Global demographic projections: Future trajectories and associated uncertainty

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(revised 8 March 2015)

Outline

- Motivation
- Overview of population projection methods
- UN approach for probabilistic projections
  - Probabilistic fertility projections
  - Probabilistic mortality projections
- UN probabilistic population projections
- Summary
- Software and reference

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Why population projections?

- To assess hypothetical population trends based on specific assumptions about future trends in fertility, mortality and migration
- To help understand the determinants of population change and inform policy discussions
- To provide a base for other projections essential for social and economic planning (labor, education, social security, agriculture, health, housing, urbanization, energy, transport, climate, environment, etc.)
- To produce current demographic estimates using latest available data on population size (by age and sex) and its components of change (fertility, mortality and migration)
- To identify realistic goals and targets for future development trends

Future is unknown, but we know some basic demographic trends

- Demographic processes are long-term
  - Lasting impact of past and current changes
  - Population momentum
- Components of population change
  - Fertility
  - Mortality
  - Migration
- Demographic transition as guiding principle
  - Countries move from high to low levels of mortality and fertility
  - Still in progress in many developing countries

UN population projections

- UN Population Division publishes estimates and projections, by age and sex, of population counts and vital rates for all countries, for 5-year intervals of age and time, from 1950 to 2100, every two years in World Population Prospects (WPP)
  - Used throughout UN system, especially as denominators
  - Key input for development planning, monitoring (e.g. MDGs) and modeling (e.g. climate)
  - UN has produced 23 sets of global population projections since 1951
  - Latest version: the 2012 Revision, published in May 2013
- Population can be projected far into the future using current population by age, and age-specific rates of fertility, mortality, and migration
  - Governments often project over shorter intervals: 2060 (EU, USA, Japan), 2046 (Ireland)
  - UN projects to 2100 due to demand for long-term trends

Uncertainty

- Need some means of reflecting the uncertainty of population projections
- Different methods of depicting and/or measuring uncertainty
  - Describe a range of scenarios based on specific assumptions
  - Choose a central scenario and model the uncertainty around that scenario
  - Draw on the variability of expert predictions
- Major challenges in transmitting the meaning of uncertainty, especially to lay audiences

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Cohort component method

The method starts from current population estimates and projects population forward:

- Demographic balancing equation:

$$\text{Pop}(t+1) = \text{Pop}(t) + \text{Births}(t) - \text{Deaths}(t) + \text{Immig}(t) - \text{Emigr}(t)$$

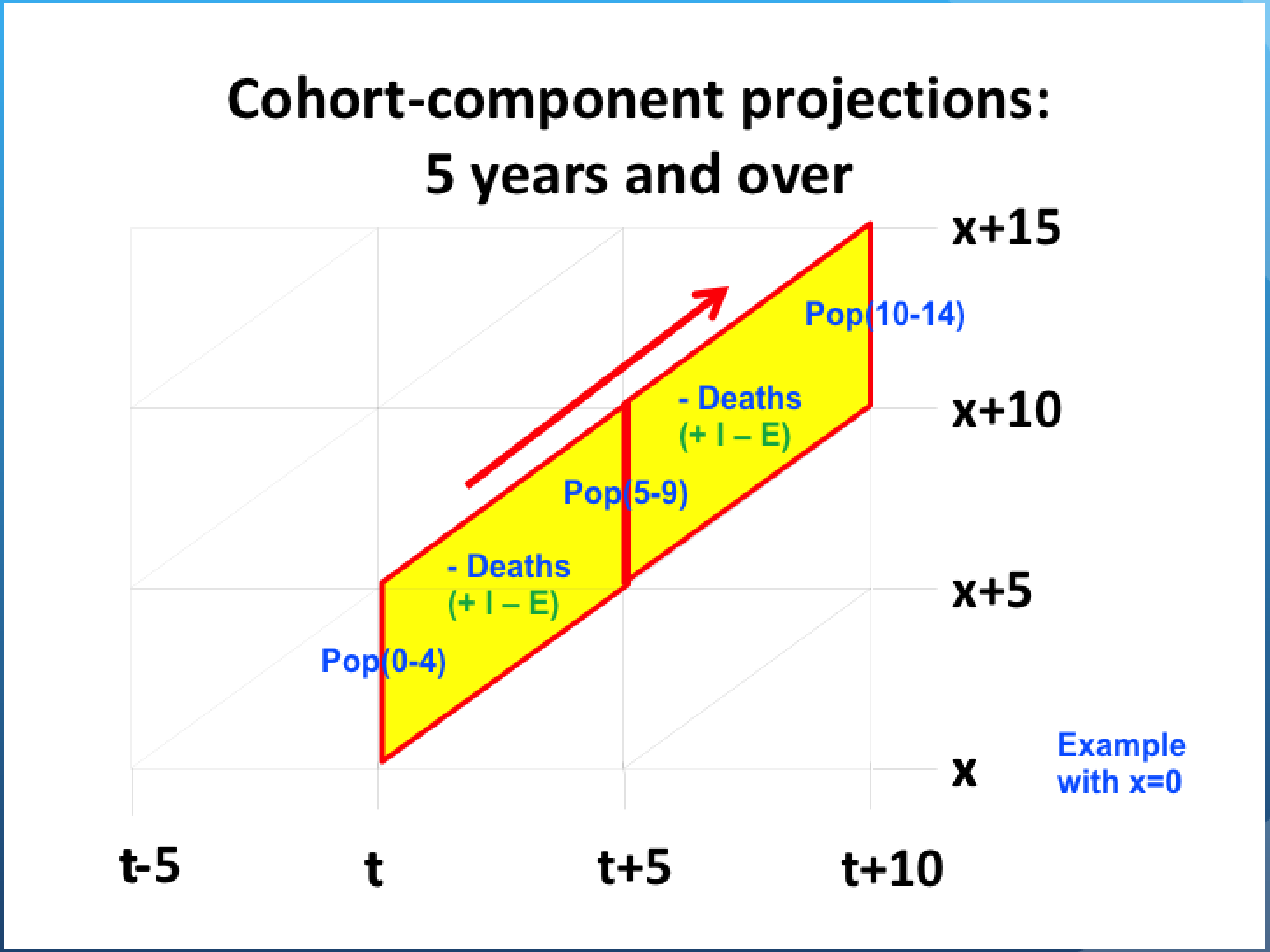
- Age-structured version:

$$\text{Pop}(x+1,t+1) = \text{Pop}(x,t) * \text{Survival}(x,t) + \text{Net migr}(x,t)$$

$$\text{Pop}(0,t+1) = \Sigma\ \text{Women}(x,t) * \text{Fertility}(x,t)$$

- The cohort component method is based on age-structured populations and components of change (i.e., births, deaths, migration)

Cohort-component projections: step by step



Variants and scenarios

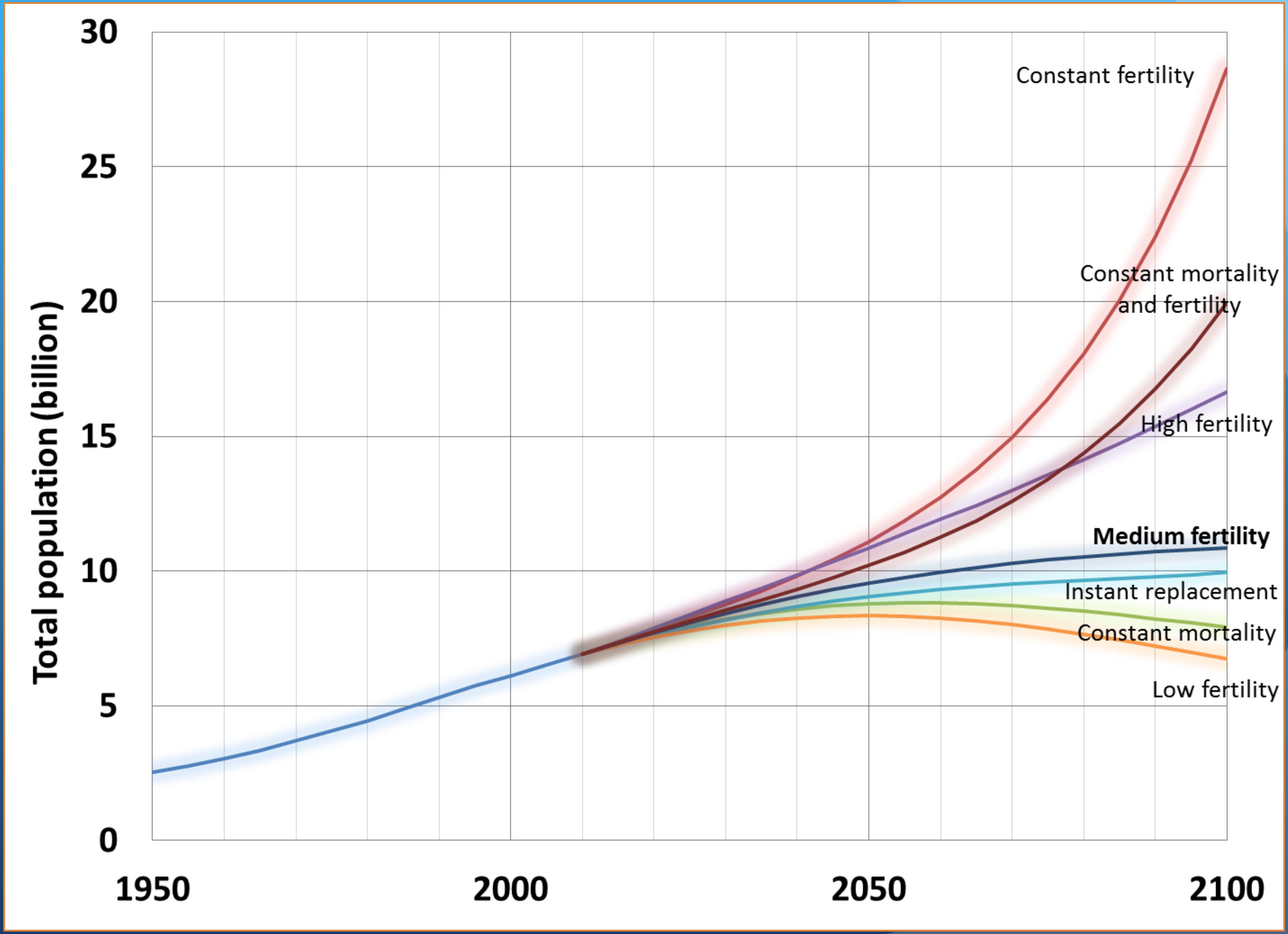
- Uncertainty of future outcomes can be illustrated using variants and scenarios
- Variants describe a range of assumptions for a particular component of change (e.g. fertility), illustrating the sensitivity of outcomes to changes in assumptions
- Scenarios describe a series of hypothetical (often simplified) future trajectories, illustrating core concepts such as population momentum

UN deterministic projection scenarios

8 scenarios included in the 2012 Revision of the UN World Population Prospects

#	UN projection scenarios	Fertility variant	Mortality variant	International Migration variant
		Assumptions		
1	Low fertility	Low (= medium - 0.5 child)	Normal	Normal
2	**Medium fertility**	**Medium**	**Normal**	**Normal**
3	High fertility	High (= medium + 0.5 child)	Normal	Normal
4	Constant-fertility	Constant as of 2005-2010	Normal	Normal
5	Instant-replacement-fertility	Instant-replacement as of 2010-2015	Normal	Normal
6	Constant-mortality	Medium	Constant as of 2005-2010	Normal
7	No change	Constant as of 2005-2010	Constant as of 2005-2010	Normal
8	Zero-migration	Medium	Normal	Zero as of 2010-2015

UN deterministic scenarios, total population: World 2010-2100



Uncertainty in demographic projections

Nathan Keyfitz (1981):

“Demographers can no more be held responsible for inaccuracy in forecasting population 20 years ahead, than geologists, meteorologists, or economists when they fail to announce earthquakes, cold winters, or depressions 20 years ahead. What we can be held responsible for is warning one another and our public what the error of our estimates is likely to be.”

Three approaches to probabilistic projections

- Ex-post analysis based on the errors in past forecasts (Keyfitz 1981; Stoto 1983; Alho 2006; Alders 2007; Alho 2008)
- Time series methods use past time series of forecast inputs, such as fertility and mortality, to estimate a statistical time series model, which is then used to simulate a large number of stochastic possible future demographic pathways. Simulated trajectories of forecast inputs are combined via a cohort component projection model to produce predictive distributions of forecast outputs (Lee 1994; Tuljapurkar 1999)
- Expert-based approaches rely on experts to provide distributions for each forecast input. These are then used to construct predictive distributions of forecast outputs using a stochastic method similar to the time series method (National Research Council 2000; Booth 2006; Pflaumer 1988; Lutz 1996, 1998, 2004)

Some limitations of expert opinion

- Difficulty of identifying a pool of experts qualified to provide quantitative predictions
- Difficulty of understanding and measuring potential biases in this pool
- Experts tend to overemphasize current situation and miss historical shifts
  - Baby Boom
  - HIV/AIDS
  - Fall of Soviet Union
  - Below-replacement fertility

Projections for England by ONS

Figure 2. Past Projections of Total Fertility Rates and Actual Rates, England[3,10]

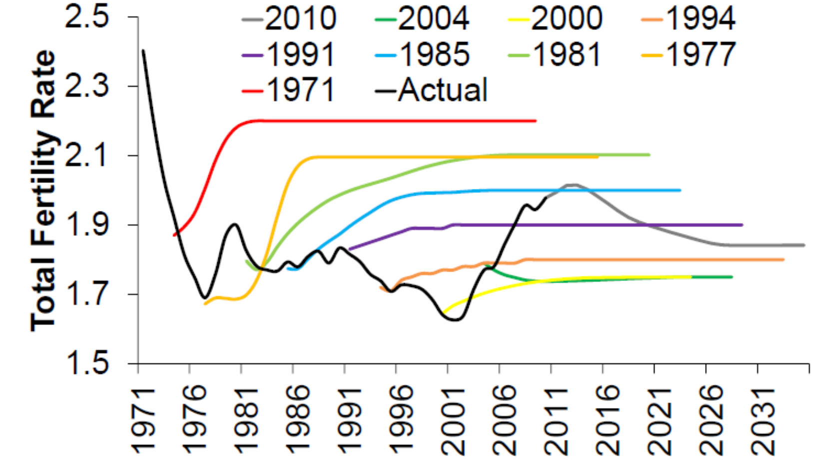


Figure 3. Past Projections of Life Expectancy at Birth and Actual Figures, England[3,10]

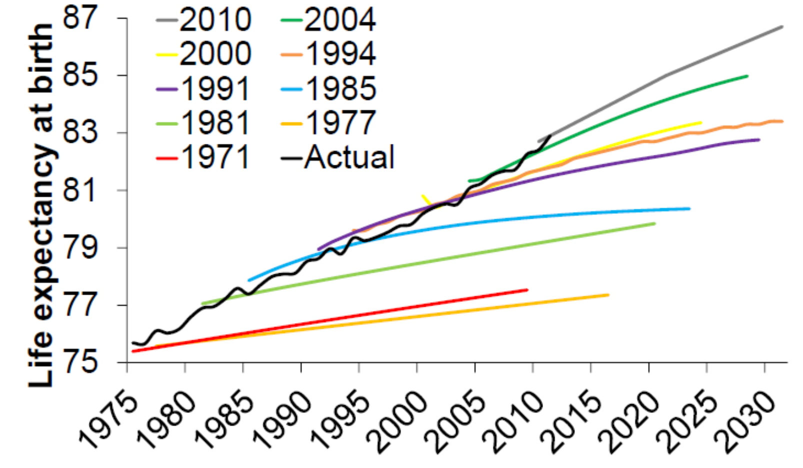
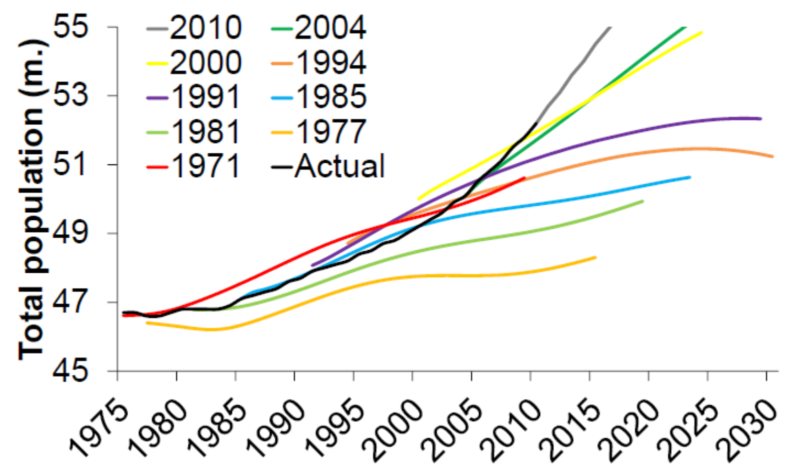


Figure 4. Past Projections of Total Population Size and Actual Figures, England[3,10]



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Probabilistic population projections: UN approach

- Probabilistic approach for modelling demographic transition using parametric functions (Raftery et al. 2012, 2014)
- Probabilistic projections of TFR from a time series model
  - Sample trajectories from the predictive distribution of future TFRs for each country and period
  - Convert each trajectory to age-specific fertility rates
- Currently, the UN uses a similar approach for life expectancy (probabilistic) but not migration (deterministic)
- Apply cohort-component projection model to each sample (Raftery et al. 2012; Gerland et al 2014)
- Yields many possible futures of world population and thus probabilistic forecasts of any population indicator
- Method assessed by out-of-sample prediction for 5, 10, . . . , 30 years: Projection intervals reasonably well calibrated

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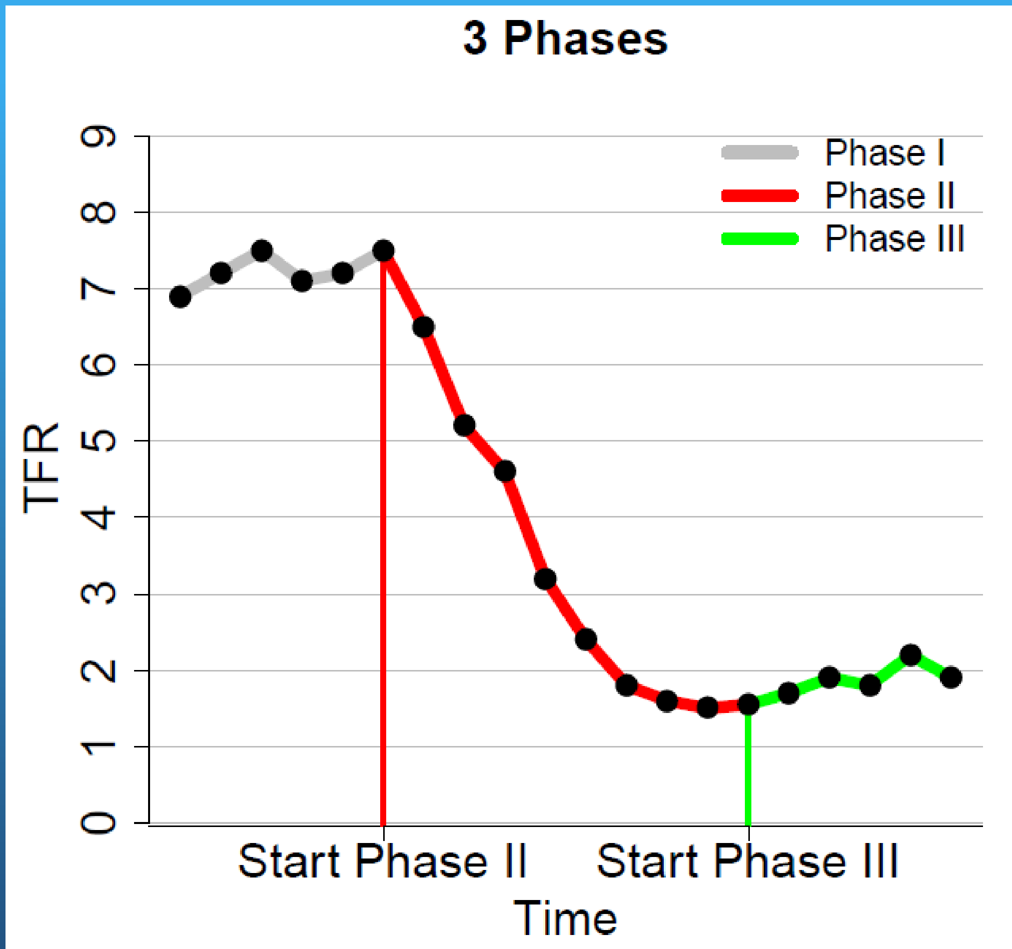
Probabilistic TFR projections



3 phases

Phase I: pre-transition high fertility

Phase II: fertility decline to below replacement level

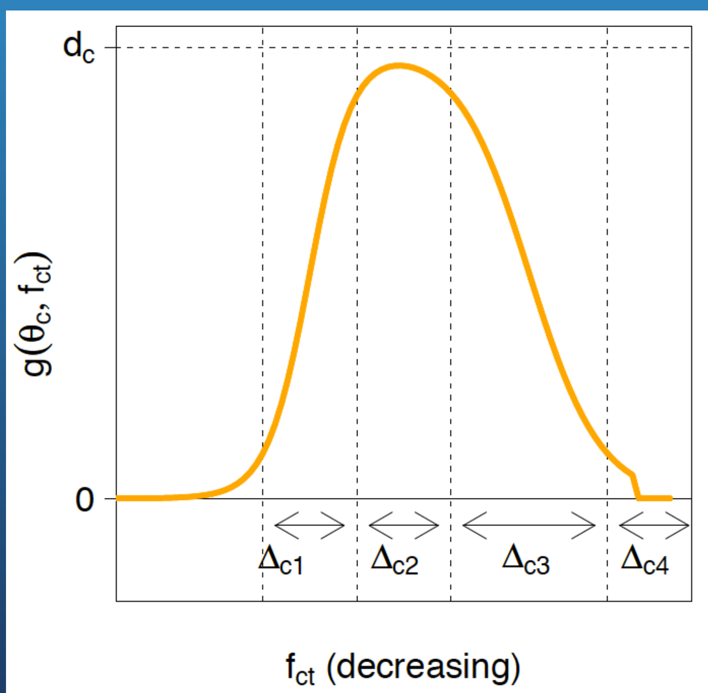
Phase III: post-transition low fertility, with turnaround and fluctuations

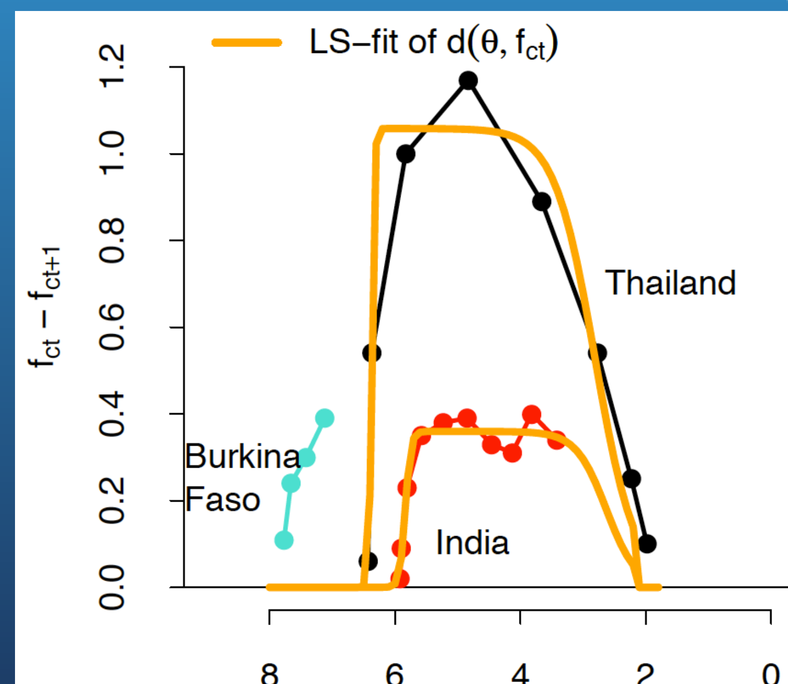
Fertility transition has started in all countries

⇒ Phase I not modelled (all countries already in Phase II or III)

Phase II model: Fertility transition

- Fertility decline:
  - starts slowly at high TFR values
  - accelerates and peaks around TFR 5
  - decelerates towards the end of the transition
  - stops below replacement level
- TFR decline model: double logistic funcion (sum of 2 logistic curve)
- Random error term → Random walk with non-constant drift



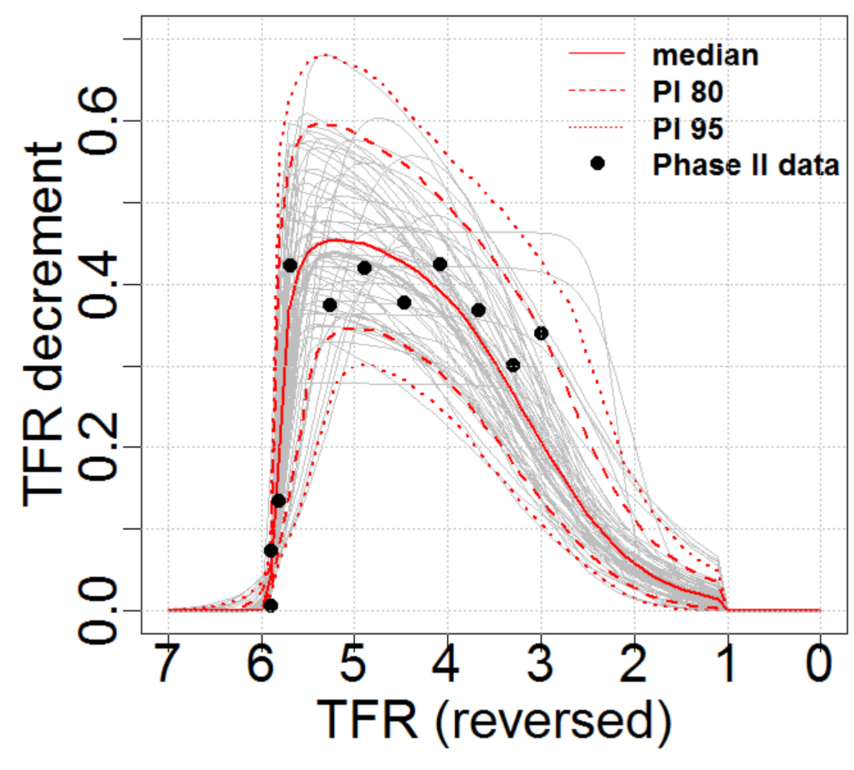


Bayesian hierarchical model (BHM)

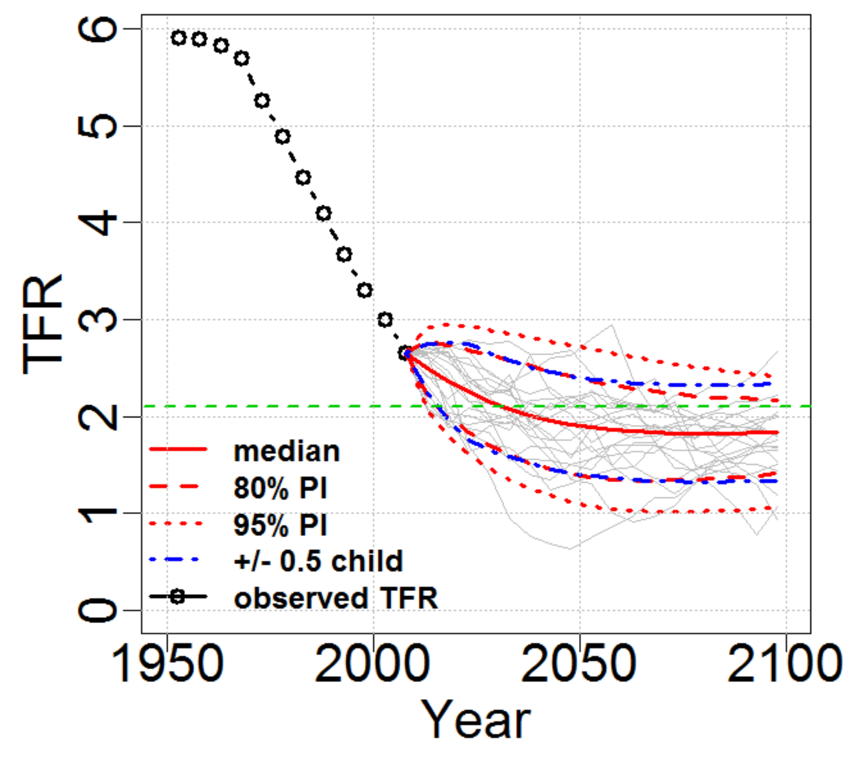
- Separate estimation for each country not feasible
  - Sparse data
  - Historical trend only partially observed
- Solution: For each country, borrow info from other countries
- Hierarchical model:
  - Country parameters distributed around world average
  - World and country parameters estimated simultaneously
- Between-country correlation in forecast errors included in prediction algorithm (Fosdick et al. 2014): Correlation is a function of whether 2 countries are neighbors, in the same UN region (out of 22), or had the same colonizer in 1945

India: Probabilistic TFR projection

- Double-logistic decline function



- Probabilistic projections of TFR

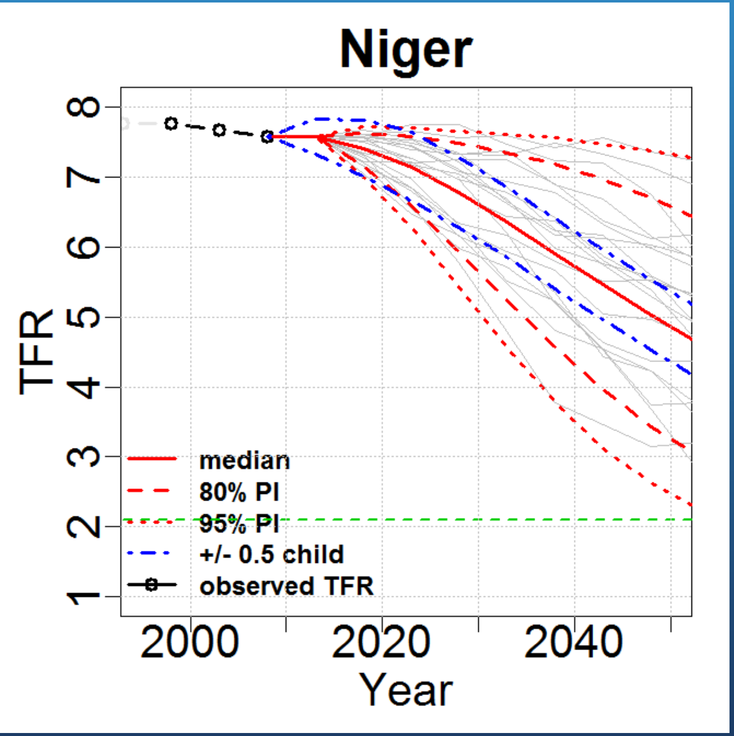


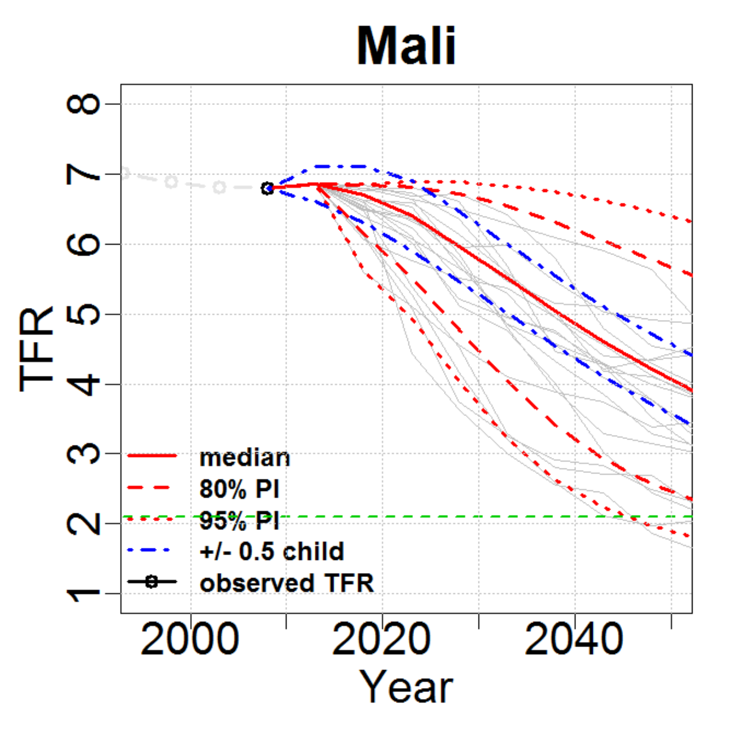
Uncertainty for high-fertility countries

- Uncertainty increases over time
- Uncertainty increases with current level of the TFR

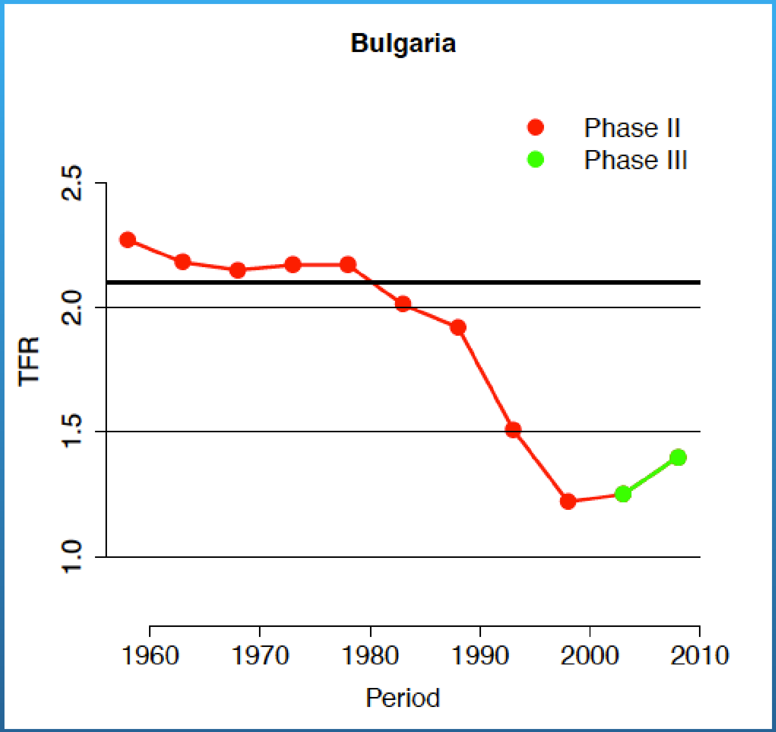
Burkina Faso: 2005-10 = 6.1
2045-50 80% prediction interval = 2.2-4.3

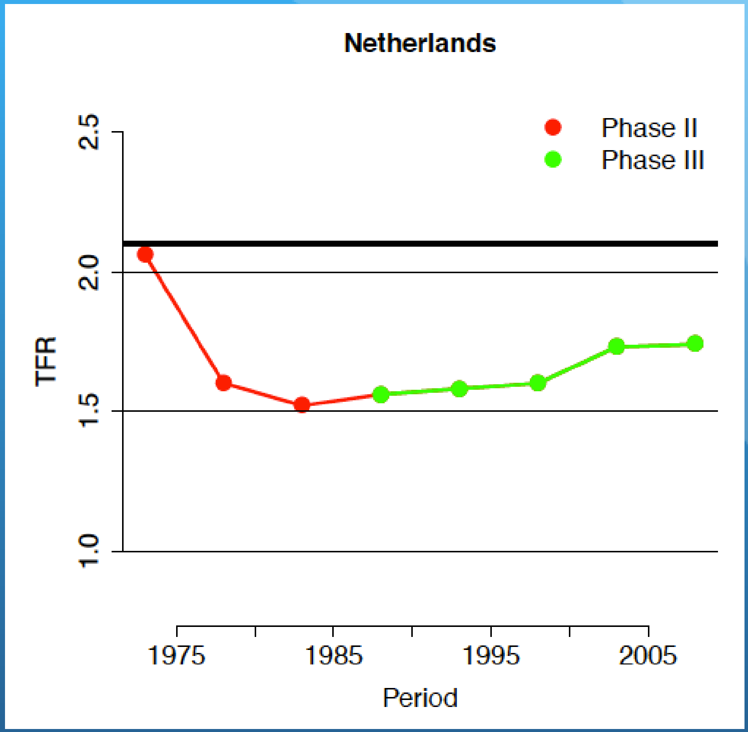
Mali: 2005-10 = 6.8
2045-50 80% prediction interval = 2.6-5.8





Phase III: Post-transition low-fertility rebound

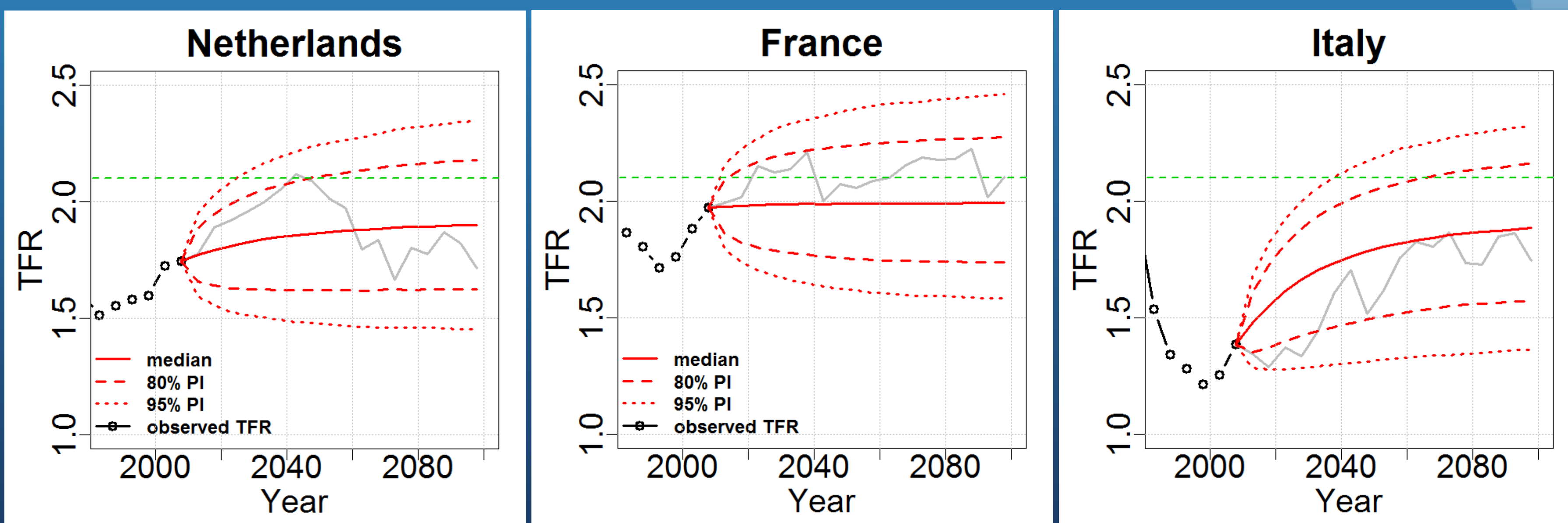




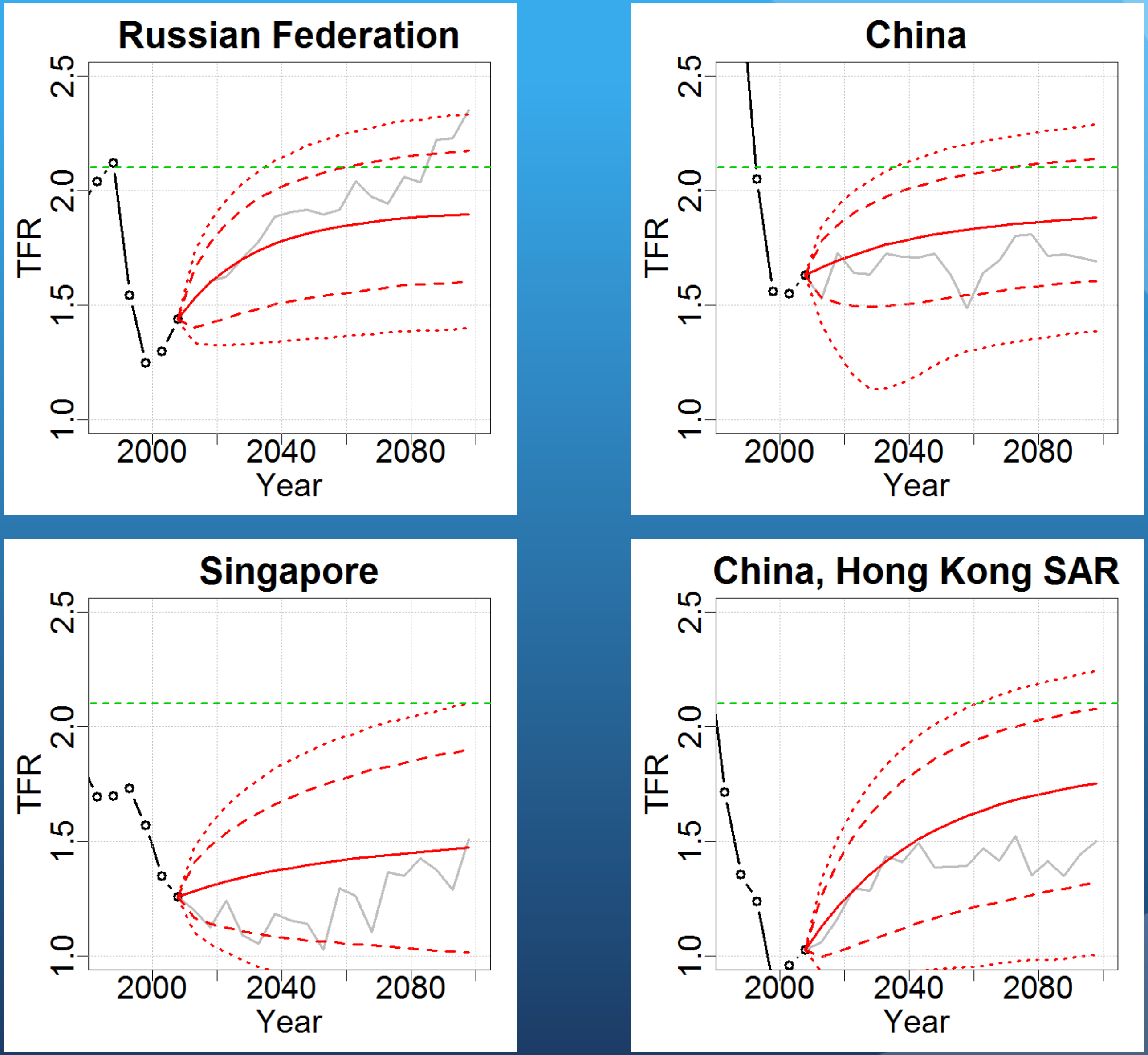
- Within observation period: Start of Phase III defined by the two earliest consecutive 5-year increases below 2
- Observed in 25 countries/areas: 20 European countries, plus Singapore, Hong Kong, USA, Canada, Barbados

Projections for low-fertility countries

- Bayesian hierarchical autoregressive (AR(1)) time series recovery model used for Phase III
- Use all below-replacement TFRs to estimate uncertainty in long-term projections
- Country-specific asymptotes estimated from data, resulting in global asymptote of 1.85 (80% projection interval 1.5-2.1)



Projections for countries with lowest fertility



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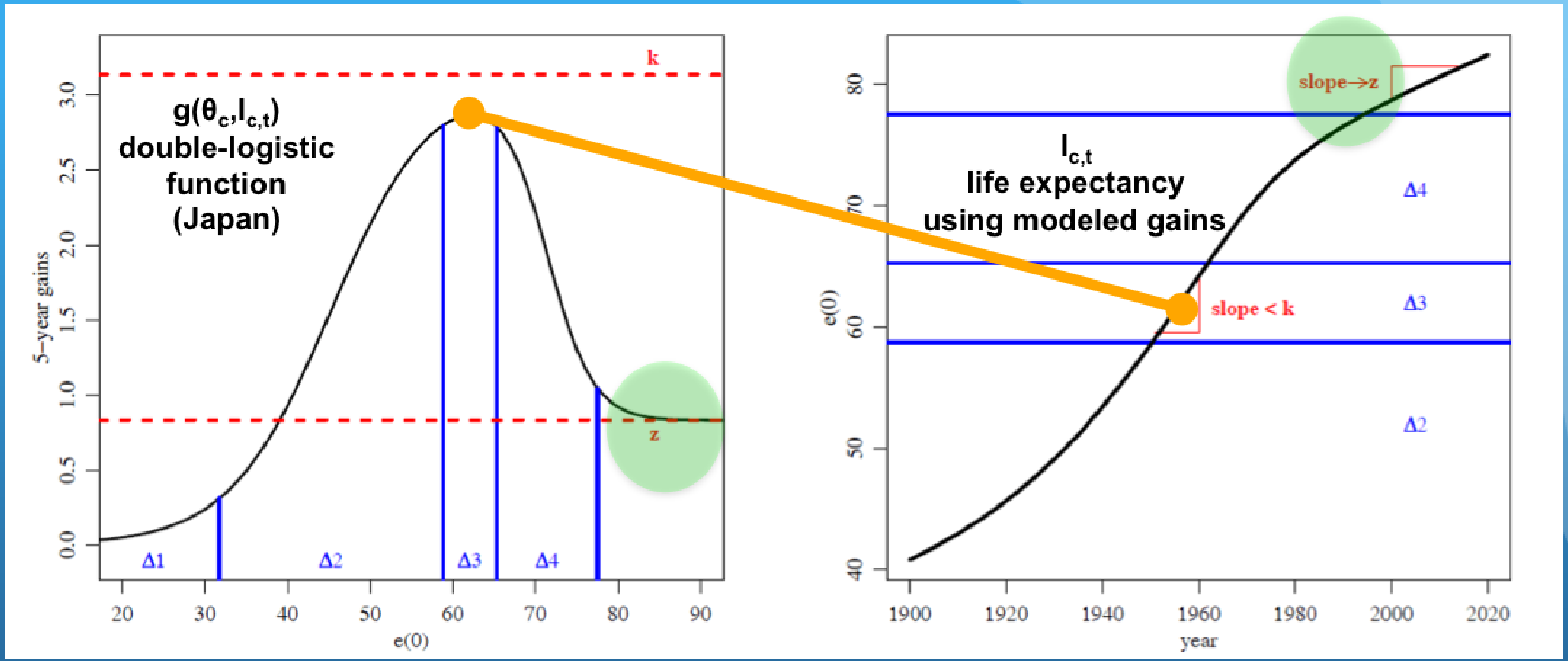
Projecting mortality

- Probabilistic projections of all future age-specific mortality rates desired for all countries.
- But data availability and quality vary greatly (WPP 2012):
  - Good vital registration data: 91 countries (Germany)
  - Incomplete vital registration data: 40 countries (Sri Lanka)
  - Survey estimates of child and adult mortality: 61 countries (Senegal)
  - Survey estimates of child mortality only: 17 countries (Laos)
  - Limited or no data: 22 countries (North Korea)
- Estimate past life expectancy at birth (e_0) for all countries:
  - Life tables (data for all ages, usually from VR)
  - Model life tables (data for some ages, often from surveys)
  - Life tables from similar countries (no data)
- Converts data from all countries to a common currency: e_0

Probabilistic projection model of female e_0



Random walk with a Bayesian hierarchical model drift:

$$l(c,t+1) = l(c,t) + g(\theta_c, l(c,t)) + \varepsilon(c,t+1)$$

- Increase in e_0 modeled by BHM using double-logistic function
- Parameters estimated via MCMC
- Produce country-specific double-logistic parameters $g(\theta_c, l(c,t))$
- BHM pools information about the rates of gains across countries
- Variance of distortion term, $\varepsilon(c,t)$, decreases as e_0 increases

Bayesian hierarchical model

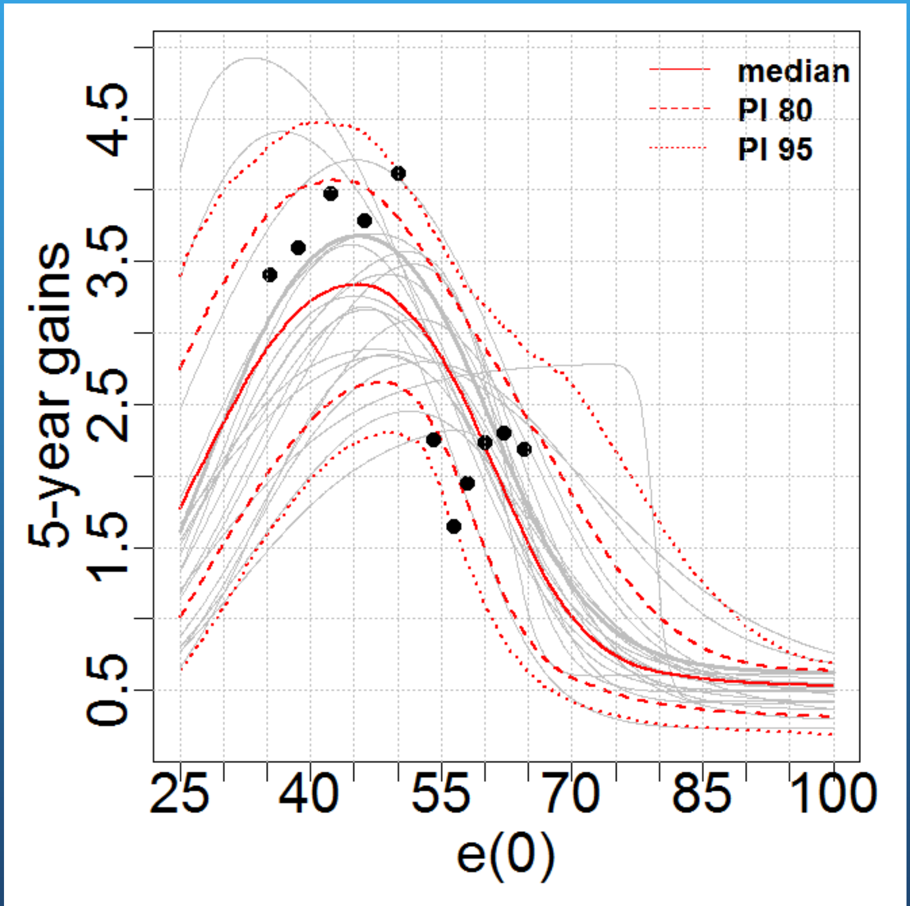
- Separate estimation for each country not feasible because of few data and only part of the evolution observed
- Solution: For each country, draw on information from other countries
- Hierarchical model:
  - Double logistic parameters for a country distributed about "world average"
  - World and country-specific parameters estimated simultaneously
  - Based on observed gains in all countries, determine range of possible improvement curves
    - Get country-specific improvement curves
    - Combine overall outcome with observed decline in country

Probabilistic projection of mortality

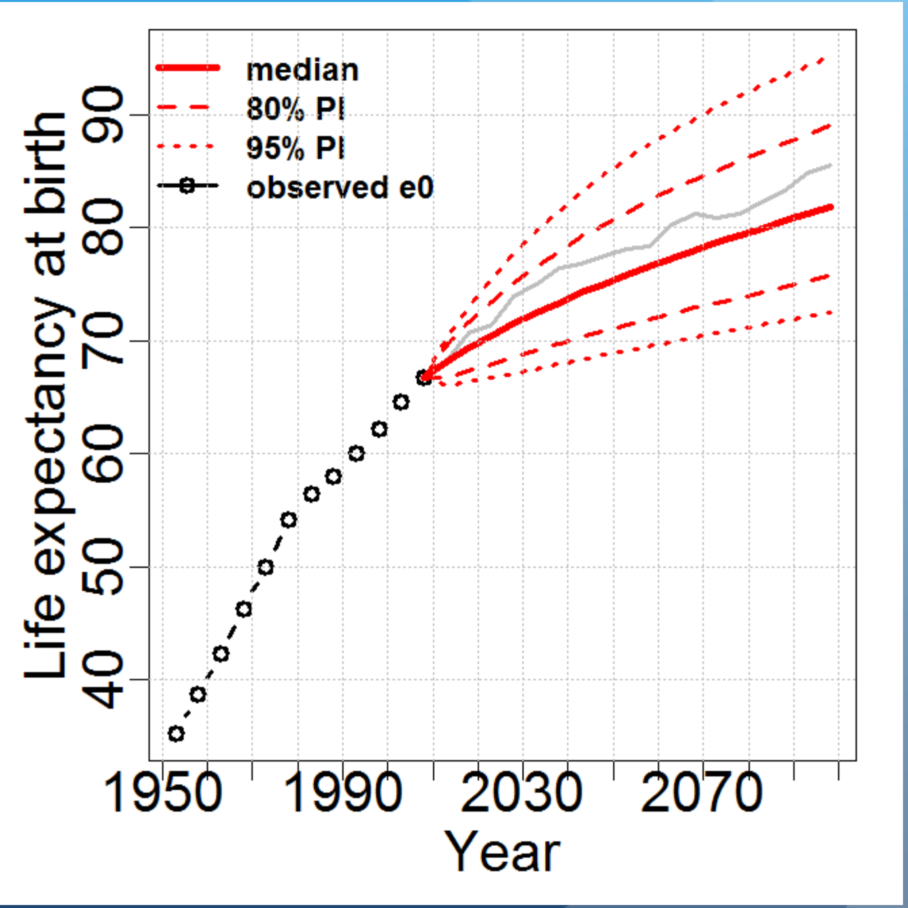
- Project female e_0 using a similar BHM to TFR (Raftery, Chunn & Gerland 2013)
  - Asymptotic linear increase to 2100
  - Original choice: asymptote based on long-term trend in record e_0, or 2.3 years/decade (Oppen & Vaupel 2002)
  - Revised choice: asymptote based on trend in maximum age at death for Sweden since around 1970, or 1.3 years/decade (Wilmoth et al 2000, updated)
- Probabilistic projection of the female-male gap in e_0 (Raftery, Lalic & Gerland 2014)
- Convert each sample at each future year to age-specific mortality rates using a modified Lee-Carter method (essentially Lee-Miller)
- Kannisto function (logistic with upper asymptote of 1.0) used to extrapolate mortality rates to high ages (i.e., 100+)
- Result: Sample from predictive distribution of female and male age-specific mortality rates in each future time period and country

India: Probabilistic female e0 projection

Double-logistic gain in e0 function

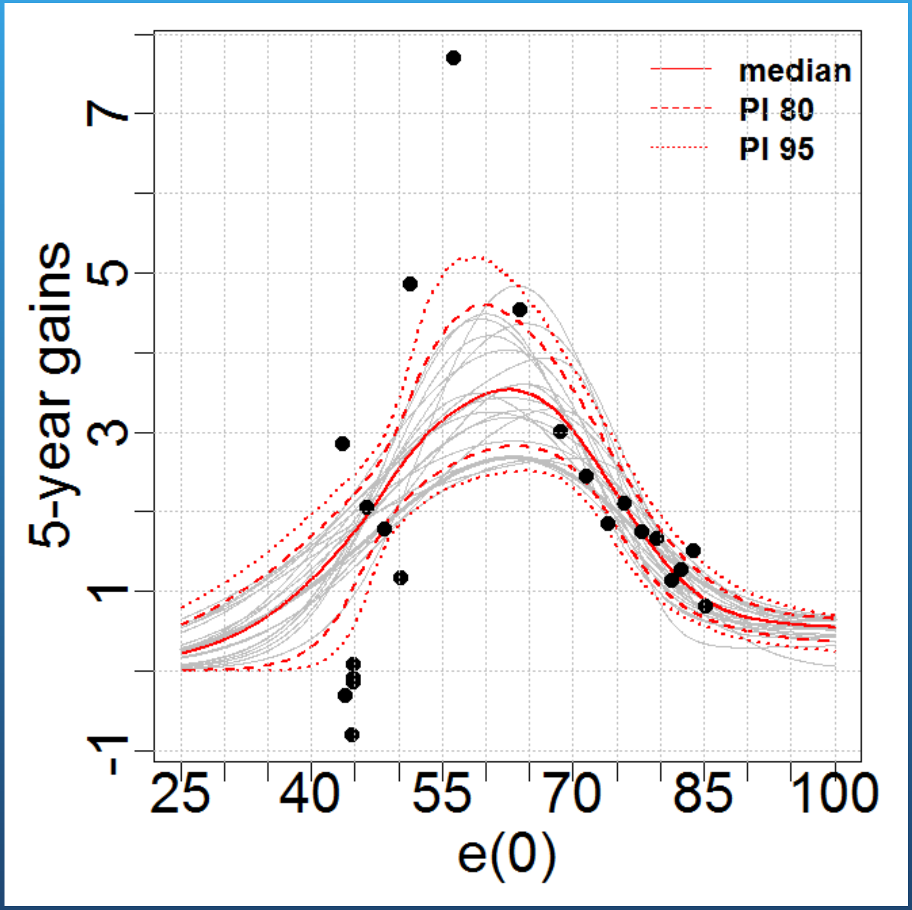


Probabilistic projections of e0

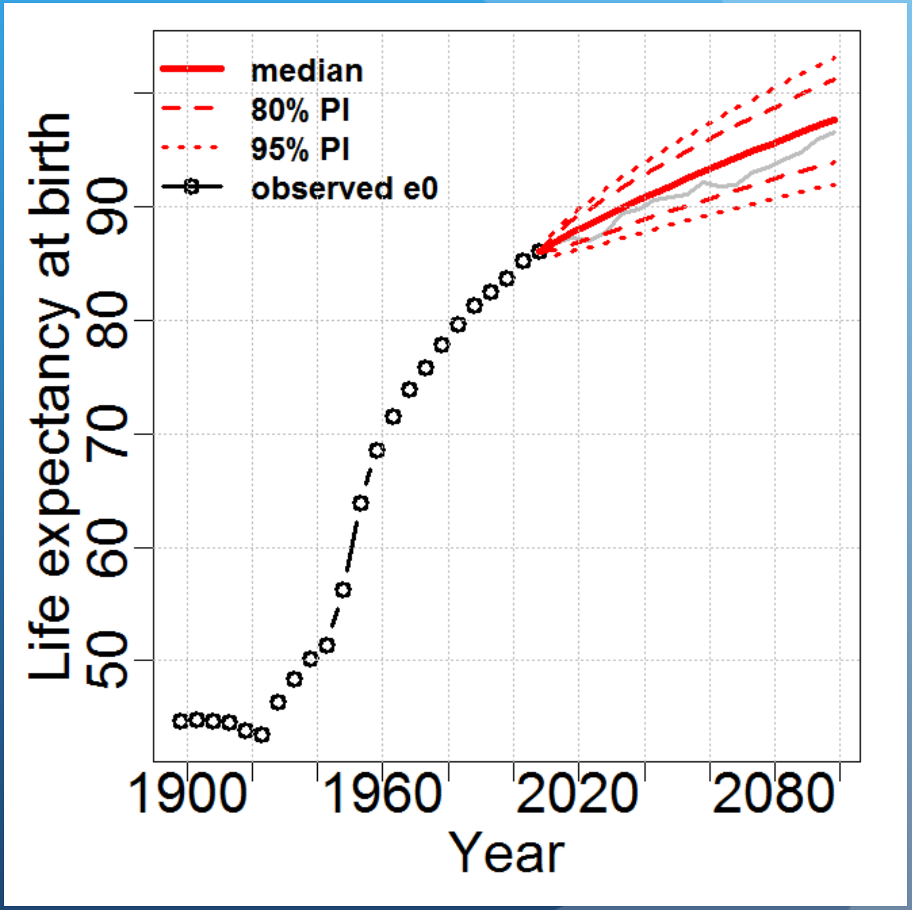


Japan: Probabilistic female e0 projection

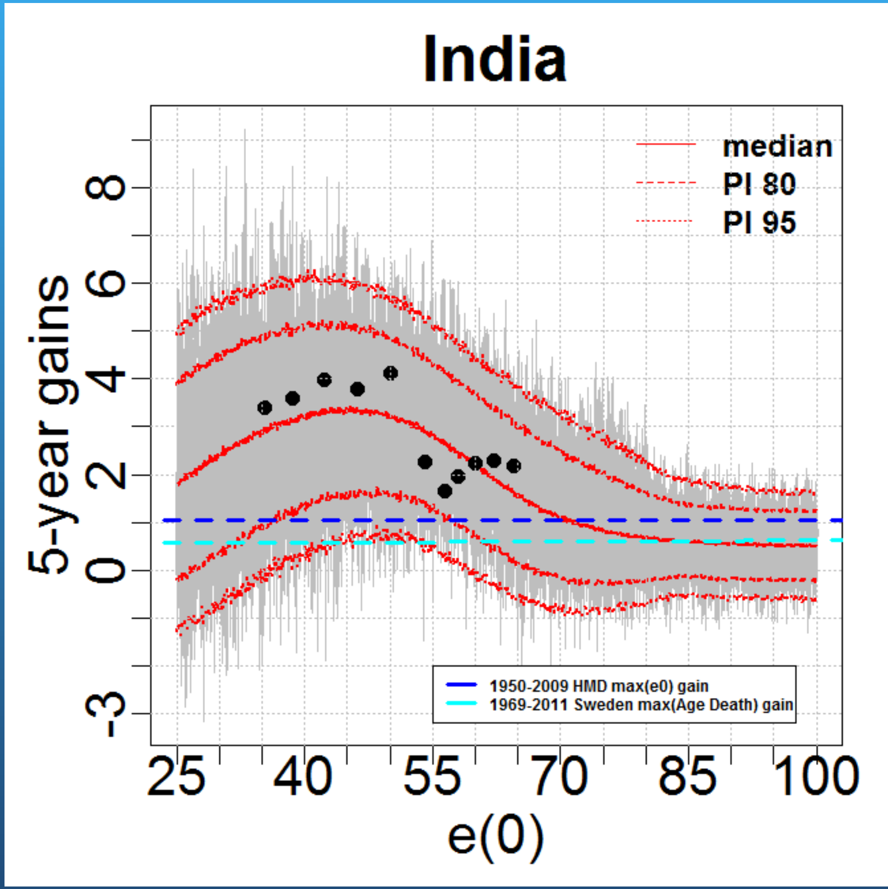
Double-logistic gain in e0 function

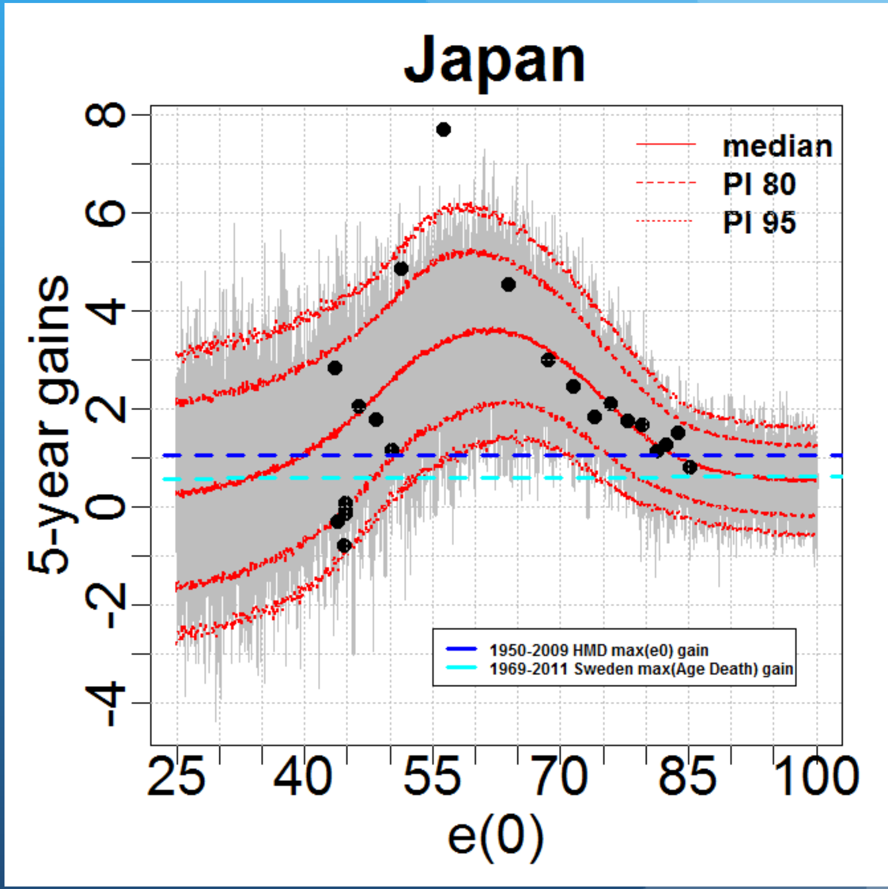


Probabilistic projections of e_0



Predictive distribution of gains in female e_0





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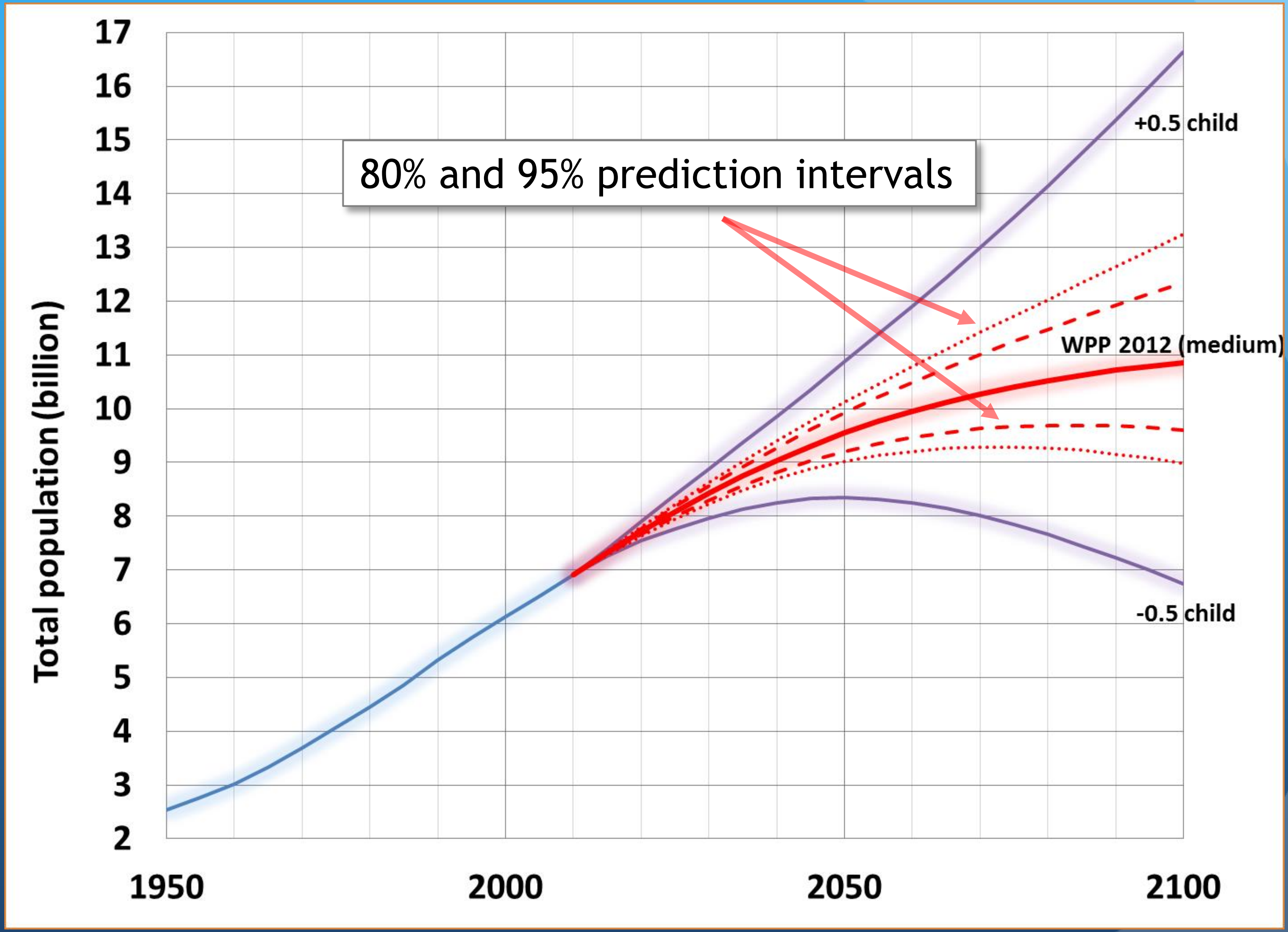
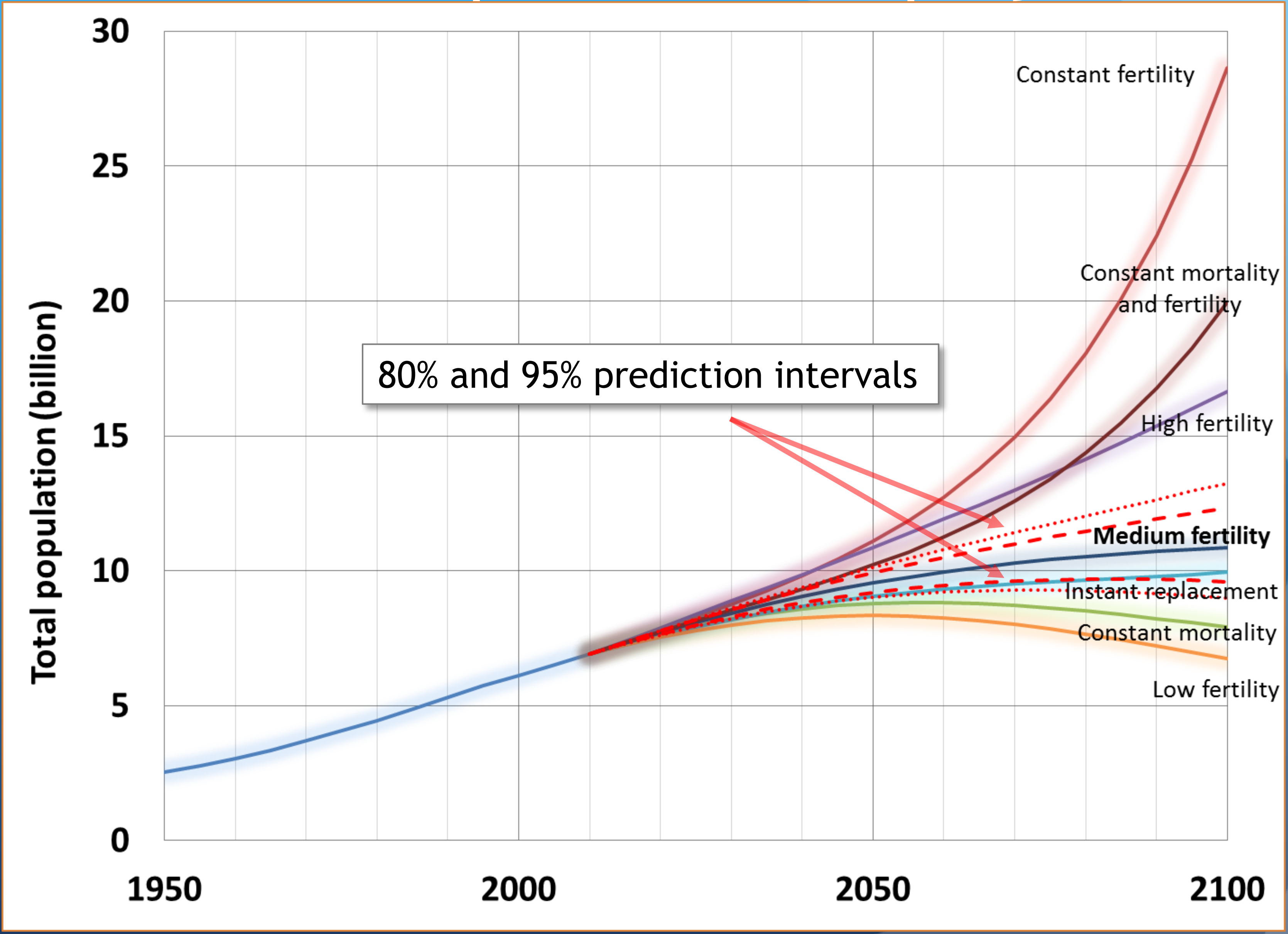
World population projections

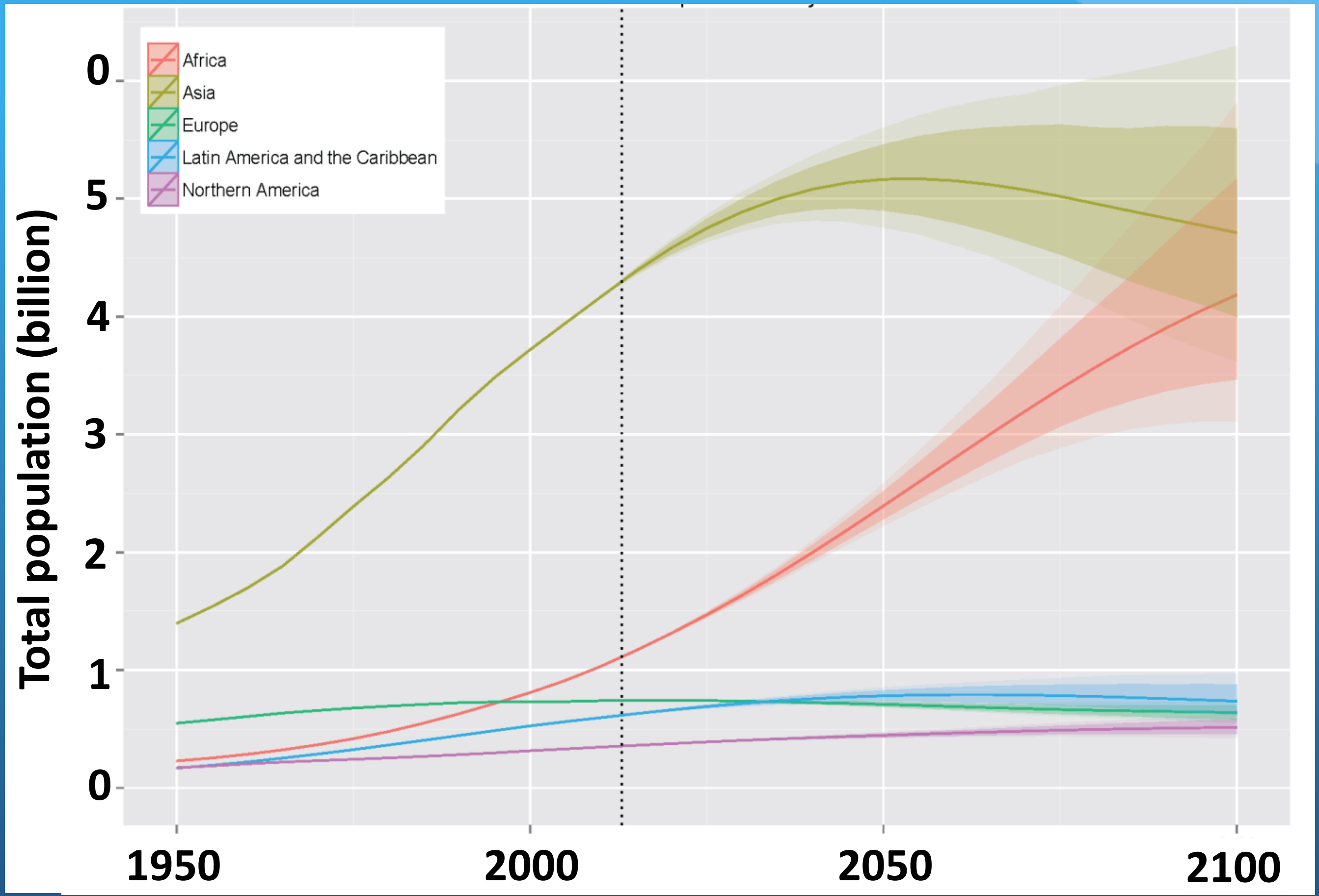


Source: Gerland et al. (2014), "World population stabilization unlikely this century," *Science* 346(6206):234-237.

Scenarios vs. probabilistic projections



Where will the increase happen?



Africa:
Now ~1 bil.

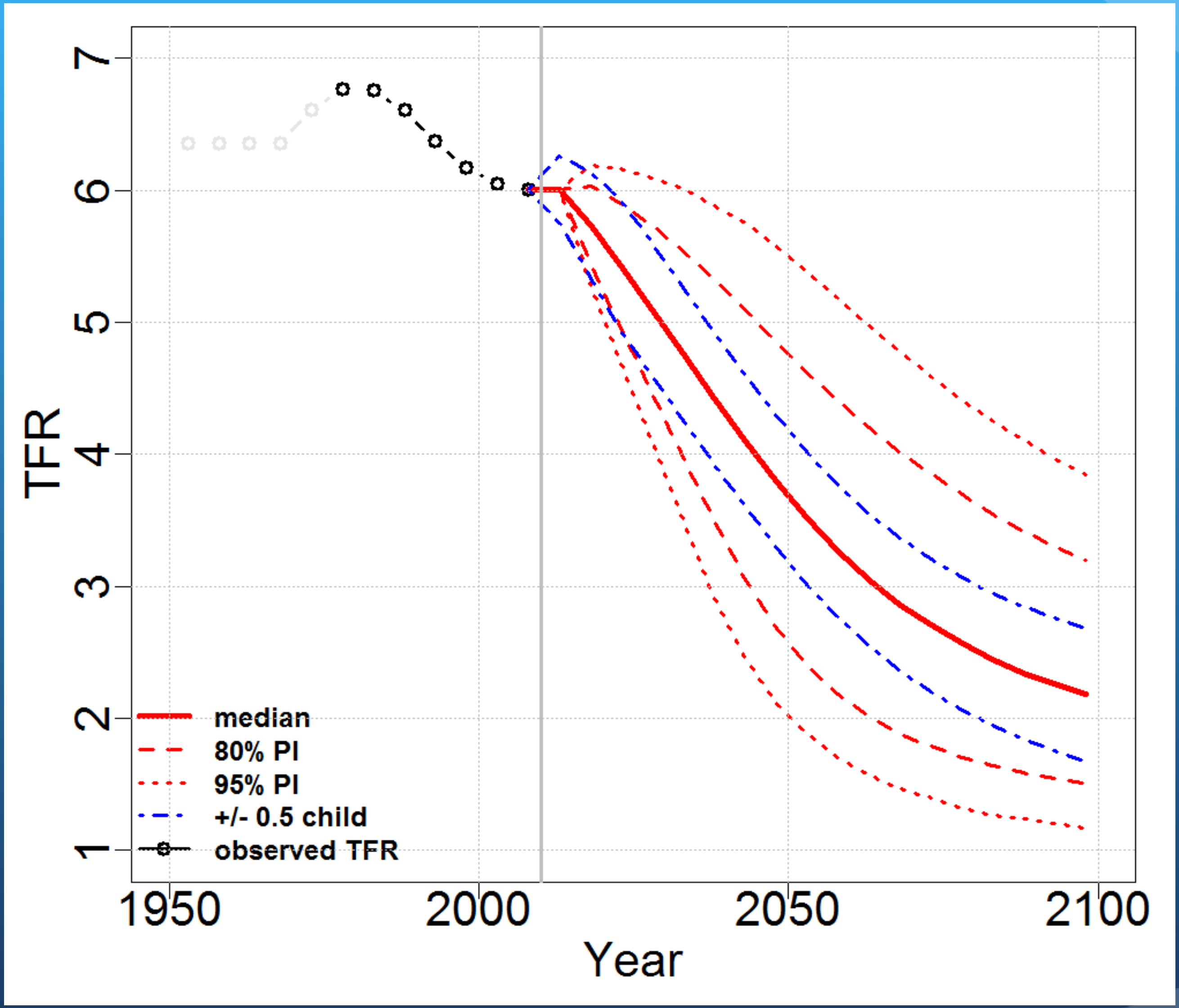
2100:
4.2 bil.

80% range:
3.5-5.1 bil.

Recent slowdown/stall of fertility decline in some countries of sub-Saharan Africa

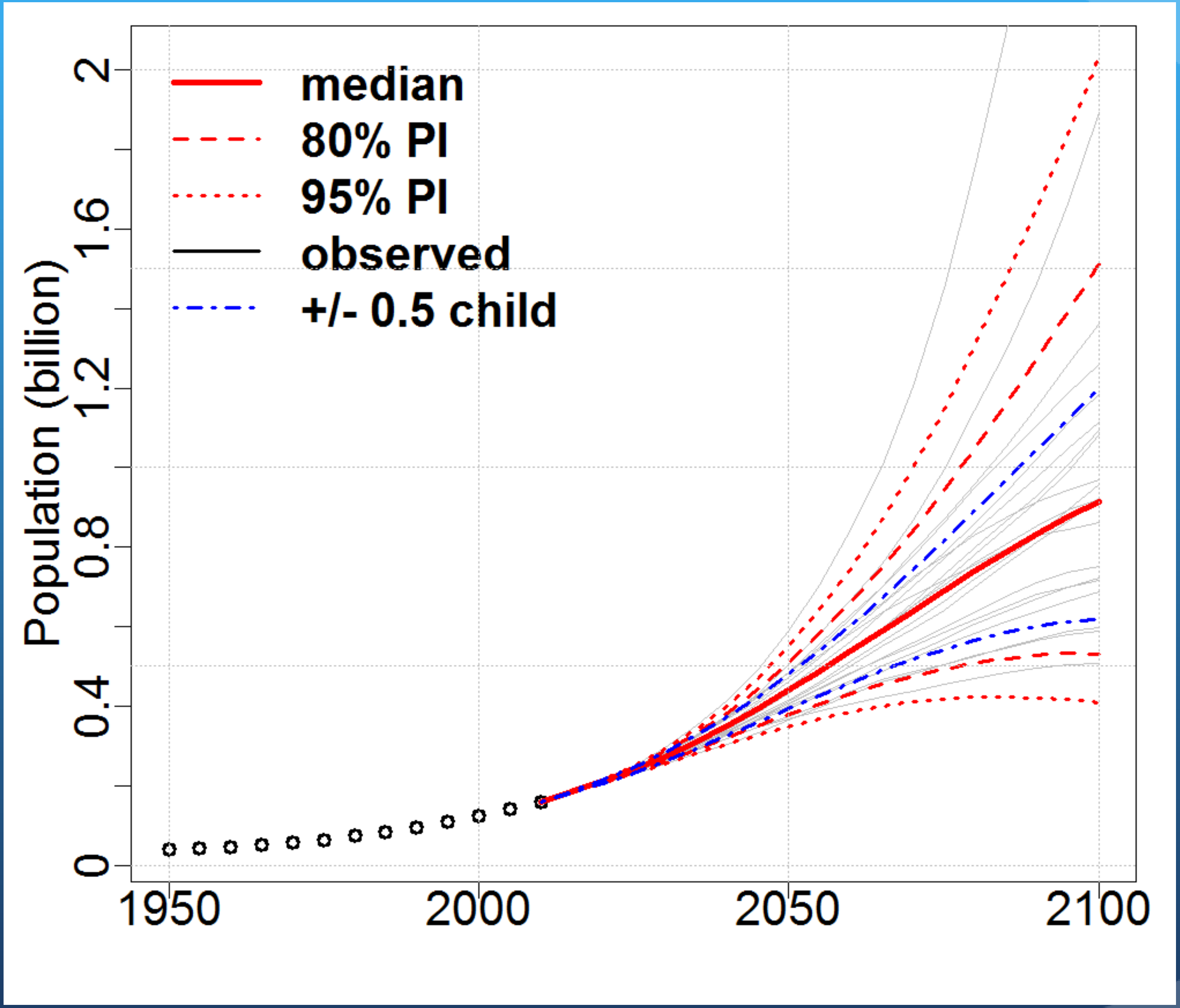
- Unmet need for contraception (~25% in SSA over past 20 years)
- Ideal family size has declined but remains high (~4.5)

TFR projection for Nigeria



- Decline stalled past 10 years
- Expect renewed decline, but stall could continue
- Much uncertainty
- UN high/low scenarios too narrow
- 2100 median just above replacement: 2.2 (1.5-3.2)

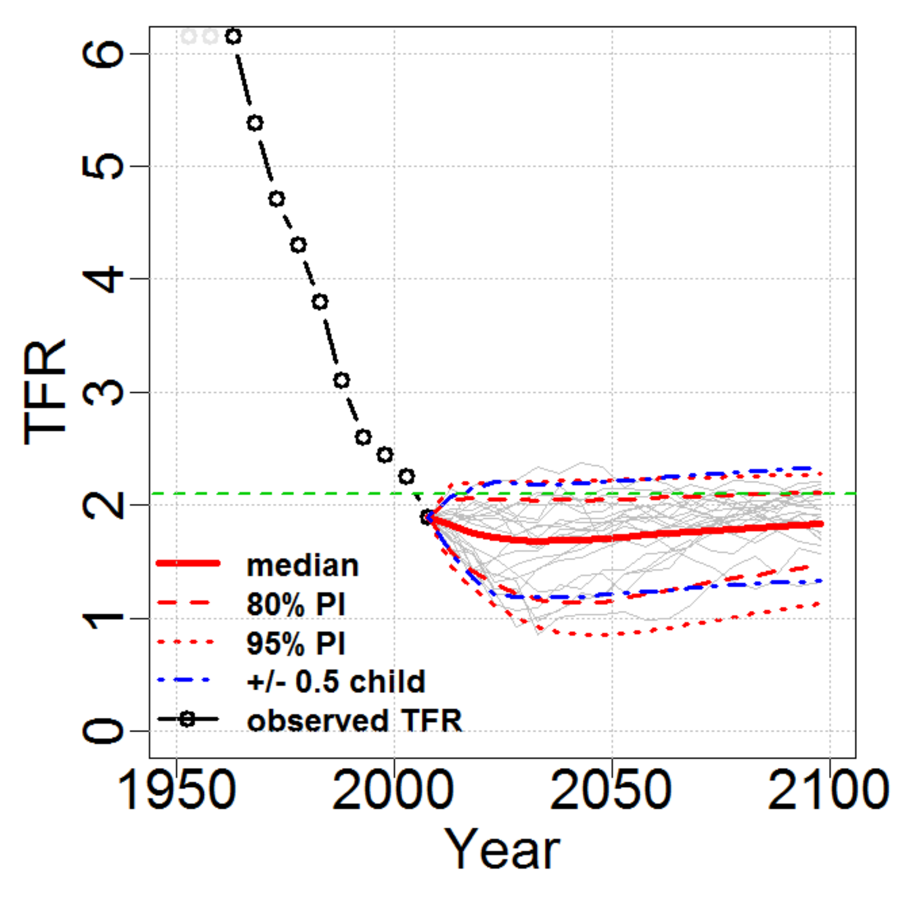
Population projection for Nigeria



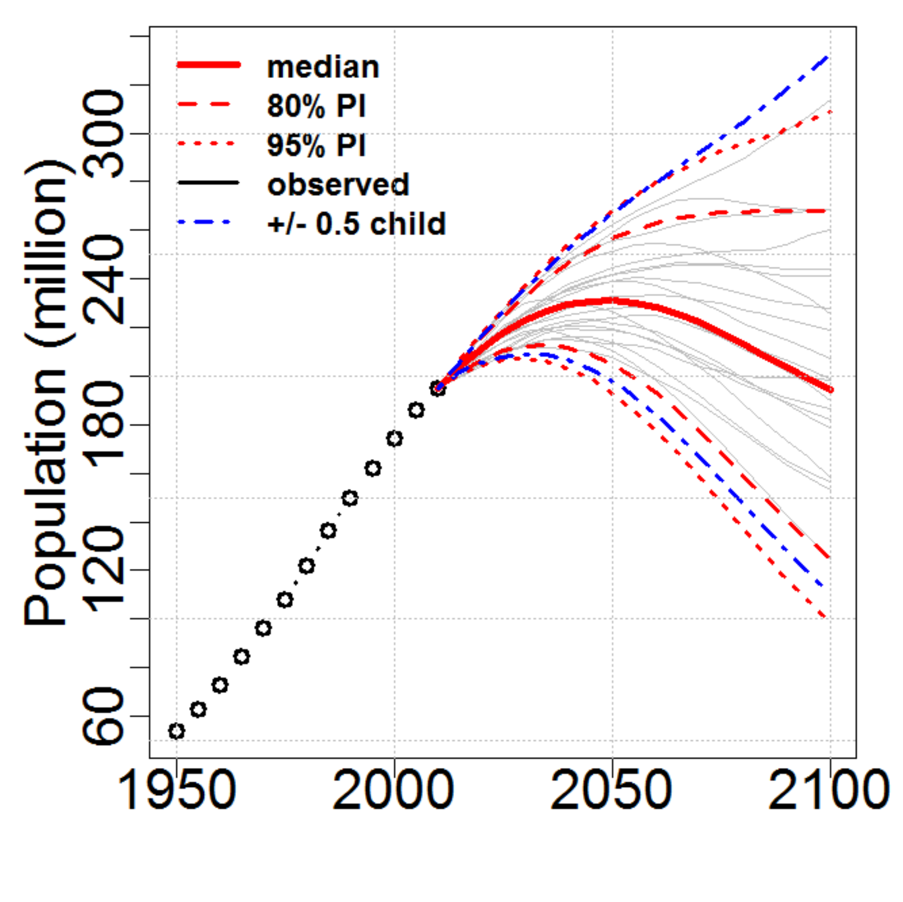
- Now: 160 mil.
- 2100: 914 mil.
  - Lower 10%: 532 mil.
- UN fertility variants (+/- half child) understate uncertainty of future trends (when today's TFR > 3)

Brazil

Total fertility rate

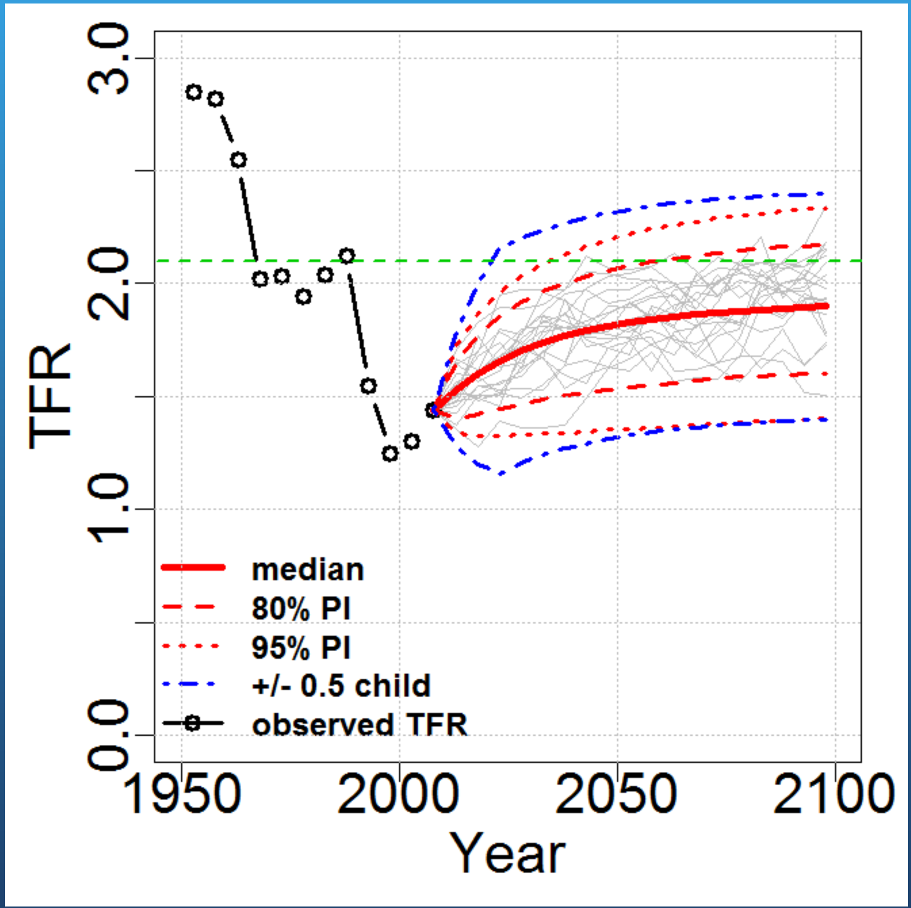


Total population

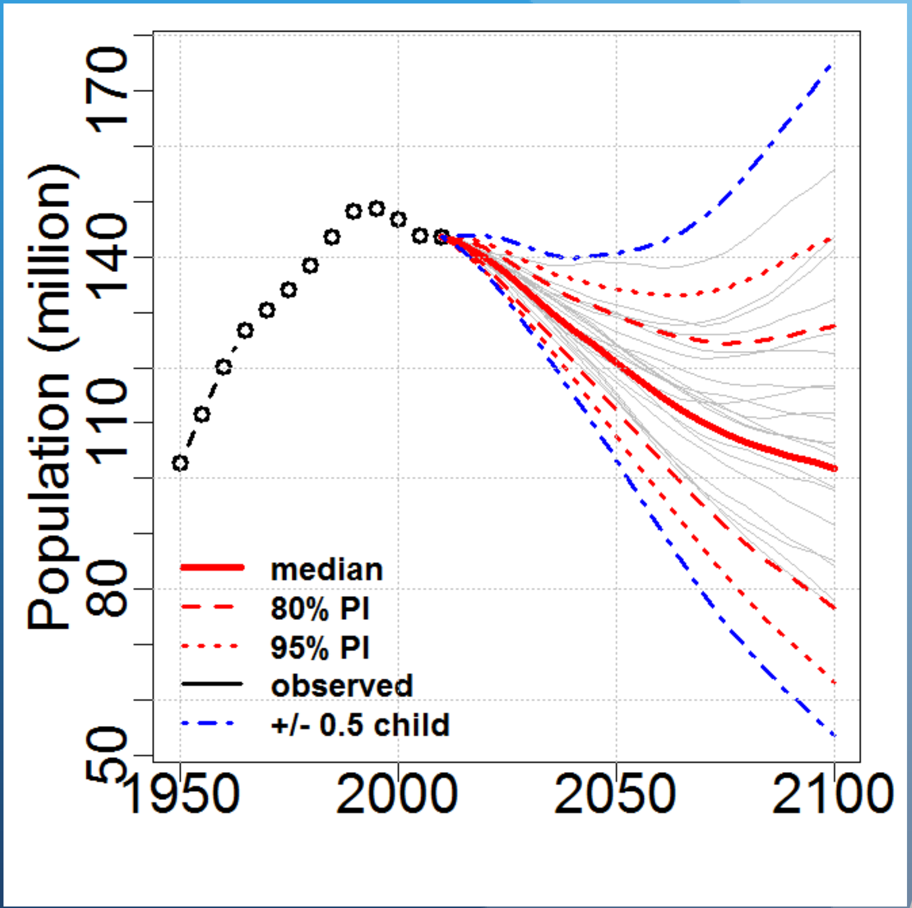


Russian Federation

Total fertility rate



Total population



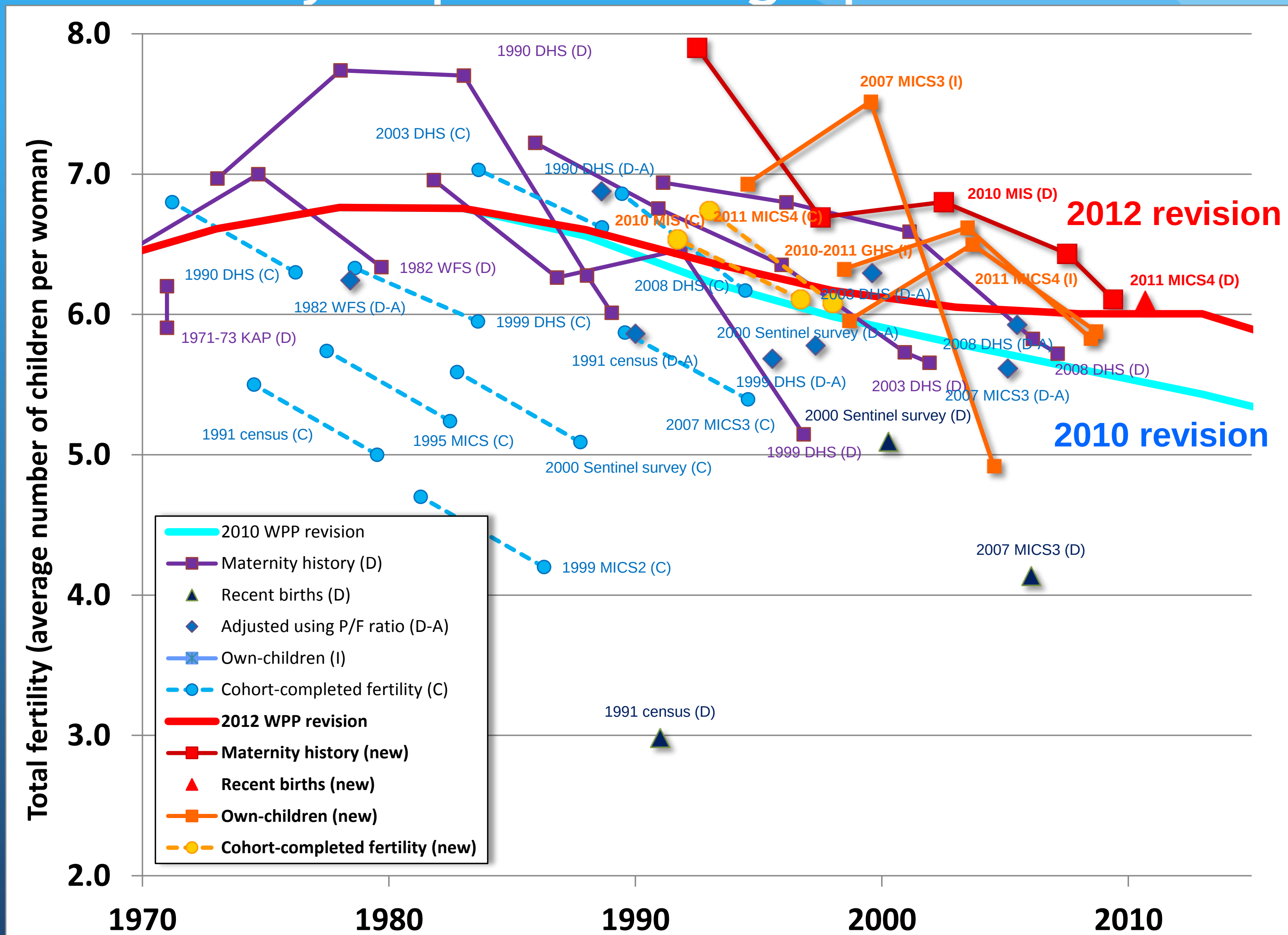
What have we learned from probabilistic projections?

- UN fertility variants (+/- half child)
  - Overstate the uncertainty of future trends at the global level, and also for some low-fertility countries
  - Understate the uncertainty of future trends for high-fertility countries
- World population growth
  - 95% prediction interval for 2050: 9.0 – 10.1 billion
  - 95% prediction interval for 2100: 9.0 – 13.3 billion
  - Population stabilization unlikely in this century, but not impossible (probability ~30%)

What uncertainty is not (yet) accounted for?

- Uncertainty about the baseline population and current levels of fertility, mortality and migration
- Uncertainty about model specification (e.g., parameter to determine asymptotic increase of e_0)
- Uncertainty about future age patterns of fertility and mortality
- For countries with high prevalence of HIV, uncertainty about the future path of the epidemic
- Uncertainty about future sex ratios at birth
- Uncertainty about future trends in international migration

Uncertainty in past demographic estimates



Source: United Nations (2014). *World Population Prospects: The 2012 Revision – Methodology*

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Key messages

- Population projections usually include a middle scenario taken as a “best guess” for future trends
- Important to communicate that this “best guess” is only one possible outcome
  - Any prediction of the future is uncertainty
  - Smart policies should anticipate multiple possible outcomes
- United Nations now employs two methods of illustrating the uncertainty of future trends
  - Alternative scenarios
  - Probabilistic models
- Fertility variants (+/- half child) are useful illustrations but potentially misleading in some cases
- Population stabilization is unlikely in this century

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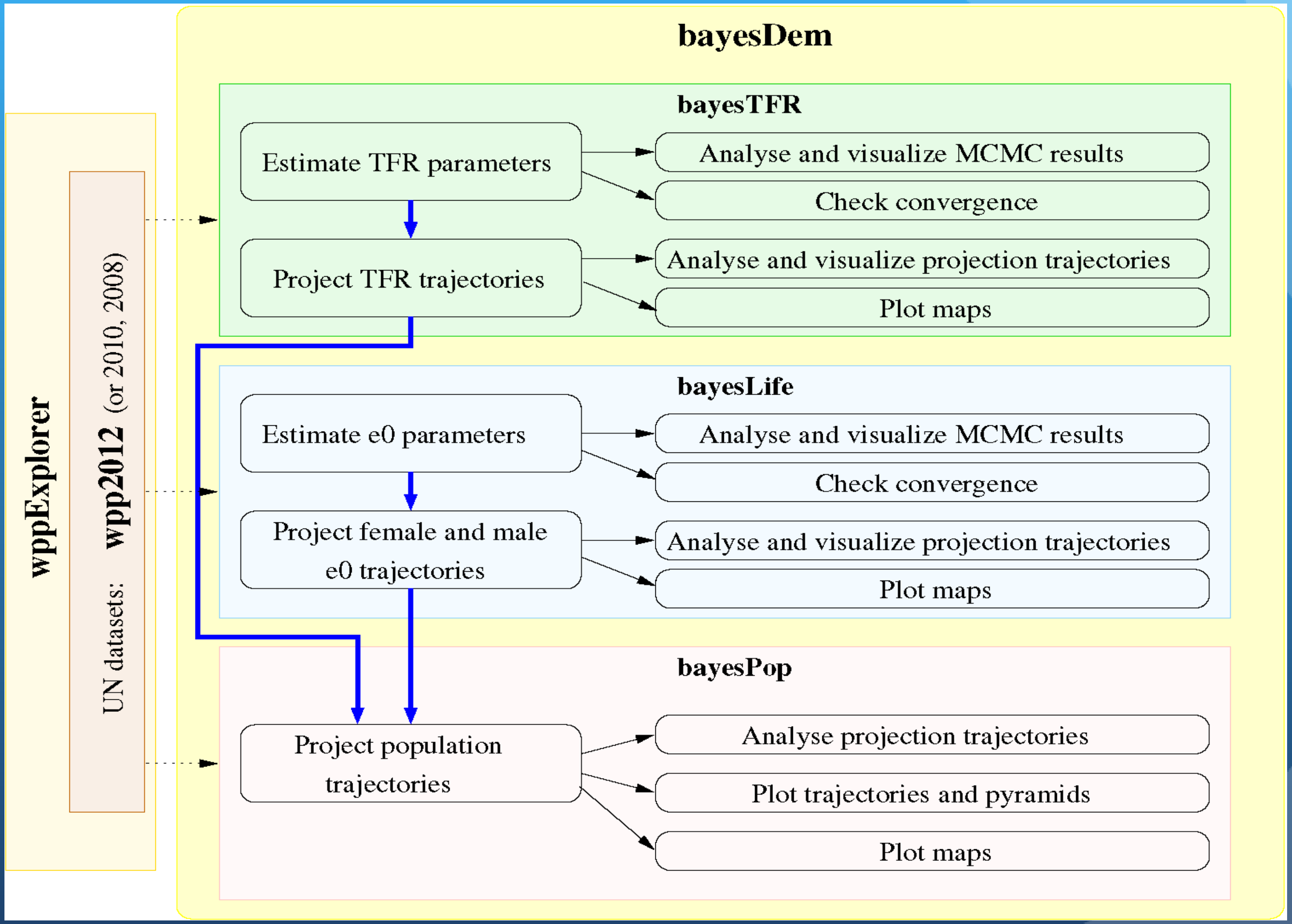
R packages (free open source) available at http://cran.r-project.org

- Probabilistic projections of total fertility rate: bayesTFR
- Probabilistic projections of life expectancy at birth: bayesLife
- Probabilistic population projections: bayesPop
- Graphical user interface: bayesDem, wppExplorer
- UN datasets: wpp2012, wpp2010, wpp2008

R packages



bayesDem
bayesTFR
Estimate TFR parameters
Analyse and visualize MCMC results
Check convergence
Project TFR trajectories
Analyse and visualize projection trajectories
Plot maps
bayesLife
Estimate e0 parameters
Analyse and visualize MCMC results
Check convergence
Project female and male e0 trajectories
Analyse and visualize projection trajectories
Plot maps
bayesPop
Project population trajectories
Analyse projection trajectories
Plot trajectories and pyramids
Plot maps
wppExplorer
UN datasets: wpp2012 (or 2010, 2008)

References

- Alders M, Keilman N, Cruijsen H (2007) Assumptions for long-term stochastic population forecasts in 18 European countries. Eur J Popul 23:33-69.
- Alho JM, Jensen SEH, Lassila J (2008) Uncertain Demographics and Fiscal Sustainability. Cambridge University Press, Cambridge.
- Alho JM, et al. (2006) New forecast: Population decline postponed in Europe. Stat J Unit Nation Econ Comm Eur 23:1-10.
- Alkema L. et al. (2011). ”Probabilistic Projections of the Total Fertility Rate for All Countries.” in: Demography, 48:815-839.
- Andreev K, Kantorov´a V, Bongaarts J (2013) Technical Paper No. 2013/3: Demographic Components of Future Population Growth, Population Division, DESA, United Nations, New York, NY.
- Booth H (2006) Demographic forecasting: 1980 to 2005 in review. Int J Forecast 22:547-581.
- Gerland P, Raftery AE, et al. (2014). ”World population stabilization unlikely this century.” in Science 346(6206):234-237.
- Hinde, A. (1998) Demographic Methods. London: Arnold.
- Keyfitz N (1981) The limits of population forecasting. Popul Dev Rev 7:579-593.

References

- Lee RD, Tuljapurkar S (1994) Stochastic population forecasts for the United States: Beyond high, medium, and low. J Am Stat Assoc 89:1175-1189.
- Lutz W, Sanderson WC, Scherbov S (1996). The Future Population of the World: What Can We Assume Today? Earthscan Publications Ltd, London, Revised 1996 ed, pp 397-428.
- Lutz W, Sanderson WC, Scherbov S (1998) Expert-based probabilistic population projections. Popul Dev Rev 24:139-155.
- Lutz W, Sanderson WC, Scherbov S (2004) The End of World Population Growth in the 21st century: New Challenges for Human Capital Formation and Sustainable Development Earthscan, Sterling, VA.
- National Research Council (2000) Beyond Six Billion: Forecasting the World's Population. National Academy Press, Washington, DC.
- Newell, C. (1988) Methods and Models in Demography. New York: Guilford Press.
- Pflaumer P (1988) Confidence intervals for population projections based on Monte Carlo methods. Int J Forecast 4:135-142.
- Preston SH, Heuveline P, Guillot M (2001). Demography: Measuring and Modeling Population Processes. Malden, MA: Blackwell Publishers.
- Raftery AE, Alkema L, Gerland P (2014). "Bayesian Population Projections for the United Nations." in: Statistical Science, 29(1), 58-68.

References

- Raftery AE, Li N, Sevcikova H, Gerland P, Heilig GK (2012). ”Bayesian probabilistic population projections for all countries.” in: Proceedings of the National Academy of Sciences. 109 (35):13915-13921.
- Raftery AE, Chunn JL, Gerland P, Sevcikova H. (2013). ”Bayesian Probabilistic Projections of Life Expectancy for All Countries”. in: Demography, 5 (3), 777-801.
- Raftery AE, Lalic N, Gerland P (2014). ”Joint probabilistic projection of female and male life expectancy”. in: Demographic Research, 30(27), 795-822.
- Stoto MA (1983) The accuracy of population projections. J Am Stat Assoc 78:13-20.
- Tuljapurkar S, Boe C (1999) Validation, probability-weighted priors, and information in stochastic forecasts. Int J Forecast 15:259-271.
- United Nations (1956). Manual III: Methods for population projections by sex and age. New York, NY: DESA, Population Division.
- United Nations (2014). Probabilistic Population Projections based on the World Population Prospects: The 2012 Revision (http://esa.un.org/unpd/ppp/).

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