotic, or biological, disturbances are caused by living agents, either through direct exposure or as an indirect result of toxins and diseases that they may carry. Bark beetles, gypsy moths, fungi, viruses, and invasive exotic plants are examples of biological hazards threatening forest health throughout the world; however, global accounts are rare and often contain data gaps that hinder robust temporal and spatial trend analysis [57]. That being said, the scientific community agrees upon a significant increase in biological hazards in forests due to climate change and globalization [35,38,58].

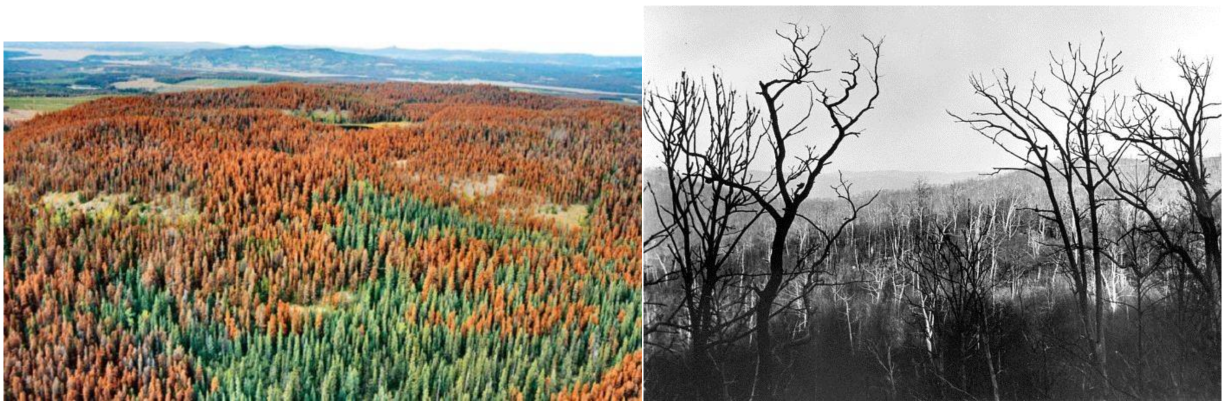

Figure 3: (a) Lodgepole pine forest showing beetle destruction. The red trees have been killed by mountain pine beetle (Credit: Canadian Forest Service - https://www.rcinet.ca/en/wp-content/uploads/sites/3/2019/07/pine-beetle-damage-wide-shot-cdn-forest-service-635x357.jpg); (b) Results of the American Chestnut blight documented on the Chattahoochee National Forest in north Georgia in 1930 (Credit: Chattahoochee National Forest - https://upload.wikimedia.org/wikipedia/commons/thumb/1/19/American_Chestnut_Blight_%2819474473565%29.jpg/1024px-American_Chestnut_Blight_%2819474473565%29.jpg).

Based on 2003-2012 forest statistics from FAO, an estimated 3% of global forests were affected by insect pests annually. Some years, insect outbreaks in forests might even affect a greater area than forest fires [59]. Bark beetles are of particular concern given their current expansion all across the world (figure 3a). In North America, for instance, warmer winters now allow larvae to survive and break out further north. The decline of forests due to insect outbreaks alters ecosystem services such as water provision, biodiversity, while increasing wildfire hazard [60]. In Canada, cumulative pine timber losses due to bark beetles have been estimated around 750 million cubic meters, or 58% of merchantable timber[3].

Still based on 2003-2012 forest statistics from FAO, forest diseases disturb forests to a lesser extent [59]: less than 0.5% of global forests annually[4]; however, large-magnitude events can happen, particularly when exotic species introduced and invade local forests. For example, during the early 1900s in the USA, the Chestnut blight—a fungus from Asia—led to the quasi extinction of American Chestnut forests. This event severely impacted the lumber and nut industries, as well as biodiversity. Although the introduction of pathogens remains overly accidental, globalization of commercial exchanges and travels has facilitated this process; now, climate change is also making their establishment more successful [38,61]. It also appears that planted forests are more sensitive to biotic disturbances than their natural counterparts [57].

3 https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/wildland-fires-insects-disturban/top-forest-insects-diseases-cana/mountain-pine-beetle/13381

4 Under-reporting might also explain this statistic.

2.2.3. Man-made origin

Human-caused, or anthropogenic, forest disturbances, "are induced entirely or predominantly by human activities and choices"[5]. Clear cuts, deforestation, pollution, and anthropogenic climate change are examples of human-caused hazards. In the Anthropocene, human-caused disturbances increasingly interact with biotic and abiotic agents. Worldwide human footprint has been leading to decline in the health of forests and their capacity to supply ecosystem services and harbour biodiversity [14].

Forest degradation from land conversion is the main human-made disturbance leading to disasters (figure 4). The Amazon, the most biodiverse place on Earth, lost around 17% of its forest area for the last 50 years. Mangroves are a critical forest type that has suffered tremendous loss these past decades, increasing the likelihood of floods and storm surge in coastal areas. Land clearing for the production of commodities accounts for 27% of global forest disturbances, and is the main driver of deforestation over the period 2001-2015, followed by forestry and shifting agriculture [37].

Anthropogenic climate change is a special case of man-made hazard because of its global and temporal scales, the direct and indirect character of its effects, and the countless—and unknown— ramifications and feedback loops that can worsen the disturbances listed above [38,58,62,63]. Many scientific publications now agree on the vast impact climate change is already having on forest ecosystems around the world and that forest-based ecosystem services are highly threatened, with cascading impacts leading to human and environmental disasters [35,38,64].

Figure 4: Typical satellite illustration of the deforestation issue in the Amazon (Credit: NASA - retrieved from https://www.smithsonianmag.com/smart-news/amazon-deforestation-has-increased-dramatically-year-180972542/)

2.2.4. Content of this background paper

Among the multiple forest disturbances mentioned above, the incidence of forest fires leading to disasters seems to increase. This background paper focuses, therefore, on forest fires. The term "forest fire" does not match one universal definition, which strongly depends on where it is applied and who applies it [65–69]. This fact relates to the complex relationship between nature, fire, and people, as well as the difficulty to even define what a forest is [28]. Fires can be naturally-caused (i.e., lightning) or intentionally-set for

[5] https://www.undrr.org/terminology/hazard

agricultural, ecological, or traditional purposes and spread to forests. Many recent extreme fire events [69] with extensive media coverage happened (partly) outside of forest ecosystems, in part due to the growing influence of climate change [70].

FAO insists that fire management efforts "should encompass other, non-forest land uses and vegetation types, such as agriculture, rangelands, savannahs, peatlands, protected areas and wildland–urban interfaces". Thus, in order to cover the diversity of the global "fire problem" [71], this background study uses the word "fire" as a "general term encompassing a diversity of controlled and uncontrolled vegetation fires with landscape-scale impacts, including agricultural land, grassland, shrubland, peatland, and forest fires" [67]. This definition excludes the use of fire for domestic purposes.

For the need of this paper, we focus as much as possible on fire disasters irrespective of fire behaviour, thereby focusing on the aftermath rather than on the highly variable characterization of extreme fire events. Readers are invited to focus on the fundamental importance of losses rather than on the area burned to qualify disastrous events.

This background paper is based on the critical review of a variety of material from numerous sources. Given the vast number of documents available nowadays on this topic, it is impossible to review and summarize them all at once to provide an exhaustive picture of the scientific, operational, and managerial knowledge published globally. Therefore, this review is based on representative content published by leading international agencies, NGOs, foundations, scientific journals and authors, and newspapers; it is further complemented by national and local sources, as well as topical papers and specific examples known to the author where necessary for illustrative purpose.

2.3. Forest fires

2.3.1. Forest fire science basics

Forest fire science revolves around the core concept of the fire triangle (figure 5, bottom left), which describes the three necessary elements needed in conjunction for combustion to start, namely a fuel, an oxidant, and a source of heat. In the right proportions, these three elements lead to pyrolysis, which is the transformation of the physical-chemical properties of organic matter at high temperature; pyrolysis releases gases that will then ignite when a critical temperature is reached, leading to flaming combustion. In the case of fire in vegetated ecosystems, the fuel is provided by some sort of vegetation (e.g., grass, tree, dead wood), the oxygen naturally present in the atmosphere provides the oxidant, and human activities or lightnings provide the source of heat, commonly called ignition.

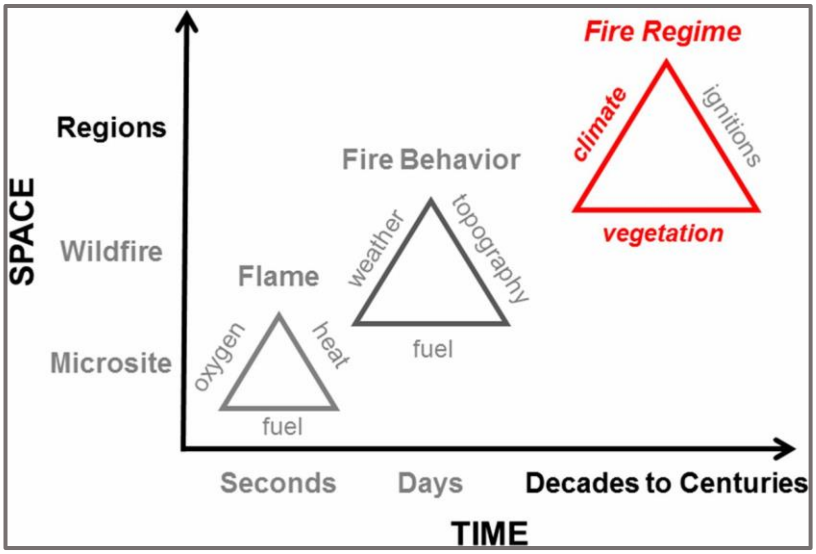

Figure 5: Controls of fire activity across temporal and spatial scales [72,73]**.**

Fire is a self-sustaining phenomenon: given that combustion releases heat, as long as fuel and oxygen remain available in sufficient proportions, pyrolysis will keep going, thereby maintaining combustion. Heat is transmitted through conduction (i.e., direct contact), radiation (i.e., wavelets), and convection (i.e., fluid dynamics). In the case of a forest fire, heat transfers through air dry up surrounding fuels, increase their internal temperature, trigger pyrolysis, which eventually leads to combustion, thereby allowing fire to spread. Fire spread is thus highly limited by the amount of heat that is released, and, for a single fire event, this amount is controlled by the combination of weather, topography, and fuel characteristics (figure 5, middle). Simply put, strong wind and high temperatures over large plains covered by dry conifer fuels is a perfect combination that can lead to extremely large fires, as observed in boreal forests across Canada, where lightning-caused wildfires regularly burn over 5,000 km², individually. However, variations in the combination of weather, fuel, and topography lead to different fire behaviours and thus fire types, namely ground, surface, or crown fire (figure 6), each bringing different management challenges.

Figure 6: Simple classification of fire types. (Credit: Government of Ontario, https://twitter.com/ONforestfires/status/1102634466831409153?s=20)

When a certain type of fire activity happens to dominate over a substantial area and varies little over time, this fire activity becomes what is called a **fire regime**, a fundamental characteristic necessary to understand the location and the functioning of most vegetated landscapes of the world (figure 5, upper right) [74–76]. Climate patterns (e.g., seasons), vegetation traits (e.g., conifers vs deciduous), and ignition patterns (e.g., human vs natural) interact to exert important control over fire regimes. For example, dry woodlands in the tropics often experience small-scale, low-severity fires set by human every 2 to 5 years to favour the growth of new grass more palatable for cattle; whereas in the northern boreal forest of Canada, fires are usually ignited by lightning and burn at a high severity over a large swath of land (>3,000 km²) once a century.

2.3.2. Fire in the Earth system

Fire has appeared on Earth nearly 400 million years ago and has since profoundly shaped ecosystems. The current global distribution, biodiversity, and services and benefits these ecosystems provide would be sensibly different in a fire-deprived world [11,77–82]. Fire, as an ubiquitous process integrated within Earth System dynamics, is part of a subtle balance that influences climate, vegetation, land cover and land use, but is also influenced by them in return [83]. Some argue that over half the world's terrestrial ecosystems need fire to stay healthy. Fire is thus an accelerator of evolution [82]. Over the 400 million hectares burned annually around the planet, forests account for less than 100 million hectares. Indeed, grasslands are by far the ecosystems that burn the most.

There is consensus that vegetation assemblages and cover co-evolved with fire activity across the world, each alternatively adapting to each other, to a point where ecosystem reached a dynamic equilibrium with their fire regime [84]. Vegetal species have for instance adapted traits to become fire-resistant, or fire-dependent, or both, such as thick barks that insulate from heat, or serotinous cones that need the heat from a fire to open. Moreover, fires do not burn in a uniform fashion through a landscape but rather create a patchwork of unburned and burned patches, these burned patches displaying different types of fire severity, thereby creating **pyrodiversity**. This pyrodiversity, combined to the rejuvenating effect of fire, promotes a mosaic of habitats of different ages, which promote biodiversity and ecosystem resistance to future disturbances [15]. It is increasingly suggested that biodiversity loss could promote fire activity [85]. This also means that altered fire regimes, from direct human action such as fire exclusion, or indirect action through climate change, will likely lead to the disappearance of species; such issue was put to the fore during the impact assessment in the aftermath of the 2019-2020 Australian Black Summer.

On a global scale fire activity is primarily driven by climate patterns; according to the fire-productivity hypothesis (figure 7) [86], natural fire activity can only happen within a range of biomass productivity controlled by climatic factors: fuel-limited systems are too dry to support a continuous vegetation cover, despite having a climate conducive to fire (e.g., the Sahara); on the converse, flammability-limited systems have a high productivity and thus a high fuel load, but climate conditions dampen fire activity (e.g., tropical rainforests). Ignition patterns and density also play a major role, and even location presenting the right climatic and fuel conditions may not burn if ignition are limited in number.

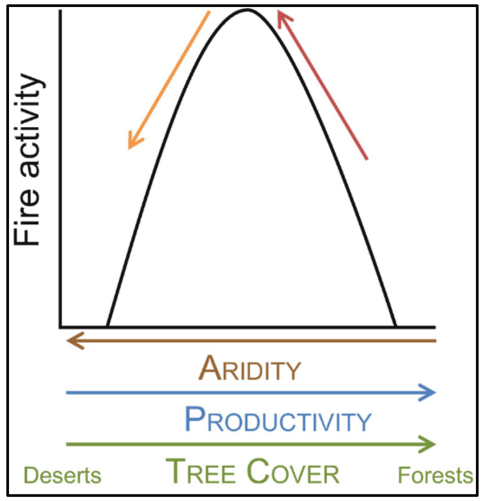

Figure 7: Illustration of the fire-productivity hypothesis; peak fire activity naturally happens in ecosystems where climate allows both vegetation to strive while experiencing dry seasons conducive to fire activity. (Source: https://media.springernature.com/original/springer-static/image/chp%3A10.1007%2F978-3-030-41192-3_1/MediaObjects/448910_1_En_1_Fig3_HTML.png from https://link.springer.com/chapter/10.1007/978-3-030-41192-3_1)

Given the role of fire in the global arrangement of ecosystems and their functions, services, and benefits, and given that the elements of fire regimes (i.e., climate, ignition, vegetation) are arranged in a delicate balance, fire activity across the world is highly sensitive to global environmental change, in particular temperature rising favouring fire-prone weather and expanding human footprint leading to increased ignitions and fuel overload. Between 1998 and 2015, global area burned has decreased by 24 % [87], due mostly to intensification of agricultural development. Global environmental change can trigger a series of what scientists call feedback loops, which can be understood as circular, cascading, and self-sustaining (either amplifying or dampening) chain of events. For instance, historical increase in GHGs from human activities has led to more fire-prone climate patterns, leading to higher occurrence of large and severe fires conducing to greater GHG emissions from fire smoke, further accelerating climate change (figure 8). New regions will be affected by fire [88], with areas greening from more rainfall and CO2 favouring vegetation, and thus fuel, growth [89]. Eventually, feedback loops can lead to thresholds, known as tipping points, beyond which ecosystems cannot recover and shift to a new state (e.g., forest to grassland).

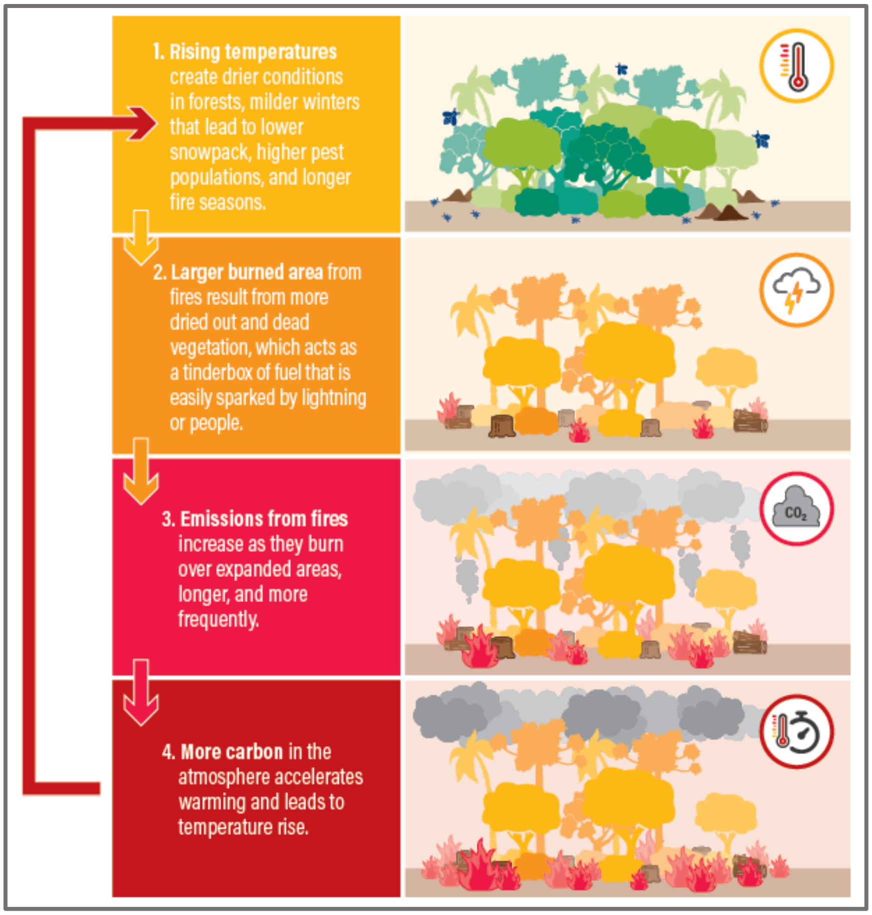

Figure 8: Fires and climate feedback loop, with a focus on smoke. (Credit: Global Forest Watch/World Resources Institute - https://files.wri.org/s3fs-public/uploads/fires-emissions-climate-feedback-loop-wri.png)

2.3.3. Importance of fire in human history

Modern humans have used fire for, at least, the past 300,000 years [90]. *Homo sapiens* is the only known species to have harnessed fire [90–92]. There is a deep-rooted link between humankind and fire, and many landscapes, even those that seem untouched, have experienced "landscape engineering" through a long and controlled use of flames for the benefit of human communities on every continent (except Antarctica) [93–95]. Some claim that areas with long historical use of fire by humans (millennia) has created levels of biodiversity greater that what would have happened with natural fire activity alone [95,96].

As humanity entered the Anthropocene, many fire-adapted and fire-dependent landscapes were progressively deprived from flames [91,97]. Reasons are numerous: rural exodus, negative perception of fire leading to fire exclusion, improvement of firefighting technologies, protection of timber resources, stringent fire control imposed on aboriginal people after European colonization, climate change, among others. These mechanisms are often associated to some degree, but there is no unique pattern defining these relationships, or syndromes [75]; indeed, the social, economic, and natural diversity of cultural landscapes makes them impossible to list in an exhaustive manner from a fire-use perspective [91].

Nonetheless, this situation has put many ecosystems off-balance with their fire regime, leading in part to the fire disasters the world is experiencing now. In a globalized world, the role of teleconnections is coming on top of the listed issues; for instance, consumption patterns of the most affluent are responsible for a significant part of fires worldwide [37,98,99]. Contrary to popular belief, highly fuelled by 24/7

sensational media coverage, global burned area has been decreasing for decades [87,100]. Wildfire related disasters however seem to increase, as they often overlap with dense human settlements, and greatest area burned is increasingly attributed to a lower number of fire events.

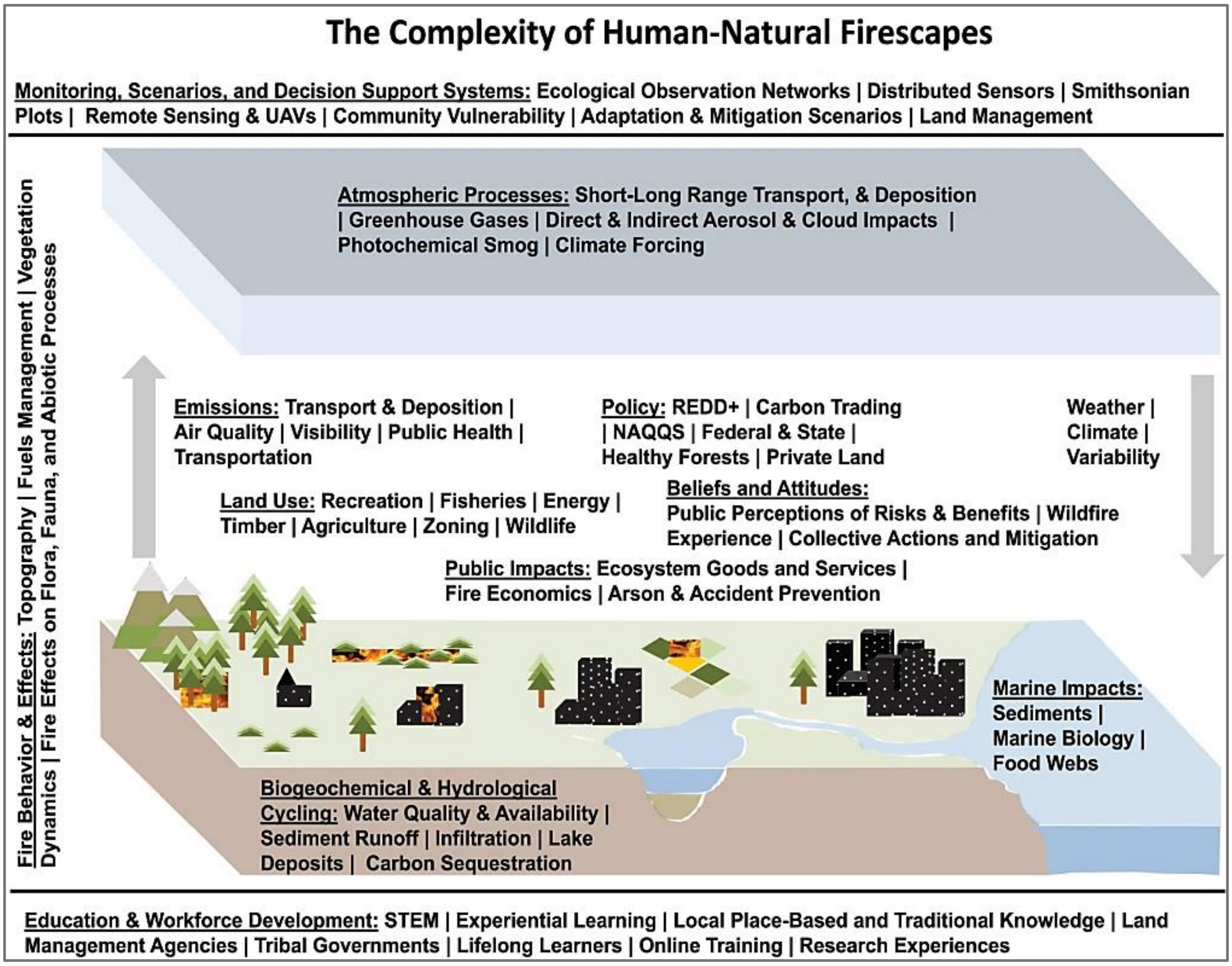

Figure 9: "The complexity of Human-Natural firescapes", from [101].

2.3.4. Extreme fire events

Extreme wildfire events, or EWEs, are those fires that release so much heat and behave in such erratic way that they make suppression and control impossible. Suppression, or direct attack, is usually possible up until 4,000 kWm−1, and control is possible up until 10,000 kWm−1; EWEs release ≥ 10,000 kWm−1, with possible energy release up to 100,000 kWm-1. EWEs also move fast—over 3 km per hour—and move ambers and firebrands over 1 km ahead of the flaming front [69]t. According to the wildfire event classification, EWEs occupy ranks 5 to 7 [69]. These fires can happen in very different kinds of environmental settings, and occur naturally or are the product of human activity [102]. EWEs represent maximum threat to highly-valued resources and assets and have a high potential to cause disaster; however, recent estimates suggest than less than a third of these events turn into disasters.

3. Global status of forest fire activity

3.1. Recent significant events (2015-2020)

3.1.1. In Africa

The most significant events in Africa for the period 2015-2020 are as follow:

- South Africa experienced wildfire disasters during the 2015 and 2017 fire seasons. In 2015, Western Cape region experienced human-caused 7,000-hectare blaze that killed one person, injured 56, and damaged 13 properties. In 2017, the naturally-caused Knysna fires burned 19,000 hectares, killed seven persons, displaced 10,000, and damaged 900 structures[6].
- The 2019 human-caused fires in Mount Kenya national park also drew attention, totalling over 20,000 hectares. The park is a World Heritage site, an important source of income from tourism, and one of Kenya's Water Towers, thus a critical source of freshwater [103].
- Wildfires are common in South Sudan, but in 2019 they killed at least 50 persons, injured at least 60, with over 100 houses damaged and 10,000 cattle heads lost, the latter being critical for people's livelihood[7].
- The 2017 fires in Algeria caused great damages to agricultural resources, namely: over 200,000 olive trees, 74,000 fruit trees, and 5,000 beehives [104]. These assets represent an important source of income due to the value of derived products on local and international markets.

3.1.2. In Asia and Middle East

The most significant events in Asia and Middle East for the period 2015-2020 are as follow:

- In 2015, Indonesia experienced a massive wildfire, burning 2.6 million hectares; and in 2019, 850,000 hectares. These fire events are mostly linked to deforestation on drained peatlands to extend oil palm plantations. These peatland fires also produce vast amount of toxic haze leading to premature death from respiratory health issues [105].
- In 2016, India experienced a series of wildfires in Uttarakhand region, burning over 4,500 hectares and killing seven persons [8]. India often experiences toxic haze from widespread stubble burning (>23 million tonnes estimated), leading dangerous air pollution levels for extended periods of time in populated centres, such as Delhi, as in 2019 and 2020 [9].
- In 2020, the Zagros mountains in the western part of Iran experienced human-caused fire activity. Although the area burnt seemed limited in comparison to other fire events that happened in 2020, these fires still caused damage due to reliance on the forest for livelihood [106].
- In China, 18 firefighters died in duty in 2020, where dangerous fire weather conditions allowed fire to move fast over 1,000 hectares, leading to the evacuation of 25,000 people [10].

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[6] https://www.nytimes.com/2017/06/08/world/africa/south-africa-fire-knysna.html

[7] https://reliefweb.int/report/south-sudan/wildfire-kills-50-people-south-sudan

[8] https://www.bbc.com/news/world-asia-india-36184817

[9] https://www.nationalgeographic.com/environment/article/new-delhi-burning-season-makes-air-even-more-dangerous-can-anything-be-done

[10] https://www.theguardian.com/world/2020/mar/31/forest-fire-kills-18-firefighters-one-guide-xichang-china

- In 2016 in Israel, dry vegetation and fire prone weather fuelled natural and human-caused fires. Despite a fairly small area burned (~2,000 hectares), events happened fast and led to the evacuation of 75,000 people and the destruction of 77 buildings [11].

3.1.3. In Europe

The most significant events in Europe for the period 2015-2020 are as follow:

- In 2020, Siberia experienced record-breaking heat early in the summer, up to 38°C, and 14°C above normal; this exceptional climate situation drove fire activity North of the arctic circle [107].
- In July 2018 in Greece, several fires started around Athens during high fire danger conditions (i.e., hot, dry, windy weather). With flames reaching 30 meters high, fires spread fast and reached settlements, taking the population by surprise. 100 persons died, 1650 homes were destroyed, and nearly 1,500 hectares burned [107].
- In 2017, lightning-caused fires sparked in Portugal during severe fire danger conditions, burning over 500,000 hectares. 120 persons died, many trapped in their cars while trying to drive away from the fast-spreading fires [12].
- In 2018, unusually warm and dry conditions favoured fire spread across Scandinavia. Sweden was particularly impacted, with 25,000 hectares burned, mostly forests, in a country where timber is major source of revenue, and between 300-500 people were evacuated [13].
- In 2020, wildfires in the exclusion zone of Chernobyl 2020, in Ukraine [108], burned nearly 50,000 hectares.
- In Poland in 2020, during prolonged drought conditions, human-caused fires spread through the Biebrza National Park, the largest protected area in the country. Fires burned nearly 6,000 hectares, or 10% of the park, which is home to exceptional biodiversity [14].

3.1.4. In North America

The most significant events in North America for the period 2015-2020 are as follow:

- In the USA, after several years of record-breaking fire seasons in the western part of the country and numerous related disaster (the 2018 Camp Fire in Paradise, where 85 persons died), 2020 culminated with over 1.6 million hectares burned in California alone. This last fire season might cost up to $13 billion to insurers [15]. In 2016, a fire spread from the Appalachian Mountains through Gatlinburg, Tennessee in the Eastern USA, claiming 14 lives and damaging or destroying 1,000 buildings.
- In 2016 in Western Canada, during very dry conditions, the Horse Creek fire burned nearly 600,000 hectares, impacting the municipality of Fort McMurray. 88,000 people were evacuated and nearly 2,400 building destroyed or damaged [109]. It took until August 2017 to extinguish residual smouldering fires in peatlands [16].
- In 2017, Western Greenland experienced an unusual fire season. Although small "soil" fires have happened there in the past, it never reached such extent in recorded history, the largest fire reaching

[11] https://www.nytimes.com/2016/11/24/world/middleeast/israel-fires.html

[12] https://www.theguardian.com/world/2017/jun/22/portugal-forest-fires-under-control

[13] https://www.theguardian.com/world/2018/jul/18/sweden-calls-for-help-as-arctic-circle-hit-by-wildfires

[14] https://phys.org/news/2020-04-huge-ravages-poland-largest-nature.html

[15] https://www.reuters.com/article/us-usa-wildfires-insured-losses-trfn-idUSKBN28P2NQ

[16] https://www.bbc.com/news/world-us-canada-36224767

nearly 1,500 hectares (figure 10). In 2019, a second wildfire occurred in Greenland along the Arctic Circle Trail, burning for a month – just like the 2017 wildfire event [17].

Figure 10: wildfire in western Greenland, 2017. https://pierre-markuse.net/2017/09/18/greenland-wildfire-august-2017-before-after-images/

3.1.5. In Oceania

The most significant events in Oceania for the period 2015-2020 are as follow:

- During the 2019-2020 summer in Australia (now called "Black Summer"), over 18 million hectares burned, killed 34 persons, destroying 5900 buildings, including over 2800 homes, and threatening many endangered species in the aftermath of the fire, such as koalas and endemic freshwater fish species. IUCN declared that most of the 100 threatened species of plants and animals were impacted by fires, leading them closer to extinction [110].
- In 2017 in New-Zealand, the Port Hills fire killed one and destroyed nine houses in Christchurch. It was dubbed "emblematic" of changing fire regime. The event happened while the community was still recovering from the 2011 destructive earthquake [18].

3.1.6. In South and Central America

The most significant events in South and Central America for the period 2015-2020 are as follow:

- In January 2017 in Chile, what is considered as the worst fire event on record killed at least 11 persons, destroyed over 1000 buildings, with over 500,000 hectares burned [19].
- In 2020 in Brazil, human-caused fires burned an estimated 2.2 million hectares of tropical rainforests [20]. In particular, fires in the Pantanal, one of the largest wetlands in the world and a biodiversity hotspot, burned over 10% of its area [111]. Many Indigenous communities subsisting on these forests for livelihood were negatively impacted.

[17] https://earthobservatory.nasa.gov/images/145302/another-fire-in-greenland

[18] https://wildfiretoday.com/2017/02/15/wildfire-threatens-christchurch-new-zealand/

[19] https://www.nationalgeographic.com/science/article/chile-wildfires-photos

[20] https://phys.org/news/2021-01-brazil-wildfires-surge.html

- In 2019, the Amazon region experienced a fire season above normal activity, with 47 million hectares burnt in total over Brazil, Bolivia, Paraguay, and Peru. 33.6 million hectares were burnt in Brazil alone. These fires seemed related to human-caused illegal deforestation for farming, cattle ranching, and mining [21].
- In Argentina in 2020, drought conditions favoured the occurrence of fires, burning over 60,000 hectares; at least two people died. The delta of the Paraná river, the second largest river is South America, burned out of control; the area is indeed drying out due to the combination of climate change and conversion of wildlands to intensive agriculture [22].

3.2. Historical trends

3.2.1. Methodological background

Historical trends in fire regime can be studied using diverse and increasingly complementary sources. In countries where they exist, national fire databases provide important information beyond fire size and frequency; for instance, the Canadian National Fire Database provides other fire attributes such as the cause, as well as start and end date, which are attributes that are hard to retrieve from satellite imagery.

Where these statistics are unavailable, either because no such database is maintained or because there is no public access, then satellite-based data are used. The Global Fire Emission Database[23] and Global Wildfire Information System[24] rely on remote-sensing techniques to detect and collect fire occurrence back to the late 1990s. Often, historical trends focus on fire frequency and area burned. However, increasingly the recourse to remote-sensing data helps to further fire regime reconstitution and ongoing or potential changes they experience, especially at the global scale, combined with other social-economic variables and knowledge of regional/local fire use [74,87,102].

Increasingly, changing trends in fire activity across the world are attributed to climate change. Attribution is a highly active field of climate science that seeks to understand if recent extreme meteorological and climatic phenomena are the product of natural variations or if they are directly related to climate change, everything else being equal [88,112].

Historical trends are derived from satellite records and complemented with accounts from national statistics and available scientific publications, including attribution to climate change. Importantly, satellite data cover a fairly short period of time and it can be unwise to draw firm conclusions from them: the Landsat satellite archive is available from 1985 onwards but with a global coverage starting in 2000, whereas MODIS, VIIRS, and Sentinel satellite systems create global coverage from 2001 and 2014, respectively; many fire regimes have fire return intervals longer than available satellite record. Despite a reported general decrease in global fire activity, there is strong spatial and temporal variability [113]. For example, trends are quite different when recent satellite records are compared with longer fire statistics for countries that have been recording fire activity since the mid-20th century—such as Spain and France.

3.2.2. Globally

It is estimated that over 420 million hectares burn every year on the planet, on average, between 2002 and 2016 [114]; Although all biomes might experience fire, grasslands and savannas experience most of the area burned [86,87,114,115]. Since the beginning of the 20th century, however, global area burned

[21] https://www.nytimes.com/2019/08/23/world/americas/amazon-fire-brazil-bolsonaro.html

[22] https://earthobservatory.nasa.gov/images/147031/the-parched-parana-river

[23] https://www.globalfiredata.org/

[24] https://gwis.jrc.ec.europa.eu/static/gwis.statistics.portal/

has been decreasing, a trend confirmed by recent studies using satellite data available since the mid-1990s [87,100,116], despite strong regional disparities. This decrease is attributed to human activities, through fire suppression and land-use/land-cover change that increase landscape fragmentation and limit fire spread [75,81,117,118]. On parallel, climatic conditions have been more favourable to fire activity, with longer and drier fire seasons [88]; furthermore, impacts from fire activity on societies and ecosystems has been constantly increasing, revealing an increase in the vulnerability of highly-valued resources and assets (e.g., expansion of suburbs in wildlands) [100].

3.2.3. In Africa

Africa shows a generalized continental decline in fire [87], with spatial variability [119]. Between 1998 and 2015, North Africa (i.e., Mediterranean) displays increasing area burned whereas sub-Saharan Africa, and particularly southern Africa, shows a decreasing trend. Savannas have especially shown a decrease in area burned. Overall, during the 20th century, the continent experienced a slow but constant increase in area burned [113].

There is a general significant decrease in the number of fires, as well as individual fire size, especially in sub-Saharan Africa. Fire frequency increases in south hemisphere savannahs, whereas no clear trend shows in Mediterranean Africa [87,116]. Fire activity is dominated by human ignition for agricultural purpose. Fire activity is also noticeable within deforestation fronts in Central and Eastern Africa.

There is high dependence to precipitation, with a strong influence of El Niño Southern Oscillation (ENSO). Noticeable increases in fire activity in Southern Africa are driven by ENSO, while also linked to decrease in fire activity in sub-Saharan Africa. Due to climate change, there is a significant increase in fire weather season length as well as in the occurrence of long fire seasons in central and western sub-Saharan Africa, Northern Africa, and Madagascar, while western Africa shows a decrease [88].

3.2.4. In Asia and Middle East

In Central Asia and at the southern fringe of the boreal forest, there is a decrease in area burned, while north-eastern China and northern India show increases due to growing agricultural pressure. Southeast Asia experiences a slight increase in area burned from 1998 to 2015, but an increase from 2003-2015, while Middle East displays a mix of decrease and increase. Area burned in boreal Asia—including Siberia and Far East Russia—seems stable. Overall, recent studies show many areas where trends are unclear. Over the course of the 20th century, area burned in boreal and East Asia decreased, whereas area burned in Central Asia and Southeast Asia has been increasing since the 1970s-1990s [113].

Fire frequency decreased in Central Asia and Southeast Asia, while changes in fire frequency is unclear in the Middle East, in Southeast Mainland Asia, and Indonesia; an increase is noticeable in the boreal part of the continent, in north-eastern China, northern India, Pakistan, and Vietnam [87,116,120]. Fire activity is dominated by human ignitions linked to forest degradation and agricultural maintenance, in particular in areas of deforestation [37,41].

Precipitation drives fire activity in South and Southeast Asia, with a strong influence of ENSO. Moreover, due to climate change, there is an increased frequency of long fire season between 1979-2013 throughout boreal Asia, the Middle East, and around the Caspian Sea. The length of the fire season also increased across all the Middle East, Mongolia and eastern China, and slightly decreased in southern India, central China and Kazakhstan [88].

3.2.5. In Europe

Since the 1980's, there is a general decreasing trend in area burned, expect for Portugal [107,119,121]. Variability remains important though, with more fire activity during years of more conducive fire weather,

which explain spikes in area burned, especially in recent years [122,123]. After an early decrease at the start of the 20th century, area burned became stable until the 1970s and have been increasing since [113].

Fire frequency, after an increase during 1990-2010, has been decreasing. The average size per fire also has decreased, from nearly 20 hectares on average in 1980 to 7 hectares on average in 2019 for the southern part of Europe [87,116,121]. There is however an increasing trend in fire frequency in eastern and northern Europe, as well as European Russia [87]. Over 95% of fires are human-caused and linked to accidents, tourism, and arsons.

Although fire activity seems to decline slightly, climate patterns are already tainted by climate change, with 2019 the warmest temperature on record in Europe, and recent temperature trends above by 0.5 to 1.5C compared to 1981-2010 normal temperatures [88]. The length of the fire season is increasing in Spain and central Europe, but is decreasing in parts of Scandinavia; however, the frequency of long fire seasons is increasing in most of southern Europe, parts of Nordic countries, and European Russia [88].

3.2.6. In North America

In North America, Canada does not show a general increasing trend in area burned but significant regional increases [119,124,125], while the trend is clearly increasing in the USA, except for Alaska where a trend is not noticeable. Mexico shows an overall decreasing trend [87]. Since the 1900s, there was a decrease in area burned all across the USA until the 1960s, then an increasing trend until now [113,126].

Fire frequency has decreased, but individual fires are getting larger [87]. Canada is seeing an increase in lightning-caused fires but a significant decrease in human ignitions, although with regional variability [127]. Fire frequency has increased in boreal Canada and Alaska, as well as in the Western and South-eastern USA and northern Mexico [87]. There is also a strong seasonal pattern, with fire frequency increasing in Canada between March and May, as well as during summer in USA and Mexico, with a continental increase in Autumn throughout [116].

Fire activity in North America is highly driven by fire exclusion, increase in WUI and other human-dominated interfaces overall, and a lengthening of the fire season. There is indeed a marked increase in fire season length in parts of Alaska, the western USA and Mexico, and strong increase in frequency of long fire seasons throughout most of Alaska, USA, Mexico, but only parts of Canada [88].

3.2.7. In Oceania

Area burned shows an general decrease in Australia during the period 1998-2015, despite a recent increase [87]. There is however spatial and seasonal variability, with a few pockets in central and western Australia showing an increase [87,119]. During the 20th century, savannas of Australia show a slow steady decrease, along with a sharp decrease in forest area burned [113]. These trends are likely linked to fire exclusion and disappearance of traditional indigenous burning.

Fire frequency has been increasing in western and north-east Australia, but individual fire size has been decreasing. There is no clear trend in New Zealand, while fire frequency in Papua New Guinea seems to be increasing [87,116]. Fires in Hawai'i have increased since the mid-1990s to present, with most fires occurring in the WUI and in non-native grasses and shrubs that comprise about ¼ of the islands total surface area [128].

Fire-conducive climate is common in Australia, and one might argue that there is a year-long fire season. There is however a strong increase in occurrence of long fire seasons in Papua New Guinea, in western Australia, and parts of eastern Australia [88].

3.2.8. In South and Central America

Area burned is generally declining in South America despite high variability [87,119]. This is not true for Brazil that shows a large increasing trend, with a few increasing pockets scattered in surrounding

countries. Recent area burned in Brazil was above long-term average (33.6 million in 2019, four times 2018) while fire frequency remains stable. Recent fire activity in several regions of South America seem to be linked to deforestation-related activities, and not climate change or natural fire regime. During the 20th century, fire activity decreased sharply in temperate South America, while area burned in Amazonia increased sharply from almost non-existent in the 1970s.

Fire frequency has generally decreased, yet individual fire size has increased. Regional increase in fire frequency is visible in southern Chile and at the southern fringe of the Amazon, while there is a decrease in fire frequency in the Amazon overall, as well as in northern South America and throughout Central America [87,116]. This fire activity is highly driven by deforestation for large-scale farming and open-burning in agricultural systems, although the Cerrado is a naturally fire-prone grassland region experiencing natural ignitions.

The fire season is getting longer in eastern and central South America, as well as at the extreme south of the continent (Tierra Del Fuego), while shortening in western South America as well as in several parts of central America. Overall, the frequency of long fire seasons has remained stable since the 1970s [88].

3.3. Predicted trends

3.3.1. Methodological background

Predicting trends in future fire activity is challenging, given the number of elements that control fire regimes. Some studies focus on predicting future fire weather only, which can be used to compute fire danger indices and extrapolate potential impacts on fire activity [129–131]. Other studies adopt an integrated approach in which physical models of wildfire activity are ran as part of Earth System models, which include interactions and feedback loops among hundreds of variables, including vegetation change and human influence. The ultimate goal is to simulate future fire activity and understand how fire regime elements (e.g., season, cause, severity) might change; however, great uncertainty subsists [89,132]. The Fire Model Intercomparison Project (FireMIP) is an important example of the current joint effort to unravel future wildfire activity [133], as well as tease apart the contributions of human drivers of fire activity. The trends presented hereafter are the result of a compilation of references from different scientific studies.

3.3.2. Globally

On a global scale, ongoing climate change is predicted to increase the potential for fire in many regions of the globe, mostly due to longer dry and warm seasons and higher lightning activity [134,135]. Fire frequency, area burned, and severity may therefore increase [130,136], but these expected trends are still largely debated owed, in part, to our limited—but growing—understanding of climate-vegetation-fire feedbacks. Furthermore, the influence on human activities, which tend to alter, if not dampen fire activity in many regions around the world, may counterbalance the effect of a warmer and drier climate on fire activity [137]. Changes in global fire activity will probably display strong regional differences [115].

3.3.3. In Africa

Area burned in Africa might generally decrease, except for a band north of the equator [138]. Increase in population density appears to be an important agent, as climate-only simulations suggest a decrease in West Africa and a slight increase in area burned in East and Southern Africa [135].

Based on the worst-case scenario of future world development (i.e., RCP8.5 and SSP5), several regions of West Africa, along the northern and southern fringe of the tropical forest, and North Africa will experience an increase in fire-frequency by 2100.

The length of the fire season might not change much, but fire weather will make fire control more challenging throughout most of the continent by the end of the century [130].

3.3.4. In Asia and Middle East

Asia might experience a strong increase—20-100%—in area burned in most of northern and eastern regions, in China, in Indonesia, and in southern India. A lower increase—10%—in Mainland Southeast Asia and Central Asia is possible, while the Middle East might experience a mix trend [135].

Fire frequency will likely increase in central Asia, south of Indonesia, south of China, all across the Middle East, with only a few areas of decrease throughout China, according to the worst case scenario [132]. Human activity will likely remain the dominant driver of fire regime in these areas.

By 2100, most of Asia might experience significant increase in suppression difficulties, as well as >20 days increase in fire season length. The length of fire seasons might not change much in south Asia, including India, while east Asia, the Middle East, and south of China might experience an increase of 3 to 20 days.

3.3.5. In Europe

Area burned is predicted to decrease over most of Europe in climate-only simulations, except for the Alps, northern UK, and Fennoscandia [135]. The Mediterranean will very likely see its fire danger increase, with area burned expected to increase sharply if warming crosses 2°C [139].

In a worst-case scenario, increases in fire frequency will happen in southern Europe [132], in part due to the continuous expansion of WUIs. While this is being debated in the scientific literature [140], the existence of highly flammable eucalyptus stands for timber—which have now become invasive in the Iberian Peninsula—may increase unusual fire activity as well.

The fire season length might increase by more than 20 days for virtually all Europe by 2100, with significant increase in suppression difficulties. There is also a medium level of confidence that the occurrence of droughts, an essential driver of fire activity, will increase in Europe, leading to a certain increase in fire danger [141,142]. Wildfire danger will likely expand northward and display zones of moderate to high risk, couple to a generalized shift to high fire risk in western and central Europe [107,142].

3.3.6. In North America

Area burned might increase throughout most of the boreal biome [143], with sharp increases in eastern Canada, Yukon, and Alaska. Most of the USA might experience an increase as well, while Mexico does not show a clear trend, based only on climate change by 2100 [135]. Many regions of low fire activity in central USA, south western Canada, South-eastern US, and a few pockets in Mexico will become fire prone [132]. Growing population and expanding human activities might dominate fire regimes.

There will likely be an increasing influence of large-scale climate patterns on top of climate change that will worsen fire activity [144]. Predicted increase in fire intensity will make suppression harder, with longer fire seasons throughout Canada [129,145]. Fire season length might not change for Mexico, and increase by >20 days in most of USA and, the southern half of Canada by 2100 [130].

3.3.7. In Oceania

Australia and New Zealand might experience a slight increase in area burned [135]. Several regions of western Papua and Australia might also see an increase in the frequency of fire [132].

Fire severity ratings are predicted to increase by 2100, making suppression more challenging, yet fire season length will remain (already yearlong) [130]. However, recent events in Australia might be a sign that climate change is changing fire danger faster than initially predicted [146].

3.3.8. In South and Central America

Based on climate change only, area burned might decrease throughout the Amazon, while some pockets of land will experience an increase in Chile, Ecuador, and Columbia [135]. However, fire frequency will keep increasing in the southern Amazon frontier, with ignition driven by human activity, especially in dry savannas and evergreen forests [132,147].

There might not be change in fire season length but there will likely be an increase in the severity ratings by 2100 in Central America. During the same period, South America might experience a large increase in fire season severity, no change around the equator, and then mostly an increase for the southern part of the continent, except for the Andes. Fire season might increase by over 20 days in the Southern Andes and Tierra del Fuego [130].

4. Causes and drivers of wildfire disasters

4.1. Land conversion and degradation

Although no agreed-upon number exists, it is estimated that 70 to 90 % of fire on Earth are started by human. These estimates, however, cover a wide array of fire uses: arsons, broadcast fire, cultural fire, hazard reduction and prescribed burn, deforestation, landscape maintenance, and open burning in agriculture [101].

Given the global human footprint, it is estimated that 25% of the world is degraded and 420 million hectares of forest have been lost to agriculture since the 1990s. Fire is a cheap and efficient tool to clear land and maintain open clearings. In the past 15 years, an estimated 3 million hectares of Indonesia's peatlands have been burned to make way for farming and the production of commodities, and fire activity is associated to all deforestation fronts in the world [37,98,148–150].

Urbanization is a form of land conversion that is conducive to more fire disasters. More than half the world population now lives in urban areas, which invariably increases the density of wildland-society interfaces, leading to more fires ignition, as well as more assets exposed to burning [17,151–153]. In Europe, for instance, the end of the 20th century has seen an increase in suburban development leading to increasing WUI density, coupled with increased tourism and unemployment [153,154].

Widespread land abandonment is another cause of land cover change that increases wildfire risk. In Europe, including European Russia, rural exodus during most of the 20th century has led to landscape closure and shrub encroachment that has increased fuel load [123,155]. Such dynamic has been reported in South America as well [156]. Suppressed traditional—Indigenous or not—fire use also led to a forced abandonment or significant changes of ancestral land management practices, with similar consequences as observed in Europe's land abandonment—a significant increase in biomass, and thus, fuel load, and fire hazard [97,157].

4.2. Forest management

Forest, and vegetation management more generally, is a strong driver of fire activity. For instance, after the 1910 "Big Burn" in the Western USA, fire suppression became standard practice for forest management, in an intent to protect, in part, timber resources. A similar mindset led to fire exclusion in Australia, where Aboriginal people were not allowed to burn anymore. The result is now overstock forests coupled to bush encroachment in many regions of the world, comparable to tinderboxes leading to extreme fire events.

In Europe, land abandonment caused by the 20th century rural exodus, as well as the collapse of the Soviet Union, has led to afforestation through natural landscape closure and thus fuel build-up. When combined

to an increased use of the landscape by human activities, this fuel build-up has favoured the occurrence of extreme fire events leading to disasters.

The introduction of exotic species can also seriously impact fuel load and fire behaviour. The continuing increase of planted forest cover since 1990 may be of concern from a wildfire hazard standpoint in several areas of the world, especially where non-native, fire-prone species are used for fast timber generation [158]. Eucalypt and conifer species in particular have been associated with several extreme wildfire events with disastrous consequences for surrounding communities, although the relationship between afforestation and fire activity is not unequivocal [140,159–161]. In an era where planting trees to fight climate change has become a fashion, we need to think about the consequences for fire regimes; in some areas, planting more trees without a clear understanding of the consequences on fire activity might have more negative effects on the long run.

4.3. Climate change

Climate change, as threat multiplier, is becoming a leading driver of global fire activity [62]. Weather extremes are now on the rise, and droughts and heat waves—as underlying factors of fire activity—are happening more often and at a great magnitude. A warmer climate has been directly linked to higher fire danger [130,134,162]: fire seasons will become longer; drier and warmer conditions will make more vegetation available for fuel; increase in lightning activity will lead to more natural ignitions.

Predicted changes in vegetation assemblages and health, as well as improved spread capacities for invasive species, will lead to fire regime shifts [142]; actually, fire might even accelerate vegetation transition towards novel ecosystems [163]. European ecosystems are already suffering from these changes, leading to compounding problems such as droughts leading to further tree die-off and thus increased fire hazard [107,164]. However, studies suggest that long-term feedbacks might also lead to decreasing vegetation recovery and overall cover, leading to a decrease in hazard on the long run as fuel load diminishes [139]; the loss of ecosystems to the combined effect of climate change and fire is in itself a disaster.

Increasing length and severity of fire seasons create a particular concern for northern latitudes ecosystems where climate change is happening two to three times faster than on the rest of the planet [107,165,166]. As climate change is causing permafrost thaw, peatland ecosystems are increasingly exposed to burning, which then accelerates thaw, releasing methane and making more peatlands exposed to burning, thereby creating a gigantic feedback loop to can accelerate climate change [167,168].

5. Impacts of fire-caused disasters

Disasters caused by forest fires can lead to human death, infrastructure losses, and impairment of ecosystem services and benefits. When evaluated through the lens of global environmental change, extreme wildfire events and their potential for disastrous consequences can delay the achievement of many SDGs (figure 11) [65].

Figure 11: Direct and indirect impacts of forest fires can be detrimental to the completion of the Sustainable Development Goals (from [65]**).**

5.1. Ecosystem health

5.1.1. Impairment of ecosystem services

Fires need not to be extreme or to impact man-made infrastructures to have deleterious consequences. A wildfire might be limited to a distant, upstream watershed that supplies several communities downstream [169,170]; water pollution and decreased availability can be seen as detrimental, although not a disaster *per se*. That being said, extreme wildfire events have a destructive potential that can severely impact natural processes and functions, and thus the many ecosystem services and benefits that are supplied to communities [65,171,172].

There is now increased acknowledgement of risks to ecosystem services from atypical fire activity [78,173–175]. For instance, forested watersheds provide an estimated 70% of the world's water supply, but severely damaged forests can compromise municipal water supplies, among other uses [176–179]. Wildfires can have negative impacts on cultural and spiritual ecosystem services, such as archaeological values; with ongoing climate change, an increasing number of UNESCO World Heritage Sites are at risks from wildfires [180], such as the Mesa Verde National Park, in USA, with more than 4,500 archaeological sites. The sight of a burn landscape and the perception of a fire hazard can deter potential home buyers, which can be reflected in a dropping prices of properties on the housing market [181]. The closure of parks and other natural areas due to wildfire occurrence might drive tourists away and decrease important revenues for local people, along with associated losses of timber and other forest products. Finally, the impairment of air quality due to smoke is receiving an increased scrutiny from researchers and health services, as effects on health can be dramatic, on top of possible large effects on rainfall patterns [182,183].

5.1.2. Ecosystem recovery failure

The effect of climate change is already visible in many ecosystems in which fire plays an important natural role; this effect is predicted to amplify and change vegetation assemblages profoundly.

As increased temperatures and drier conditions will stress vegetation, fire might spread more easily through landscapes, including in locations that never or rarely experienced fire in recent history [184]. After the fire, different, sometimes more extreme, climate conditions might lead to difficulties for ecosystems to recover, even in fire-adapted ecosystems [185]. Even after recovery, generally more fire prone conditions will increase fire frequency in these ecosystems, shortening rotation and making it impossible for trees to reach maturity, leading to a slow decline in seed bank. Forest ecosystems might get younger, and eventually reach a tipping point and shift to a novel ecosystem [53,163,185,186].

These issues must be seen in the larger issue of forest health decline and potential failure to recover by natural means as climate change drives forests into uncharted territories; slow-recovery forest ecosystems may never come back, and fire might just accelerate shift to other, less productive ecosystems [187].

5.1.3. Impacts on biodiversity

Long-established fire regimes are acknowledged as vectors of biodiversity, whereas recent and future shifts in fire regimes across the planet are expected to negatively impact it. In some parts of Europe, a decline in native insect populations has been caused by increasing fire activity. IUCN reports, for instance, that green bush cricket (*Calliphona alluaudi*), an endangered species of the Canary Islands, has lost one quarter of its range due to a large fire in 2007[25].

The extent and gravity of the 2019-2020 fire season in Australia impacted the range of 832 species of vertebrate, including 21 endangered species, some ranges being burned over 30% [188]. WWF-Australia estimated that over 3 billion animals might have been impacted[26]; out of 113 priority fauna species needing post-fire assistance for survival, 60% were freshwater species[27]. Massive media coverage of burned koalas and starving kangaroos eating carrots has pointed at the increasing need to invest in post-fire biodiversity conservation [189].

Orangutans have been the emblem of tropical wet forests loss to deforestation fires and the production of commodities [190,191]. The species is labelled as 'critically endangered' on the IUCN red list. It has lost 60% of its habitat in Indonesia over the past 40 years, and it is estimated that up to 5,000 die every year, out of a remaining number close to 50,000. The combination of safeguarding efforts combined to a slow decline in deforestation brings hope for the survival of this species [192].

5.2. Social health

5.2.1. Fatalities, injuries, and health issues

Direct death from wildfires remains rare in comparison to the number of people impacted by a fire disaster, and relative to other disasters types. From 1980 to 2021, the disaster database EM-DAT, reports 2,805 direct fatalities and 8,540 injured [28]. Often, firefighters and aircraft pilots, given their work on the frontline, are the most exposed. That being said, the 2009 Black Saturday in Australia and the 2018 Camp Fire in California led to shocking death tolls, with 173 and 85 people who perished in the flames,

[25] https://www.iucn.org/news/secretariat/201702/intensive-agriculture-and-wildfires-threaten-over-quarter-europe%E2%80%99s-grasshoppers-and-crickets

[26] https://www.wwf.org.au/news/news/2020/3-billion-animals-impacted-by-australia-bushfire-crisis#gs.q7giyt

[27] https://theconversation.com/sure-save-furry-animals-after-the-bushfires-but-our-river-creatures-are-suffering-too-133004

[28] https://public.emdat.be/

respectively. Indirect fatalities can also happen during evacuation, as happened during the 2016 Fort McMurray fire in western Canada where two people died in a car accident.

The most widespread health issues relate to smoke. Smoke from vegetation fires can produce black carbon, soot, carbon dioxide, methane, carbon monoxide, and significant amounts of particulate matter ≤ 2.5 micrometres. From 1997 to 2006, an estimated average of 339,000 people died annually from health issues related to wildfire smoke [193]. During the 2015 fire season in Indonesia, 43 million people suffered from long-term exposure to haze, and as many as 100,000 people died prematurely due to smoke and decreased air quality; according to the World Bank, these fires led to $151 million in direct health costs. A study is now suggesting that smoke could also help the transport infectious agents [194]. The 2019-2020 fire season in Australia caused an estimated 417 excess death in relation to poor air quality [195].

An emerging concern relates to the possible deferred health effects linked to legacies of environmental degradation, although to an undefine extent that still require more research [196]; however, the recent fires in the Chernobyl contaminated area point at the importance of legacy issues [108]. Recent research in formerly-mined areas showed increased arsenic levels in water supplies running off the area [196]; arsenic is a highly toxic compound considered carcinogenic.

5.2.2. Psychological toll

There is increasing acknowledgement of fire effects on mental health, from firefighters to evacuated homeowners [197]. Non-trivial levels of PTSD have been reported in studies involving firefighters, fire-injured adults, children whose house burnt, animals, evacuees, and even people that were only exposed through media coverage; these impacts can be long-lasting [197–200]. Disasters involve human perception; although management agencies and researchers have been working on setting quantitative thresholds which tend to consider disasters as the overlapping of an extreme wildfire event with numerous assets, a small fire burning one house, although a minor event by today's standards, is still a disaster for the owners who have lost their property and the memories and assets associated to it. This reality cannot be discarded.

5.2.3. Impairment of day-to-day life

During and after a disaster, effects on livelihood can rapidly feel acute, beyond impacts on ecosystem services and human health. According to EM-DAT, almost 7 million people were affected between 1980 and 2021. In 2017, 550,000 people were evacuated due to wildfires [201].

Living downstream of burned areas causes an additional stress, as it means being exposed to dangerous post-fire debris flows and flash floods [202]; the 2018 Montecito landslide in California caused 23 fatalities. Damages to energy and transportation infrastructures during or after the fire can significantly affect communities livelihood [203]. The possibility of a NATECH such as severe damages to water treatment plants and water distribution pipes, or the explosion of industrial facilities [24,204,205] can further impair a quick return to normal, or at least to functional life. Preventive power shutdowns in California during highly fire-prone weather causes disruption to millions of people and create social unrest. Damages to archaeological/heritage sites can occur as well, usually during suppression operations, can prevent Indigenous people from keeping their culture alive and/or to perform ceremonies. Evacuations might overwhelm the capacity of emergency services to deal with "wildfire refugees" (figure 12). As fire seasons become longer, the possibility of facing 'Smoke seasons'[29] is a deterring outlook for people leaving near fire-prone areas.

[29] https://www.weforum.org/agenda/2018/08/wildfire-smoke-fills-u-s-canadian-skies-as-cities-ponder-options/

All the issues listed above, and more, are expected to become more common and affect more people as WUIs keep growing and fire regimes keep changing [206].

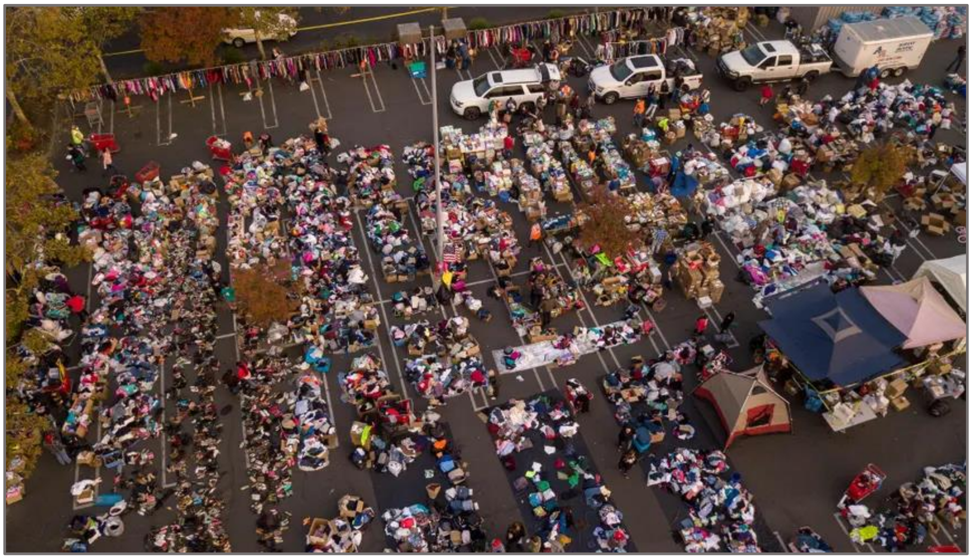

Figure 12: Fire evacuees sift through a surplus of donated items in a parking lot in Chico, California. (Credit: Josh Edelson/AFP/Getty Images – retrieved from: https://www.theguardian.com/us-news/2018/nov/20/california-wildfire-refugees-mudslides-ryan-zinke-environmental-radicals)

5.3. Economic health

5.3.1. The burden of firefighting expenditures

There is mounting evidence of increasing fire suppression expenditures for the past 40 to 50 years, at least in countries that have been reporting these statistics, such as the USA and Canada. In the USA, for instance, suppression costs have sharply increased from a mere $240 million in 1985 to $1.6 billion in 2019 [207]. A growing trend in expenditures has also been reported for post-fire treatments aiming at protecting values at risk from induced effects, such as debris flows in watersheds [208]. In Canada, from 1970 to 2013, suppression costs have increased from $290 million to more than $900 million. According to the worst climate change scenario, these expenditures may increase to $1.4 billion by the end of the century [209].

5.3.2. Insured and non-insured losses

Total losses from wildfire disasters were estimated at $52 trillion in economic losses from 1984 to 2013 [100]. Given existing gaps in wildfire disaster reporting, it is not possible to give an accurate global picture of wildfire costs; it is however safe to assume that the general increase in disaster costs related to climate extremes (151%) for the past 20 years also applies to fire to some measure [210]. The numerous reports showing the soaring cost of wildfires for insurance companies in the USA supports this assumption. Some sources have estimated the total cost of the 2020's California fire season to be around USD $150 billion. The reinsurance industry estimates that the 2020 US fire season is going to cost between 7 and 13 billion dollars in insured losses and the related financial losses amounted to 1.9 per cent of gross domestic product[30].

[30] https://www.reinsurancene.ws/rms-raises-2020-us-wildfire-loss-estimate-to-between-7bn-13bn/

Hereafter are examples of the vast costs wildfire disasters can have: Europe reported $10 billion in losses in 2017, with a total of $94 billion from 2000-2017, and future projections may increase the bill to over $7.5 billion of losses per year from $3.6 billion on average for 2000-2017; The total cost of the Knysna fire in 2015 in RSA was estimated over USD $200 million; Sweden lost an estimated $100 million in timber during its 2018 fire season; The total cost of the 2019-2020 fire season in Australia is estimate around $100 billion; After the 2016 Fort McMurray fire, Canada recorded a drop in GDP of ~2%; during the 2003 fire season in California, $15 million in damage to infrastructure were reported in California; the 2015 Indonesia fires led to an estimated $16 billion loss from disruption to economic activity and reduced GDP growth, including $157 million in direct damages [211].

The increasing worth of insured values exposed to wildfires combined to worsening wildfire conditions means that the burden of fire disaster losses on insurance and re-insurance companies might become unbearable, with consequences ranging from the impossibility for home owners to get their house insured to expensive premiums [212].

5.3.3. Losses from declining ecosystem and social health

These losses are harder to capture, and while more studies are needed, they provide another facet to what a disaster might be like. While it is indeed the common practice to report disasters in terms of fatalities, injuries, and insured losses, the economic, social, and ecological losses from fire-impacted ecosystems and livelihoods might be far higher. Recent wildfires in Australia and Poland led to the loss of important biodiversity, which is directly related to the supply of ecosystem services.

A variety of potential losses from wildfires have been identified: a drop in housing prices, lesser tourism opportunities for local communities [180], and a healthcare social and economic burden that might severely increase. A striking example comes from Indonesia, with $34 million in indirect losses due to school closure and $372 million losses due to transportation delays in 2015. To date, however, the full cost of these losses remains to be assessed. A recent analysis by the World Bank reveals that land and forest fires in Indonesia in 2015 cost the country $5.2 billion in damage and economic losses this year, equivalent to 0.5% of its economy [211].

It seems that economic losses might be increasingly linked to reputation, and fire events perceived as disasters by the international community might impact worldwide trade, as exemplified by tension around deforestation fires in the Amazon and the reluctance of the EU to ratify treaties that would somehow validate environmental degradation [173]. In Indonesia, the World Bank reports that massive media coverage of deforestation fires has exacerbated the global perception of Indonesian palm oil production as being detrimental to sustainable development, driving down demand from European countries, with a plan to phase out palm-oil-based biofuel by 2030 [211].

6. Conclusion: A wicked problem

Fire is a natural phenomenon that has shaped global ecosystems for millions of years. As humanity learnt to harness fire as a tool, people started to deeply transform and maintain surrounding nature to improve their livelihood, leading to the creation of fire-dependent cultural landscapes in many parts of the world. Through the vagaries of time, land management by fire has changed, for better or worse depending on historical and natural settings. The new reality of the Anthropocene, characterized by large-scale human domination over nature leading to biodiversity loss and climate change, is now causing pervasive, detrimental, and complex changes to fire activity leading to an increase in fire-caused disaster. Beyond direct loss of life and infrastructures, there is now increasing recognition of long-term effects of fire-caused disasters on mental health, ecosystem services, and livelihood. The multiplication of catastrophic events these past decades are a harbinger of disasters to come if nothing, or not enough, is done towards achievement of the SDGs.

Given the diversity of social, economic, and environmental settings driving fire activity around the world, there is no one-size-fits-all, meaning that best management practices working in a given place might not work somewhere else. In this sense, the worldwide wildfire "problem" can be seen as a wicked problem—one of these challenges that are so complex that they might remain conundrums forever. Given our globalized, high-tech, better informed, and rapidly changing world, wildfires can impact many facets of the system; however, there are immense possibilities for new, innovative, holistic and versatile approaches to existing and pressing fire management needs that are tailored to local issues. Importantly, working with communities, thinking fire as a solution in itself for restoring nature, and making sure fire management is integrated within larger strategies targeting nature restoration and climate change adaptation are keys to success.

On the bright side, we now know enough to make a change, so it not an issue of tools or knowledge, but of willingness to act. The following recommendations take place in the larger context of climate change reduction and adaptation efforts, whose importance and details go beyond the scope of this background paper.

7. Recommendations

In light of recent wildfire disasters and their likely increase if humanity fails to achieve the SDGs, several recommendations relative to policy interventions and other measures to be undertaken emerge for international organizations, national-to-local governments, the research community, the private sector, and NGOs, in order to reduce wildfire disaster risks, according to the priorities set by the Sendaï Framework for Disaster Risk Reduction.

As underlined in the present study, disaster risks due to fire and the consequences of catastrophic events vary from place to place for a variety of reasons going from differences in vegetation assemblages to cultural perceptions of fire. Therefore, it is critical to stress that the recommendations made below might not be suitable nor desirable in all geographic contexts, and that concertation with all stakeholders regarding a portfolio of solutions is the path to successful disaster risk reduction.

The recommendations mostly revolve around the concept of Integrated Fire Management (IFM) and its implementation. FAO describes IFM as a science-based, iterative planning process involving cycles of analysis, plan formulation, implementation and evaluation that allows for continuous learning and adjustments. It means working across sectors, with all stakeholder groups and administrative levels, thereby integrating bottom-up and top-down aspects; and combining local and scientific knowledge. IFM also acknowledges that "natural" fires are needed in some cases to preserve landscapes functions and ecosystem health [213]. Essentially, IFM pushes for a shift from 80% suppression (firefighting) to 80% prevention (including use of fire) and preparedness. Stakeholders must realize that it is a slow process, and that they must be "patient for results, but not wait for strategic action."

These recommendations, delineated by sector, include—but are not limited to:

7.1. International organizations

- Members of the Collaborative Partnership on Forests (CPF) should make "learning to live with fire" a worldwide motto, which will show support for the current state of wildfire risk science and for people involved in fire disaster risk reduction across the world. This motto embodies a number of avenues towards the implementation of the priorities defined in the Sendaï Framework, namely: understanding disaster risk, strengthening disaster risk governance, investing in disaster risk reduction, and enhancing disaster preparedness [214].
- Members of the CPF, as well as UNFF Member States, and other agencies such as UNDRR should acknowledge traditional burning practices as a way towards DRR. Traditional burning practices refer

to a type of land management based on the controlled use of low-severity fire to reduce biomass and fulfil various land enhancement objectives, including wildfire hazard reduction. In Australia and the USA, aboriginal or Indigenous burning practices are increasingly advanced as a cost-effective way to reduce community and asset vulnerability. Essentially, these traditional burning practices can be summarized with the saying "fire is a good servant, but a bad master".

- All international organizations involved, even remotely, in fire-related disaster, should acknowledge that disasters will eventually happen and incite stakeholders to prepare accordingly by developing recovery strategies. In our globalized world, possible shocks from wildfire disasters might have systemic repercussions and be felt on the global market [215]. After the 2019-2020 fires in Australia, helping nature to recover is also increasingly seen as part of disaster recovery [216]; the IUCN lists a number of actions, from protecting remaining unburnt refuges and rehabilitation programs for highly impacted animal and plant species to rejuvenating and supplementing food and water sources.
- International organizations, including various UN offices, USAID, the CPF, should dedicate funding for collaborative projects aimed at fire disaster reduction, in particular in social and economic sciences, for disasters happen because of human presence, poor development planning, failures of adaptation, and lack of risk management measures. On international and national levels, dedicated IFM funding available should be directed towards countries and/or communities that need it the most [217]. In 2015, to address peatland degradation, the Government of Indonesia, the United Nations Office for Project Services, and the United States Agency for International Development (USAID) – in close partnership with UNEP – started the Gambut project [31] to address peatland fires. The example of thematic, interdisciplinary, and international Task Forces hosted by the International Union of Forest Research Organizations (IUFRO) is also to be followed. Such international groups can help craft new fire disaster reduction policies and harmonize existing ones.
- UNFCCC should revise the reporting of GHG emissions so Nationally Determined Contributions better account for fire activity outside of natural disturbance regimes [201]. At the moment, a country is only required to report GHG from fire when related to newly deforested lands, not from fires in standing forests; this can be considered a loophole, especially considering that most fires on Earth are human-caused, and that a significant portion of the world's fire activity happen because of deforestation.
- International organizations, especially those involved in disaster risk reduction, should promote and perhaps coordinate when possible: resource mutualisation among countries; knowledge sharing; equipment sharing; international cross-training; development of common risk assessments and planning procedures; development of an international terminology; development of a community of practice sharing successes and lessons learned [69,218]. Several networks already exist and must benefit from larger support and membership; for instance, the UNISDR Global Wildland Fire Network (GWFN) and the International Wildfire Preparedness Mechanism[32]. Pushing for the development of international programs for prescribed burning, as done by the Pau Costa Foundation, is also an efficient way to advance this collaborative effort while working towards more preventative actions.

7.2. Media

- The media should revise their reporting of fire events. The role of media is critical for advancing IFM, so it is important that reporting is done objectively [100,219,220]. In particular, it would be beneficial to switch from an apocalyptic and military-based narrative to a discourse on successful fire

[31] https://www.unredd.net/announcements-and-news/2392-gambut-project-addresses-indonesia-s-peatland-fires.html

[32] https://gfmc.online/iwpm/index-7.html

management initiatives and positive effects fire can have when use with care. Fire disasters happen because of underlying social, economic, and political issues. Terms such as "megafires" and "gigafires" should be generally avoided, as they hardly have scientific basis and they tend to minor the role of human intervention in the landscape, suggesting that climate change is the only cause [91,221,222]; terms such as extreme wildfire events (EWEs) and fire disasters should be used instead [69].

- Fire reporting from media and elected officials should go beyond area burned as the main metric for fire management towards other metrics such as avoided losses or ecosystem enhancement; indeed, fire statistics presented in section 3.2 show very well that area burned is not an adequate proxy for disaster [100,102].

7.3. Governments

- National, subnational, and local governments should prepare for disaster, even with well-established national fire strategies and multiple IFM working schemes. The effect of different social vulnerability can be critical and governments must consider and help in priority the most socially vulnerable people [223,224]: minorities, disenfranchised people, people with handicap, elderly, one-parent households, poor households. In the USA, it is estimated that Native communities and communities of colour are 50% more vulnerable to wildfire [225]. The rapidly emerging concerns around the long-term capacities of healthcare services and of insurance industry to face fire disasters also request the involvement on all levels of governments to avoid system collapse in case of a disaster happening.
- National governments should keep modern and well-trained suppression capacities that can be rapidly deployed. Adopting IFM does not mean that suppression must be abandoned altogether, just that it is used when and where truly necessary.
- National governments should make sure that existing budgets allocated to IFM and other related programs are not drained to face catastrophic events, thereby avoiding a "firefighting trap" draining budgets from fire prevention activities [226].

  National governments should promote the recourse to nature-based solutions (also called green infrastructure or natural capital), which benefit all aspect of vulnerability reduction, and more generally risk reduction (also called eco-DRR). This can be achieved either through ecosystem restoration or through the conservation of species or natural areas [227]. Studies show that the recourse to nature-based solutions can be more efficient at reducing risk while more interesting economically [228–231]. The restoration of wetlands, including peatlands in for instance getting traction, as their capacity to limit fire spread combined to carbon storage make these habitats worth green investments [232,233].
- National governments should invest in the development and maintenance of national fire databases. Such databases should record fire size, cause, date, costs, damages, fatalities, injuries, pre-existing mitigation efforts, etc. Reliable data collected by governmental agencies can be derived to produce critical information and knowledge helping understand the evolution of fire regimes and disaster risks [125,234]. Fire statistics tend to be underreported in lower-income countries, or at least countries without a robust system for wildfire monitoring.
- Subnational governments should push towards the development of fuel reduction programs coupled to forest restoration programs [235]. Restoring fire regimes has been shown to be an efficient way to reduce wildfire hazard, to promote habitat health, and to fight climate change. Reintroducing fire is also a way to help reach forest multifunctionality [34]. Although it is often advanced that communities are reluctant to fuel reduction, especially through prescribed fire use, evidence from literature [236] shows that lay people are generally supportive of these actions.

- Subnational governments should acknowledge and promote research regarding fire-dependent historical landscape. Understanding the historical role of fire in regional history before large-scale human activity can help restore landscapes to sustainable and safe levels of fire activity [237]. Traditional approaches to fire management are cost-effective in comparison to modern fire suppression and post-disaster recovery. Targeting historical landscape restoration through traditional fire use must be integrated in international efforts for forest restoration as part of the UN Decade on Ecosystem Restoration[33]. Where fire cannot be safely used or reintroduce, developing, popularize, and incentivize non-burning clearing methods will be necessary [238]. Climate smart agriculture, including no-burn/no-till practices have shown to have localized success in India and Peru when adopted and adapted by farmers[34].
- In regions where fire is used for economic purposes but leads to adverse environmental effects, local governments should develop and incite communities to adopt economically-viable alternatives to the use of fire. In the context of deforestation, blaming it on local people who get caught in market economy from distant influence need a way to survive; as long as setting the forest on fire for deforestation provides more immediate financial benefits than other, greener solutions, then nothing will change. Insisting on the fact that fire can only be a short-term solution is paramount; in Indonesia, fires coupled to peatland drainage result in land becoming waterlogged and unproductive. Also, shifting to sustainable practices and other approaches to leverage the land in an IFM context can create jobs.
- Local governments, particularly at the community level, should work toward reducing communities' vulnerability by implementing existing standards such as "Firewise" in South Africa[35] and the USA[36], or "Firesmart" in Canada[37]. These standards aim at reducing fuel load in strategic locations around communities in order to limit fire spread or reduce fire intensity, and subsequent damages. Such programs also help creating defensible spaces that facilitate fire suppression and protection of values at risk in WUIs. Furthermore, such IFM programs can help develop community preparedness, which means that standard operating procedures and evacuation plans must exist and be known by the community, ideally through emergency drills.
- Local governments, particularly at the community level, should limit exposure by strengthening urban planning rules. Restricting development in fire-prone areas is an effective way to limit exposure, and wherever development is allowed, strict building code must be enforced. In France, Forest Fire Risk Prevention Plans (PPRif) go as far as freezing areas to urban development.
- Local governments should seek innovative solutions to limit fuel management costs—which are often high—such as payment for ecosystem services schemes. For instance, examples of payments for "targeted grazing" paying shepherds to roam at-risk areas seems to gain traction; this type of program both reduces fuel load and provides economic opportunities [239,240]. Europe, for instance, is discussing options to revitalize rural economy, thereby creating values from rural products and lifestyle, as well as promoting new developments with more dynamic land use that can change fuel arrangements and this make the landscape less flammable [226,240].

[33] https://www.decadeonrestoration.org/

[34] https://ccacoalition.org/en/resources/addressing-agricultural-sector-open-burning-results-and-lessons-learned-ccac-no-burn

[35] https://landworksnpc.com/firewise/

[36] https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Wildfire/Firewise-USA

[37] https://firesmartcanada.ca/

7.4. Research community

- The research community should strive to apply data openness principles, so collaboration between different stakeholders and different levels of fire governance can take place. António Guterres, the current United Nations Secretary-General, said that "the availability of quality, accessible, open, timely and disaggregated data is vital for evidence-based decision-making and the full implementation of the 2030 Agenda and realization of its ambitions of leaving no one behind". Such practice enhances transparency and builds trust, on top of gaining in efficiency. The UNEP One Global Partnership, which already gathered 1,200 datasets so far, is a good example of high-level collaboration.
- The research community should develop social fire science program to better advance and monitor IFM progress and success [83,216]. Although the social side of fire science has gained momentum this past decade, the lack of dedicated funding sources makes IFM monitoring a challenge [236]. It has been reported that a general lack of monitoring programs and data precludes the development of adequate forest-livelihoods studies; thus, collecting and sharing socio-economic data and developing indicators pertaining to IFM implementation will promote the creation of stronger studies and help better understand risk perception, as well as the factors that make IFM successful or not [241,242].
- National funding agencies must work toward the expansion and maintenance of long-term ecological research sites (LTER) to monitor the evolution of ecosystems and their fire regimes [39]. Vegetation is expected to shift with climate change, with often unknown consequences on wildfire activity. Monitoring by LTER network might include data collection on post-fire forest recovery, shifting ecological structure and ecosystem services, and changing fire behaviour, on top of monitoring forest health [39,243][38]. Outcomes of such monitoring network can lead to the designation of areas where fire regime restoration must be sought, or conversely where fire must be imperatively excluded. The idea would be to maintain areas where fire regimes are considered in balance and can serve as management models for applications elsewhere [76,84]. LTER networks should be complemented by better forest inventory programs to further evaluate forest composition changes and timber losses [26].
- The research community should also persist in the development and refinement of existing modelling systems; which performance depends on data availability; they are indeed "data hungry". There are many existing long-term datasets on forests, fires, and various ecosystem services, and even though we always need more data, existing ones need to be leveraged. Fire risks decision support systems exist but need perpetual tuning; this is where seamless integration of new and old datasets can help reach better decisions [214,244–246]. Extensive datasets are also needed for Earth System modelling and the better integration of complex fire feedbacks, especially now that modelling outputs start to show good concordance with current fire activity; these models are critical to understand how fire activity, and thus disaster likelihood, will evolve [89,247].
- The research community should pursue its efforts to develop (near) real-time monitoring of fire activity and unfolding disasters and how to share this information rapidly with the authorities, for instance through the World Environment situation room[39] or the WRI's Global Forest Watch Fires[40]. Such information systems are state-of-the-art technological systems that strive to leverage real-time monitoring capacities offered by satellites. For instance, Canada will soon launch WildFireSat[41], a

[38] https://lternet.edu/stories/fire-brings-new-perspectives-on-disturbance-at-h-j-andrews-experimental-forest/

[39] http://uneplive.org/situation

[40] https://www.globalforestwatch.org/topics/fires/#footer

[41] https://www.asc-csa.gc.ca/eng/satellites/wildfiresat/default.asp

satellite offering all the necessary inputs for successful fire management. Such system will support emergency management by providing early warnings; this is the kind of information needed to then take advantage of machine-learning power towards the development of impact-based forecasting tool; results can then be disseminated on social media and trigger emergency response [248,249]. Capacities offered by drones for fire monitoring and post-fire restoration—they can disperse seeds—are promising as well [250]; the market might represent as much as $43 billion by 2024[42].

7.5. Private sector

- Private companies and land owners involved in fire risk reduction should strive to apply data openness principles; in particular, companies involved in commercial activities with controversial effects on forest environments, so corporate responsibility can be invoked when forest degradation happens. Applying data openness principles is important to show transparency, so collaboration between different stakeholders and different levels of fire governance can take place, on top of fostering social licence.
- Businesses, banks, and the insurance industry should work in the development of financial tools in collaboration with public stakeholders to advance fire disaster risk reduction. Market-based certification program like the Forest Stewardship Councils are existing avenues to provide consumers with products coming from forest where fire was not used irresponsibly. Payments for ecosystems services are another option to leverage money from within a private-public agreement so forest protection and fuel management are conducted with appropriate funding. The successful example of the Forest Resilience Bond[43] for fire hazard reduction in California watersheds is inspiring in that respect.
- Private companies in engineering and high technologies should keep working on the development of fire-resistant buildings. Building and retrofitting houses with fire-resistant material will become increasingly necessary, if not mandatory. Examples of fire-proof architecture already exist[44], and there might be a promising opportunity for private companies in the housing sector to promote this kind of design; local and regional government, as well as insurance companies could further help by providing financial assistance to incentivize such efforts.
- The insurance industry should work on the development of realistic and forward-looking long-term coverage plans. The outcomes of these plans would be premiums based on measured risk and realistic pricing so insurers remain in the market while giving time for policyholders to implement standard mitigation measures and adjust to higher premiums as necessary. The elaboration of catastrophe models, ideally in collaboration with the research sector, would provide a solid basis for the development of standardized risk-based premiums.

7.6. NGOs, foundations, and ThinkTanks

- NGOs should keep helping with the implementation of IFM and the creation of fire-adapted communities around the world. Their results so far show that their role is critical in reducing fire disasters, in particular because they work within communities. Involving communities in fire programs right from their inception has a lot of advantages: reduced vulnerability, enhanced economic development, increased employment, climate change adaptation, community social development,

[42] https://droneii.com/the-drone-market-2019-2024-5-things-you-need-to-know

[43] https://www.blueforest.org/forest-resilience-bond

[44] https://www.cnn.com/style/article/australia-bushfire-architecture/index.html

community empowerment, improved biodiversity and landscape health, reinvigorated cultural and social traditions. IFM builds on successful social interactions, on the integration of local knowledge and context, while securing financial support [236]. The success story of the Nature Conservancy in Zambia's Kafue National Park since 2011 is inspiring: the development of fire literacy has helped many stakeholders—wildlife officers, rangers, safari tour operators, and local villages—protect themselves and wildlife from damaging fires. IFM therefore help stakeholders realize that they have a responsibility in learning to live with fire. The development of FireWise communities in South Africa has also been successful in contributing to economic empowerment, and social equity (figure 16 left). such programs are thus overly beneficial to disaster risk reduction while improving surrounding land conditions and livelihoods [251].

Figure 16: Left, fire prevention workers in South Africa (from [251]**); right, community firefighters in southern France (Credit: CCFF SIMIANE-COLLONGUE)**

- NGOs should keep advocating for innovative environmental solutions for fire disaster reduction. NGOs such as the World Wildlife Fund and the World Resources Institute, for instance, have pushed for collaboration with nature [45] [46]: the development of nature-based solutions based on what is called the natural capital is increasingly acknowledged as a multi-objective solution to leaving with fire and adapt and curve climate change [173,228,252,253]. It also means that valuing nature's services need to become standard in wildfire risk assessment [254–256]. Studies suggest, for instance, that the reintroduction of large grazers and other ecosystem engineers might prove valuable to manage flammable biomass and keep moisture in the landscape. The Eurasian Fire in Nature Conservation Network (EFNCN) promotes conservation through fire where possible. Working to restore landscapes would restore biodiversity, with likely positive impact on diminishing vulnerability to extreme wildfires events [257].

[45] https://wwf.panda.org/discover/our_focus/climate_and_energy_practice/what_we_do/nature_based_solutions_for_climate/?

[46] https://www.wri.org/news/coronavirus-nature-based-solutions-economic-recovery#:~:text=Nature%2Dbased%20solutions%20(NbS),Protecting%2C%20managing%2C%20and%20restoring%20forests

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9. Annexes

9.1. Acknowledgement

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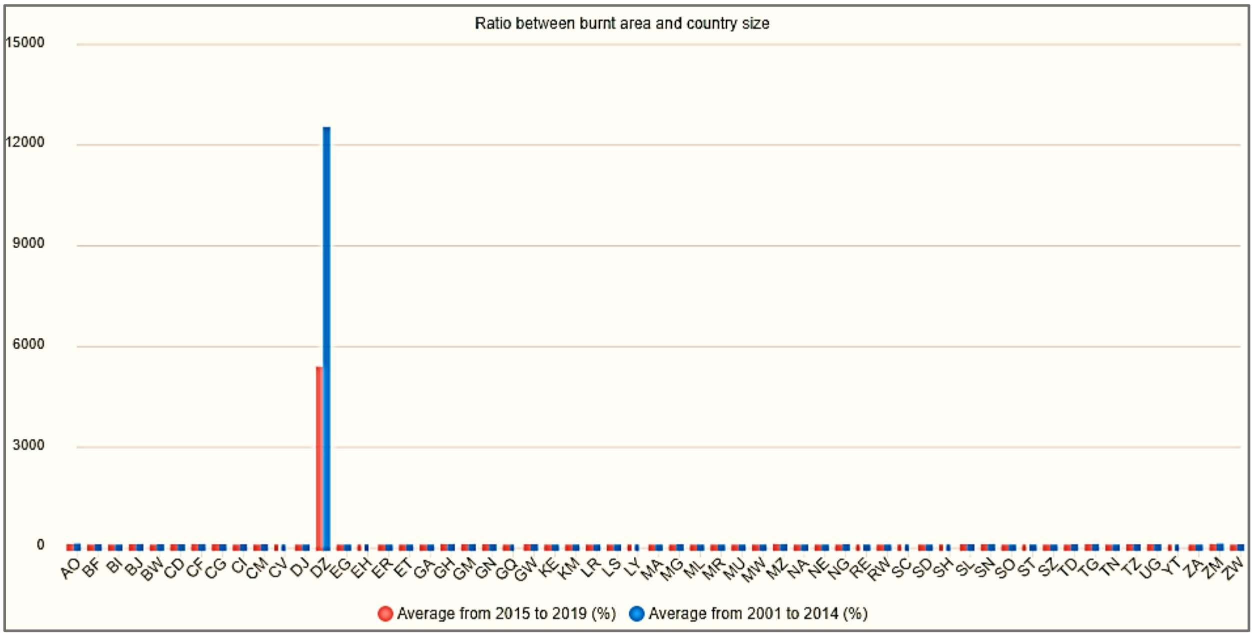
9.2. Websites of interest

- African Forest Landscape Restoration Initiative: https://afr100.org/
- Blue Forest Conservation: https://www.blueforest.org/
- Center for International Forestry Research (CIFOR): https://www.cifor.org/
- Copernicus Emergency Management Service: https://emergency.copernicus.eu/
- Fire Adapted Communities: https://fireadapted.org
- Fire Adapted Communities Learning Netwrok: https://fireadaptednetwork.org/
- Food and Agricultural Organization - Forestry: http://www.fao.org/forestry/en/
- Forests & Livelihoods: Assessment, Research, and Engagement (FLARE): http://www.forestlivelihoods.org/
- Forest Carbon Partnership Facility: https://www.forestcarbonpartnership.org/
- Global Fire Monitoring Centre: https://gfmc.online/
- Global Wildfire Information System: https://gwis.jrc.ec.europa.eu/static/gwis.statistics.portal/
- International Association of Wildland Fire: https://www.iawfonline.org/
- International Union of Forest Research Organization: https://www.iufro.org/
- Landworks https://landworksnpc.com/firewise/
- Lessons on fire: https://lessonsonfire.eu/
- Pau Costa Foundation: https://www.paucostafoundation.org/
- The Global Carbon Project: https://www.globalcarbonproject.org/
- The Gobal Fire Emission Database: http://www.globalfiredata.org/
- The Nature Conservancy: https://www.nature.org/en-us/
- The Bonn Challenge: https://www.bonnchallenge.org/
- The Fire Model Intercomparison Project (FireMIP):

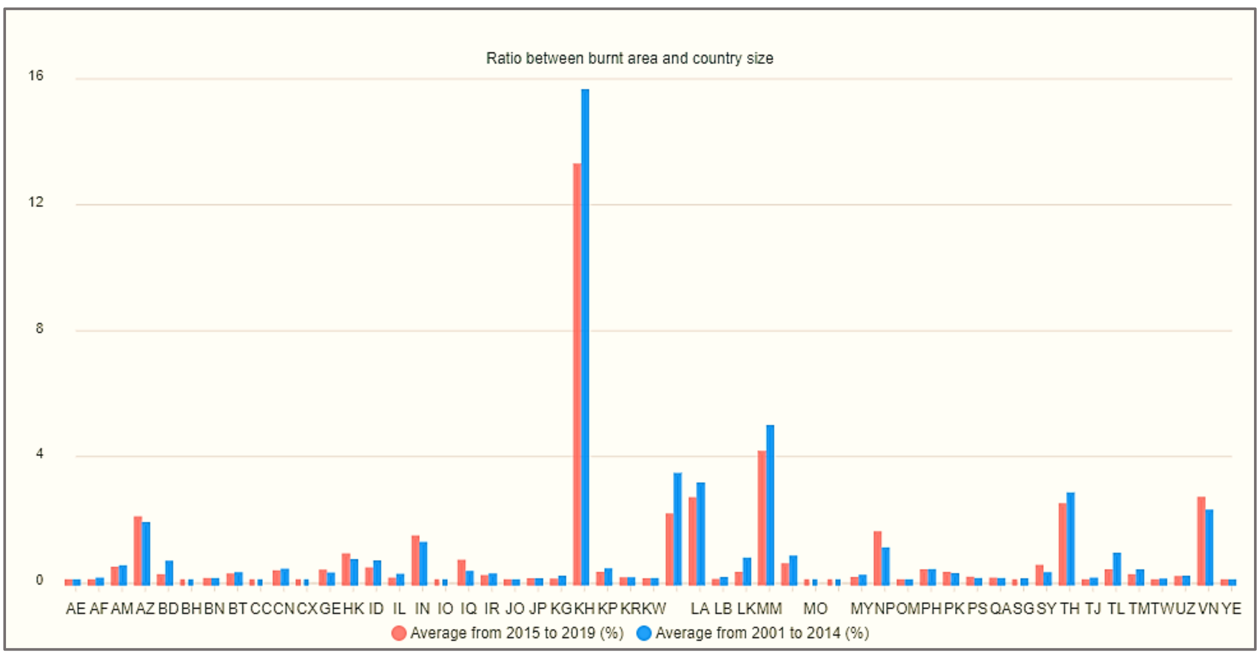
9.3. Statistics on burned area from GWIS

The figures presented below show area burned statistics derived from satellite imagery and computed for each country from 2001 to 2019. For comparison purpose, the blue bar represents the average annual area burned from 2001 to 2014, and the red bar the average area burned from 2015 to 2019.

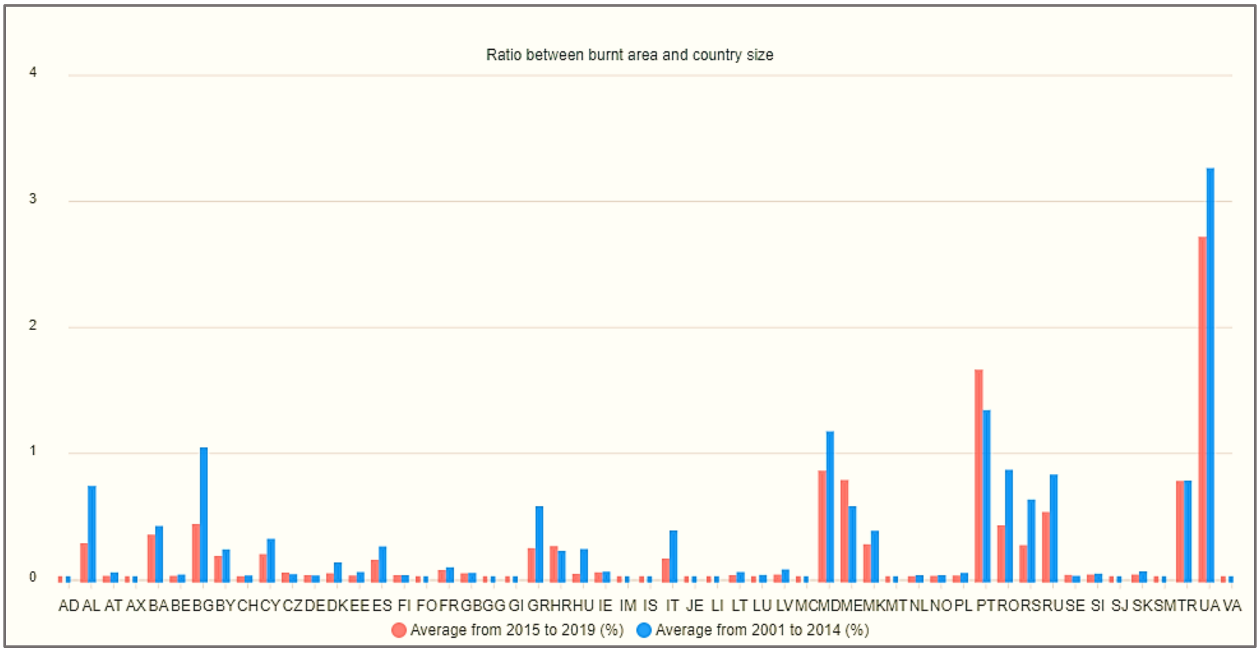
Africa



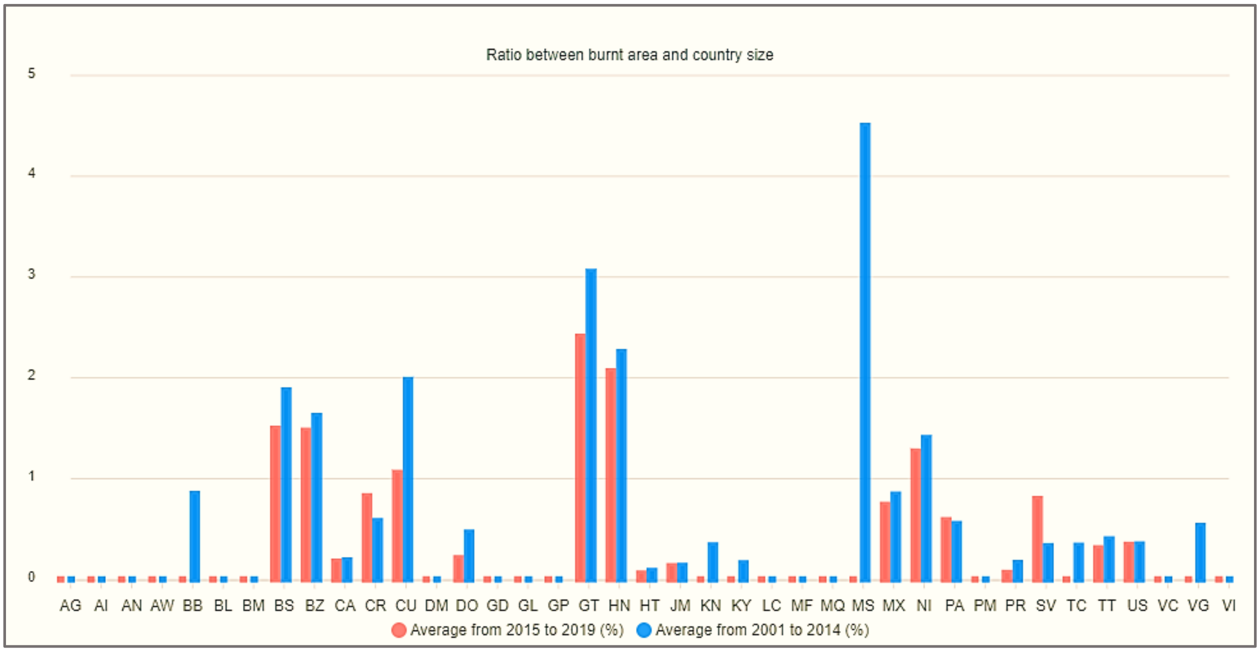
Asia and Middle East



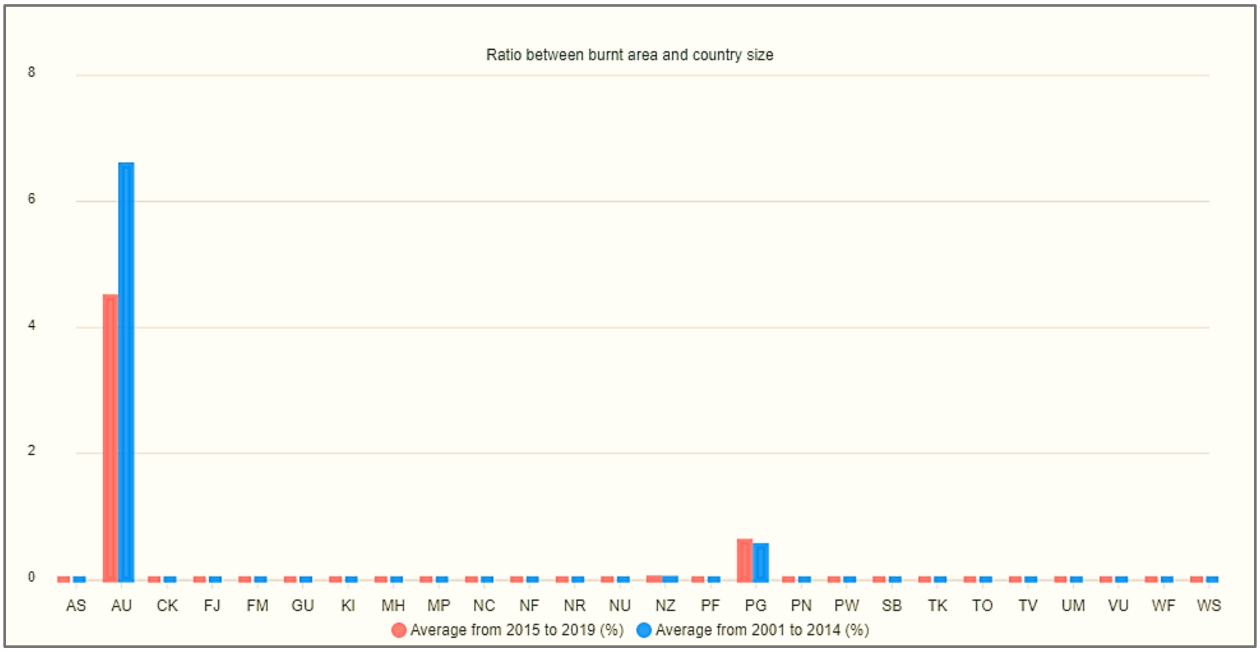
Europe



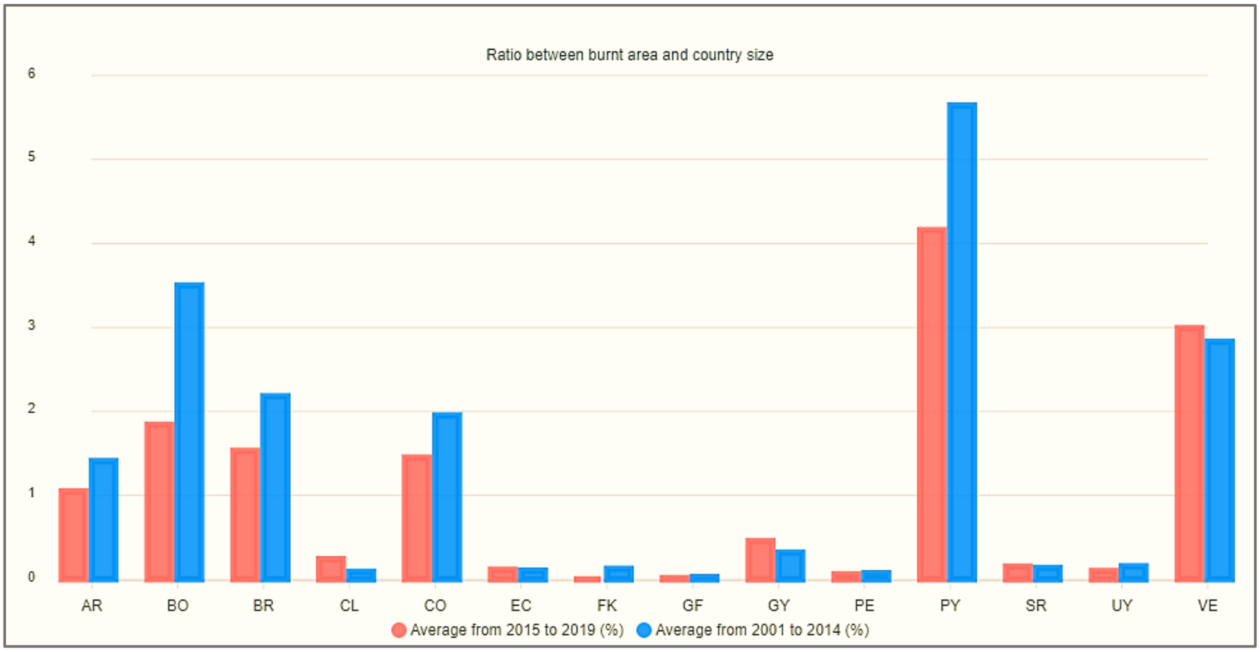
North and Central America



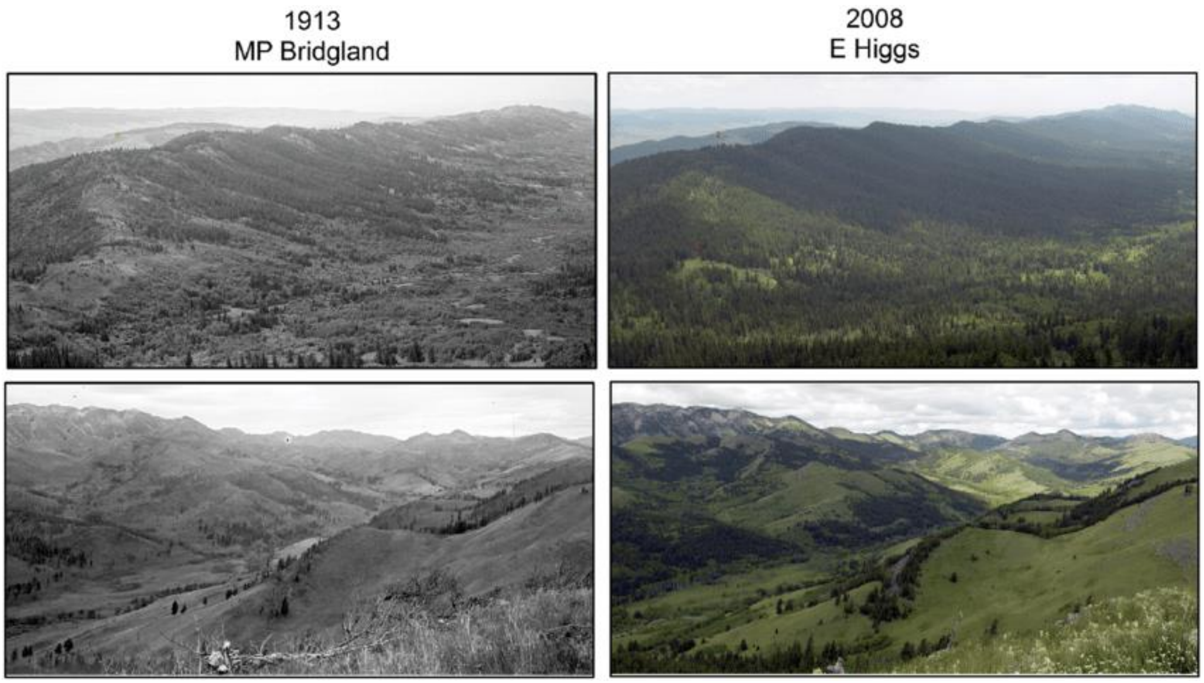
Oceania



South America



9.4. Examples of landscape transformation through fuel build-up from disappearance of traditional/historical burning practices



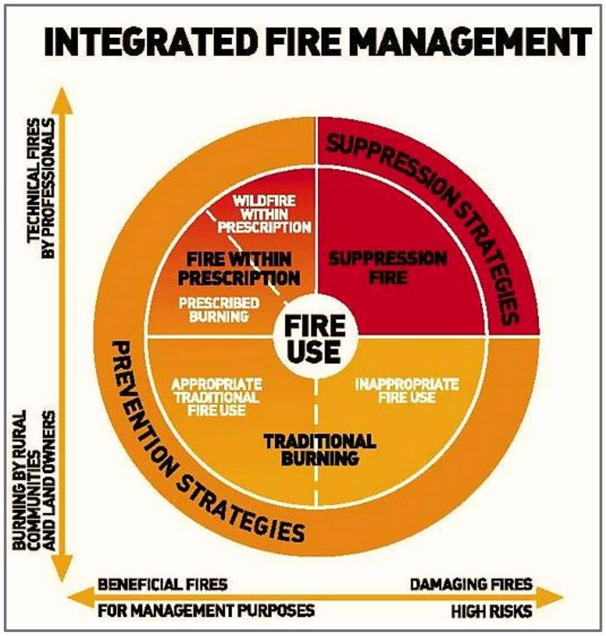
Example of forest cover changes due to fire exclusion in the Canadian Rocky Mountains. Source: [258] **and the Mountain Legacy Project.**

9.5. Integrated Fire Management (fire paradox)

10.

11. Figure 14: The Integrated Fire Manageemnt cycle. (Credit: Kishugu - https://kishugu.com/integrated-fire-management-services/?cn-reloaded=1)

In 2010, the European Fire Paradox project published its final report [259] with the following framework for integrated fire management. It differs substantially from the framework presented in the present report, but is offers a valuable approach to decision-making that embodies the core content of this background study.


INTEGRATED FIRE MANAGEMENT
TECHNICAL FIRES BY PROFESSIONALS
BURNING BY RURAL COMMUNITIES AND LAND OWNERS
SUPPRESSION STRATEGIES
PREVENTION STRATEGIES
WILDFIRE WITHIN PRESCRIPTION
FIRE WITHIN PRESCRIPTION
PRESCRIBED BURNING
SUPPRESSION FIRE
FIRE USE
APPROPRIATE TRADITIONAL FIRE USE
INAPPROPRIATE FIRE USE
TRADITIONAL BURNING
BENEFICIAL FIRES
FOR MANAGEMENT PURPOSES
DAMAGING FIRES
HIGH RISKS