United Nations | Department of Economic and Social Affairs

Population Division
UN DESA/POP/2022/DC/NO.6
July 2022

Methodology Report

World Population Prospects 2022

Methodology of the United Nations population estimates and projections

United Nations
New York,
2022

United Nations Department of Economic and Social Affairs, Population Division

The Department of Economic and Social Affairs of the United Nations Secretariat is a vital interface between global policies in the economic, social and environmental spheres and national action. The Department works in three main interlinked areas: (i) it compiles, generates and analyses a wide range of economic, social and environmental data and information on which States Members of the United Nations draw to review common problems and take stock of policy options; (ii) it facilitates the negotiations of Member States in many intergovernmental bodies on joint courses of action to address ongoing or emerging global challenges; and (iii) it advises interested Governments on the ways and means of translating policy frameworks developed in United Nations conferences and summits into programmes at the country level and, through technical assistance, helps build national capacities.

The Population Division of the Department of Economic and Social Affairs provides the international community with timely and accessible population data and analysis of population trends and development outcomes for all countries and areas of the world. To this end, the Division undertakes regular studies of population size and characteristics and of all three components of population change (fertility, mortality and migration). Founded in 1946, the Population Division provides substantive support on population and development issues to the United Nations General Assembly, the Economic and Social Council and the Commission on Population and Development. It also leads or participates in various interagency coordination mechanisms of the United Nations system. The work of the Division also contributes to strengthening the capacity of Member States to monitor population trends and to address current and emerging population issues.

Notes

The term “country” as used in this report also refers, as appropriate, to territories or areas.

This report is available in electronic format on the Division’s website at www.unpopulation.org. For further information about this report, please contact the Office of the Director, Population Division, Department of Economic and Social Affairs, United Nations, New York, 10017, USA, by fax: 1 212 963 2147 or by e-mail at population@un.org.

Suggested citation

United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022: Methodology of the United Nations population estimates and projections.* UN DESA/POP/2022/TR/NO. 4.

Official symbols of United Nations documents are composed of capital letters combined with numbers, as illustrated in the above citation.

Copyright information

PREFACE

This report provides a detailed overview of the methodology used to produce the *2022 Revision* of the official United Nations population estimates and projections, prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. The *2022 Revision* is the twenty-seventh round of global population estimates and projections produced by the Population Division since 1951.

In order to improve the standards, transparency and replicability of the *World Population Prospects* and in response to growing demand for more granular demographic indicators, several major methodological enhancements have been implemented in the *2022 Revision*. Chief among these is a transition from the historical practice of estimating and projecting population for five-year age groups and over five-year periods of time towards a framework defined by single-years of age and one-year periods of time. Additional enhancements include: a more systematic and comprehensive compilation of country-level empirical data for each demographic component, the application of probabilistic models for estimating key fertility and mortality indicators; a new protocol for evaluating and adjusting census population counts; a new accounting for "crisis" mortality impacts, such as those due to conflicts, natural disasters and epidemics, including the COVID-19 pandemic; a new model life table system to estimate mortality for countries affected by HIV and AIDS; the application of standardized methods for estimating levels and patterns of net international migration; and the upgrade of probabilistic projection models of fertility and mortality for annual time series.

This report first describes the way that country estimates have been prepared and then explains the approaches and assumptions that were used to project fertility, mortality and international migration up to the year 2100. The report also provides an overview of the scenarios used in generating the different sets of population projections as well as information on the probabilistic projection methods, which depict the uncertainty of future demographic trends. Making projections to 2100 is subject to a high degree of uncertainty, especially at the country level. In that regard, users are encouraged to focus not only on the medium scenario, which corresponds to the median of several thousand projected trajectories of specific demographic components, but also on the associated prediction intervals, which provide an assessment of the uncertainty inherent in such projections. Detailed information on the 80 and 95 per cent uncertainty bounds for different components at the country level and major geographic aggregates is available on the website of the Population Division, *www.unpopulation.org*.

The *2022 Revision* of the *World Population Prospects* was prepared by a team led by Patrick Gerland, including Guiomar Bay, Helena Cruz Castanheira, Giulia Gonnella, Danan Gu, Sara Hertog, Yumiko Kamiya, Vladimíra Kantorová, Kyaw Kyaw Lay, José H. C. Monteiro da Silva, Igor Ribeiro, Thomas Spoorenberg, Mark Wheldon, Iván Williams and Lubov Zeifman, with the assistance of Gabriel Borges, Dennis Butler, Rafaella Carnevali, Fengqing Chao, Jorge Cimentada, Sam Clark, Camille Dorion, Brian Houle, Peter Johnson, Shelmith Kariuki, Sabu Kunju, Pablo Lattes, Nan Li, Peiran Liu, Jonathan Muir, Marília Nepomuceno, Marius Pascariu, François Pelletier, Adrian Raftery, Mariana Urbina Ramirez, Tim Riffe, and Hana Ševčíková. The team is grateful to other colleagues in the Population Division for the support they have provided, as well as colleagues from the teams of the United Nations Inter-agency Group for Child Mortality Estimation (UN IGME) and the WHO-UNDESA Technical Advisory Group for COVID Mortality Assessment for their inputs and continuous support. The team is additionally grateful to John Wilmoth for reviewing this report.

CONTENTS

TABLES

FIGURES

EXPLANATORY NOTES

The following symbols have been used in the tables throughout this report:

A full stop (.) is used to indicate decimals.

Years given refer to 1 July.

References to countries, territories and areas:

The designations employed in this publication and the material presented in it do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The term "country" as used in this publication also refers, as appropriate, to territories or areas.

In this table, data for countries or areas have been aggregated in six continental regions: Africa, Asia, Europe, Latin America and the Caribbean, Northern America, and Oceania. Further information on continental regions is available from https://unstats.un.org/unsd/methodology/m49/. Countries or areas are also grouped into geographic regions based on the classification being used to track progress towards the Sustainable Development Goals of the United Nations (see: https://unstats.un.org/sdgs/indicators/regional-groups/).

The designation of "more developed" and "less developed" regions is intended for statistical purposes and does not express a judgment about the stage reached by a particular country or area in the development process. More developed regions comprise all regions of Europe plus Northern America, Australia and New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (excluding Japan), and Latin America and the Caribbean as well as Oceania (excluding Australia and New Zealand).

The group of least developed countries includes 46 countries: 32 in Sub-Saharan Africa, 2 in Northern Africa and Western Asia, 4 in Central and Southern Asia, 4 in Eastern and South-Eastern Asia, 1 in Latin America and the Caribbean, 3 in Oceania (as accessed on 24 March 2022). Further information is available at https://www.un.org/ohrlls/content/least-developed-countries.

The group of Landlocked Developing Countries (LLDCs) is composed of 32 countries or territories: 16 in Sub-Saharan Africa, 2 in Northern Africa and Western Asia, 8 in Central and Southern Asia, 2 in Eastern and South-Eastern Asia, 2 in Latin America and the Caribbean, and 2 in Europe and Northern America (as accessed on 24 March 2022). Further information is available at https://www.un.org/ohrlls/content/landlocked-developing-countries.

The group of Small Island Developing States (SIDS) is composed of 58 countries or territories: 25 in the Caribbean, 19 in the Pacific and 14 in the Atlantic, Indian Ocean and South China Sea (AIS) (as accessed on 24 March 2022). Further information is available at https://www.un.org/ohrlls/content/small-island-developing-states.

The country classification by income level is based on GNI per capita from the World Bank (as accessed on July 2022). Further information is available at https://datahelpdesk.worldbank.org/knowledgebase/articles/906519.

The following abbreviations have been used:

AIDS	Acquired immunodeficiency syndrome
AIM	Aids Impact Model
API	Application Programming Interface
ART	Antiretroviral therapy
ASFR	Age-specific fertility rate
BHM	Bayesian hierarchical model
CCMPP	Cohort Component Method for Projecting Population
CDR	Crude Death Rate
COVID-19	Coronavirus Disease 2019
CPS	Contraceptive Prevalence Surveys
DHS	Demographic and Health Surveys
DTP	Diphtheria, Tetanus, and Pertussis
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GHS	General Household Survey
GNI	Gross National Income
HDSS	Health and Demographic Surveillance Systems
HFD	Human Fertility Database
HIV	Human immunodeficiency virus
HMD	Human Mortality Database
IGME	Inter-agency Group for Child Mortality Estimation
IPUMS	Integrated Public Use Microdata Series
LAMBdA	Latin American Mortality Database
LC	Lee-Carter method for mortality forecasting
MAC	Mean age at childbearing
MICS	Multiple Indicator Cluster Survey
MIS	Malaria Indicator Survey
MLT	Model life table
PAPFAM	Pan-Arab Project for Family Health
PASFR	Proportionate age-specific fertility rate
PES	Post-Enumeration Survey
PI(s)	Prediction interval(s)
PMA	Performance Monitoring and Accountability
PMD	Pattern of Mortality Decline
RHS	Reproductive Health Surveys

SAR	Special Administrative Region
SRB	Sex ratio at birth
SQL	Structured Query Language
SVD	Singular Value Decomposition
TFR	Total fertility rate
UN	United Nations
UNAIDS	Joint United Nations Programme on HIV/AIDS
UNDESA	United Nations Department of Economic and Social Affairs
UNFPA	United Nations Population Fund
UNHCR	Office of the United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
VR	Vital Registration
WFS	World Fertility Survey
WHO	World Health Organization
WPP	World Population Prospects

INTRODUCTION

The preparation of each new revision of the official population estimates and projections of the United Nations involves two distinct processes: (a) the incorporation of new information about the demography of each country or area of the world, involving a reassessment of past estimates where warranted; and (b) the formulation of detailed assumptions about the future paths of fertility, mortality and international migration, again for every country or area of the world.

Methodological enhancements implemented for the *2022 Revision* necessitated a complete reassessment of past estimates for virtually all 237 countries or areas that together comprise the total population of the world. These enhancements include: a transition from the historical practice of estimating and projecting across five-year age groups and five-year periods of time to single year age groups and one-year periods of time; a more systematic and comprehensive compilation of country-level empirical data for each demographic component; probabilistic models for estimating total fertility, age-specific fertility rates, the sex ratio at birth, and adult mortality; a new standardized protocol for evaluating and adjusting census population counts by age and sex; a new approach to account for “crisis” mortality impacts, such as those due to conflicts, natural disasters and epidemics, including the COVID-19 pandemic; a new model life table system to estimate mortality age patterns for countries affected by HIV and AIDS; the application of standardized methods for estimating levels and patterns of net international migration; and the upgrade of probabilistic projection models of fertility and mortality for annual time series. Summaries of these procedures are provided in the body of this report.

The population estimates and projections contained in this revision cover a 150-year time horizon. Estimates refer to the period from 1 January 1950 to 1 January 2022 and projections are for the period from 1 January 2022 to 1 January 2101. For each of 237 countries or areas, the population estimates and projections were produced by starting with a base population by age and sex for 1 January 1950 and advancing the population through successive single-year intervals of time using the cohort-component method for projecting population (CCMPP). The CCMPP relies on information about: fertility by age of mother to determine the number of births taking place each year; mortality by sex and age to determine the number of deaths; and net international migration by sex and age to determine the levels and patterns of population shifts across international borders.

For estimates, complete annual series of fertility, mortality and net international migration for calendar years 1950 through 2021 were developed based on available sources of empirical information, including civil registration and vital statistics, censuses, demographic surveys, and administrative records, to name several. For this *2022 Revision*, the estimates also considered the impact of the COVID-19 pandemic on the components of demographic change, including by incorporating estimates of excess mortality through 2021 produced by the WHO. Population counts by age and sex from periodic censuses were used to benchmark the CCMPP results for most countries. These counts were adjusted, where necessary, for coverage gaps, deficiencies in age reporting, and over- or under-enumeration. For some countries, population counts from registers or estimates served as supplemental benchmarks.

For the projection horizon covering calendar years 2022 through 2100, the annual series of fertility rates for each country were developed through probabilistic models of total fertility, combined with some assumptions about how patterns of fertility by age of mother shift with changes in the total fertility level. Similarly, the annual series of mortality rates were developed through probabilistic models of life expectancies at birth, by sex, together with assumptions about how age-specific mortality rates change with improved survival. The total fertility and life expectancy models considered the historical levels and trend estimated for each country to give a median projected trajectory, as well as statistical bounds of uncertainty[1] (prediction intervals or PIs), for each of these indicators. Taken together with assumptions about the future course of net international migration in each country, the median trajectories of fertility and mortality input to the CCMPP give the "medium scenario" population projection. Alternative scenarios produced for this revision describe the effect of changes in the assumptions about the various demographic components (e.g, the projected level of fertility) on the projected size and age structure of the population.

The report begins with a description of the methods employed to revise the estimates during the preparation of the *2022 Revision*. It then examines the approaches and assumptions used to project fertility, mortality and international migration up to the year 2100. The report contains information on the probabilistic projection methods as well as an overview of the different deterministic scenarios used in generating the multiple sets of population projections.

---

[1] For further discussion about uncertainty in future population projections, see also United Nations (2019a).

I. THE PREPARATION OF POPULATION ESTIMATES

A. GENERAL ANALYTICAL STRATEGY AND MAJOR STEPS FOR PRODUCING POPULATION ESTIMATES

With each revision of the *World Population Prospects*, the Population Division of UN DESA reviews its methods and procedures to identify and prioritize areas for improvement. In light of the latest standards and expectations regarding transparency and replicability (Stevens and others, 2016), and in response to the growing demand for demographic indicators that are disaggregated by ever smaller units of age and time (Committee for the Coordination of Statistical Activities, 2020), the Division has targeted multiple areas for improvement in the *2022 Revision*. Specific areas of improvement were identified and prioritized based on the recommendations of an expert group convened by the Population Division in 2020 (United Nations, 2020).

Chief among these improvements is a transition from the historical practice of estimating and projecting population for five-year age groups and over five-year periods of time (5x5) towards a framework defined by single years of age and one-year periods of time (1x1). As a result of this transition, the *2022 Revision* provides more detailed estimates of population by age with improved fitness for use in computing indicators for age groups that do not conform to the standard 5-year framework[2]. Moreover, the 1x1 framework facilitates a more explicit and accurate accounting of shocks or cohort effects that exact short-term influence on demographic processes. Whereas in previous revisions the impact of natural disasters or conflicts on fertility, mortality and international migration were diluted within the average of a five-year period, they are more visibly represented in the precise year(s) of occurrence in the *2022 Revision.*

The transition from a 5x5 framework to 1x1 framework has, in turn, necessitated a complete re-evaluation of the historical evidence base on population and demographic trends. To be sure, a re-estimation of recent or historical demographic trends has been undertaken with every revision of the *World Population Prospects* as new data became available from censuses, demographic surveys, registries of vital events, population registers and various other sources (e.g., refugee statistics). Each new data collection gives an opportunity to extend and, if necessary, correct retrospectively, the time series of fertility, mortality and migration, as well as population by age and sex. In shifting to the 1x1 framework, re-estimation was required not only to consider newly available data, but also to ensure that any useful information by single year of age from historical sources was catalogued and utilized. The specific strategies employed to re-estimate fertility, mortality, international migration, and population by age and sex are described in sections B through E of this chapter.

The core approach underlying the population estimates and projections in the *2022 Revision* is the same as in past revisions: the cohort-component method for projecting population (CCMPP). It is the most common projection method among demographers today and has been employed by the Population Division to produce its country-level projections since the *1963 Revision*. CCMPP provides an accounting framework for the three demographic components of population change — fertility, mortality and international migration — and applies it to the population in question (United Nations, 1956) such that the “demographic balancing equation” is preserved (Preston and others, 2001; Whelpton, 1936):

$$P(t+n) = P(t) + B(t \text{ to } t+n) - D(t \text{ to } t+n) + NM(t \text{ to } t+n)$$

---

[2] For example, school enrolment ratios, for which the typical ages of primary or secondary school are not represented by five-year age groups.

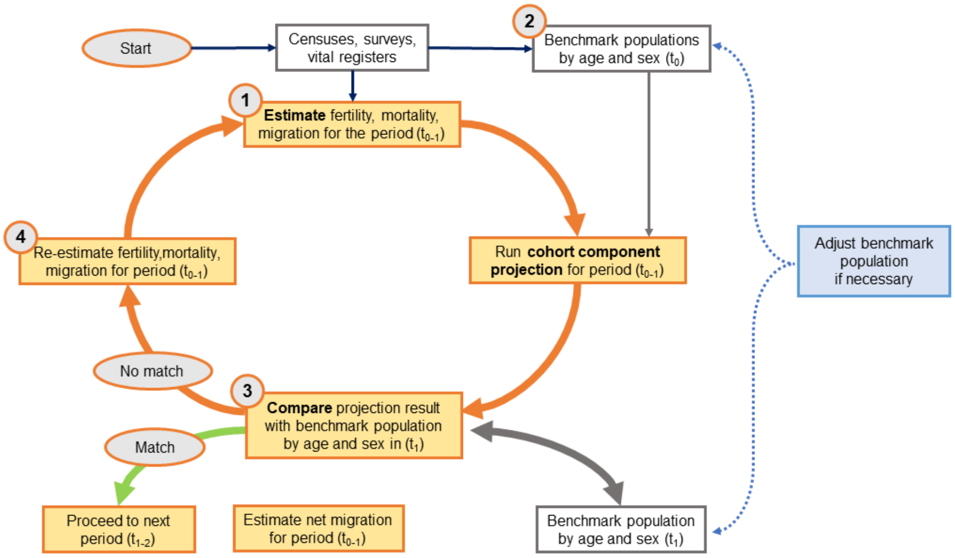
where n is the length of the projection interval, P(t) is the population at the beginning of the projection interval, P(t+n) is the population at the end of the projection interval, B(t to t+n) is the births within the projection interval, D(t to t+n) is the deaths within the projection interval, and NM(t to t+n) is the net international migration within the projection interval (immigrants less emigrants).

Technically, CCMPP is not a complete projection method on its own, since it requires that the components of change be projected in advance. Rather, it is an application of matrix algebra that enables demographers to calculate the effect of assumed future patterns of fertility, mortality, and international migration on a population at some given point in the future (Preston and others, 2001; Whelpton, 1936).

While CCMPP is commonly understood as a method for projecting future populations, it additionally provides a useful framework for reconciling historical population estimates for consistency with time series of estimated levels and trends in fertility, mortality and net international migration. In this way, the Population Division additionally employed the CCMPP as the engine to produce and validate the population estimates, including as a key approach to estimate the levels and patterns of net international migration. This process is described in figure I.1 and in the steps detailed below.

Figure I.1

Process used to ensure intercensal consistency between demographic components and the total population



NOTE: The diagram above illustrates how individual estimates of fertility, mortality and net-migration were subjected to tests of internal consistency using a cohort-component projection framework for the period between t_0 and t_1. This procedure has been applied in each new revision of the *World Population Prospects*. Past estimates are re-evaluated when new information becomes available; therefore, with every revision past demographic trends may be adjusted.

1. *Estimate the components of demographic change*: Analysts collected available data from censuses, surveys, vital and population registers, analytical reports and other sources for a given country[3]. In many cases, estimates derived from different sources or using different methods varied

---

[3] Traditionally, the data are obtained from the United Nations Statistics Division (Demographic Yearbook), national statistical offices and regional ones (e.g., Eurostat, OECD), United Nations Regional Commissions, other United Nations entities (e.g., UNAIDS, UNFPA, UNESCO, UNICEF, WHO, World Bank), and complemented using international databases (e.g., the Human Mortality Database (University of California at Berkeley (USA) and Max Planck Institute for Demographic Research (Germany), 2022) and Human Life Table Database (Max Planck Institute for Demographic Research (Germany) and others, 2020), the Human Fertility Database (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2021) and Human Fertility Collection (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2020), the Latin American Mortality Database–LAMBdA (Palloni and others, 2021), the International Data Base (U.S. Bureau of the Census, 2020), the Global Burden of Disease project (Institute for Health Metrics and Evaluation, 2020)), and public use microdata archives (e.g., DHS, MICS, IPUMS-International).

significantly, and all available empirical data sources and estimation methods were compared. Various techniques, described later in this chapter, were used to identify the most likely time series of fertility, mortality and international migration data for each country.

2. *Estimate benchmark populations by age and sex*: Population counts from censuses were evaluated for geographical coverage, completeness and several common data problems. Post-enumeration surveys were used, if available, to assess the degree and pattern of under-enumeration. Counts were adjusted, as necessary, according to the protocol described later in this chapter. Counts from population registers or other high-quality sources of population by age and sex were additionally compiled to use as benchmarks for countries where such data were available. Supplemental benchmarks considered for specific age groups included: third-dose DTP immunizations administered to children under 1 year of age (WHO/UNICEF, 2020); primary and secondary school enrolment (UNESCO Institute for Statistics, 2020); and national ID registration (World Bank, 2018) as well as voter registration data (International IDEA, 2020) for adults.[4]

3. *Compare CCMPP population against benchmarks*: The previous steps provided initial sets of independent estimates of the population and of each demographic component. In the third step, the estimates of fertility, mortality and net migration are integrated into the CCMPP where these demographic rates are applied to a base population in order to compute subsequent populations by age and sex. A comparison of the population counts by age and sex estimated through the CCMPP against the set of benchmark populations provides an assessment of whether the relationships between the benchmark populations and the estimated fertility, mortality and net migration obtained in steps 1 and 2 are internally consistent.

4. *Re-estimate the demographic components (as necessary)*: If in step 3 the benchmark populations were not adequately matched by the CCMPP, adjustments to one or more demographic components were made. In some cases, the initial base population itself was revised. Consistency was achieved through an iterative "project-and-adjust" process from one benchmark to the next to insure optimal consistency across all inputs to the CCMPP. Once all components of each country's estimates were calculated, the results were aggregated by geographical region and a final round of consistency checking took place, which involved comparing the preliminary estimates against those from other countries in the same region or at similar levels of fertility or mortality. When inconsistencies were identified, necessary adjustments were made. An important component of the work at this stage was ensuring the consistency of information on the net number of international migrants, which for each period must sum to zero at the world level.

Whereas previous revisions of the *World Population Prospects* implemented the CCMPP through a 5x5 age-time framework, the *2022 Revision* utilized a 1x1 framework. Several other changes to the CCMPP implementation are listed in Table I.1.

For the *2022 Revision*, the internal CCMPP framework used ages from 0 to 130 years, whereas the previous revision began the open-ended age group at 110 years. This change facilitates internally consistent aggregation of life tables over sex and geographies. Furthermore, it aligns the CCMPP with the approach used for the probabilistic population projections carried out in the bayesPop R package (Ševčíková and others, 2022d). While the internal framework of the CCMPP used ages up to 130 years, published estimates

---

[4] These administrative data often suffer from incomplete coverage yet may still provide a useful lower baseline reference to validate CCMPP population counts for specific age groups, especially in countries lacking recent censuses or population registers.

and projections have been summarised with open-ended age group 100+, consistent with the practice of recent previous revisions.

Other changes for the *2022 Revision* have affected the reference dates for population and vital rates. For this revision, CCMPP population inputs and outputs all referred to 1 January of the reference year and vital rates referred to calendar years from 1 January to 31 December.

Table I.1
Changes to the CCMPP implementation between the 2019 and 2022 revisions of the World Population Prospects

	2019 Revision	*2022 Revision*
Framework	5-year age groups and five-year periods (5x5)	Single-year age groups and one-year periods (1x1)
Age range	0 to 110+	0 to 130+
Population reference dates	1 July	1 January
Vital rates reference periods	1 July to 30 June	1 January to 31 December
Migration assumption	End of period or even over period (variable)	End of period
Population exposures	Not computed	Computed

The approach used to incorporate net international migration to the CCMPP was simplified for the *2022 Revision*. For all countries and time periods, net international migration was accounted for at the end of each projection cycle (e.g., 31 December). In previous revisions, migration accounting for some countries alternatively used an “even over period” assumption wherein half of net migration was added at the beginning of each projection cycle and half at the end, thereby including a portion of the net migration in exposures to fertility and mortality. Within the 5x5 framework, the “even over period” assumption option was needed to better approximate exposures over five-year periods. Given the shorter projection cycles in the 1x1 framework, the “end of period” migration assumption is sufficient to approximate exposures for all countries and is preferred since the simpler implementation facilitates the recovery of benchmark populations, as well as the balancing of net migration across countries such that the world total sums to zero for all periods.

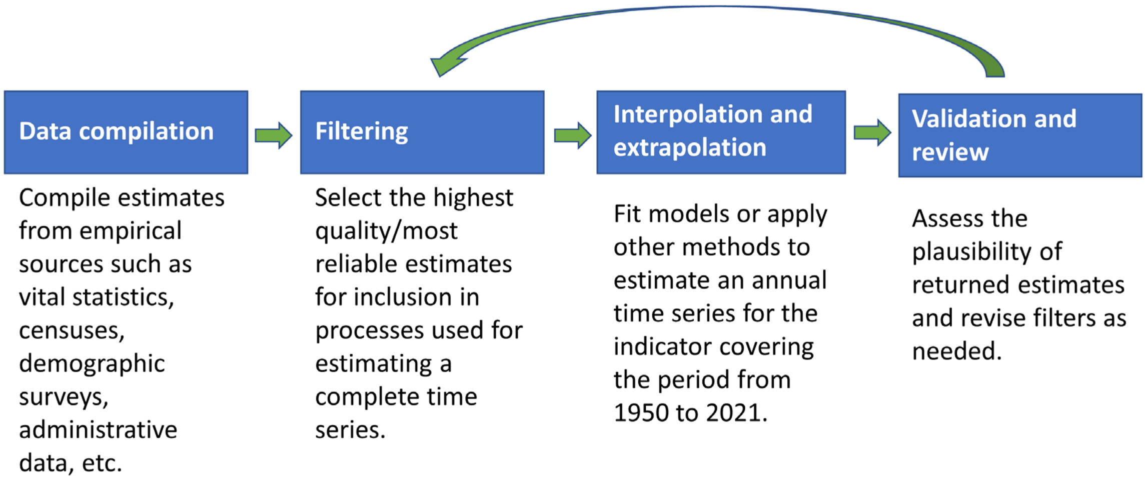
Previous revisions of the *World Population Prospects* did not explicitly compute population exposures – that is, the number of person-years lived in each interval of time. Consequently, it was not possible to recover the vital rates (i.e., age-specific fertility and mortality) from the published estimates and projections of vital events and populations. For the *2022 Revision*, population exposures by sex and age were computed and published as a separate indicator from population counts. Together with counts of vital events, the population exposures by single year of age can be used to recover the age-specific fertility and mortality rates that were input to the CCMPP. The use of the “end of period” migration assumption in the *2022 Revision* means that the exposures are not equivalent to the mid-year population. Rather, population exposures are approximately equal to the mid-year population without international migration.

The addition of the population exposures indicator obviated the need for special procedures to compute summary fertility and life table indicators for geographic aggregates. In previous revisions, indicators like the total fertility rate and the life expectancy at birth were estimated for regions or other country-groupings by taking the average of the country-level figures, weighted according to population size (by age and sex as applicable). In the *2022 Revision*, aggregate age-specific fertility rates were computed by dividing aggregated (summed) births by mothers' single-year of age by aggregated exposures of women by age. Total fertility and other fertility indicators for the country grouping were then derived from those age-specific fertility rates. Similarly, aggregate age-specific mortality rates by single year of age were computed by dividing aggregated deaths by age and sex by aggregated sex- and age-specific person-years of exposure. Complete life tables and related indicators were then derived from those mortality rates.

The CCMPP requires as inputs a full annual time series of key demographic indicators, including the total fertility rate and associate age-specific fertility rates by single year of age, the sex ratio at birth, mortality rates by sex and single year of age, and counts of net international migration by sex and single year of age. The processes used to estimate the time series vary according to the indicator, but a common general approach was applied (figure I.2). In brief, that approach entailed first compiling all available empirical data, such as from vital statistics, censuses, demographic surveys, administrative data or other sources. Next, those estimates were filtered or weighted according to their quality or reliability for inclusion in later steps. Once a preliminary set of empirical estimates was identified for the given country, models or other methods were applied to reconcile the series and interpolate or extrapolate for periods without empirical observations. In a final step, the returned time series was reviewed for plausibility and consistency. If indicated by this assessment, analysts returned to the filtering step to further refine the reference data set used to estimate the time series for the specific demographic indicator.

Figure I.2

Workflow to estimate a full annual time series of each demographic indicator from 1950-2021



Upgrades to the data information systems used by the Population Division were key to the improvements implemented in the *2022 Revision*. Those systems include: (a) an inventory of available data (DataCatalog), (b) a repository (DataArchive) of input data sources, (c) a database (DemoData[5]) to store and update the information used in preparing estimates of population estimates and of the components of population change (fertility, mortality, migration), (d) a structured set of metadata used for data analysis, statistical modelling and public documentation (ShortNotes), and (e) a dissemination platform (DataPortal[6])

---

[5] https://popdiv.dfs.un.org/DemoData/web/

[6] https://population.un.org/dataportal/

to give access to all output and input data in tabular form, as well as to provide tools for creating interactive visualizations and to query data via an open Application Programming Interface (API)[7].

In collaboration with various academic researchers and contributors, a full suite of new R libraries was developed for the *2022 Revision* to perform various demographic computations and analyses in a more transparent way. These include libraries that: dynamically query the DemoData open API[8]; standardize and harmonize empirical counts of population, deaths and births to streamline the analyses of fertility and mortality, and to evaluate and adjust population censuses; estimate intercensal net migration and compute age and sex distributions of net migration; and apply the CCMPP by single years of age and on-year periods time.

The sections that follow describe the specific methods applied to estimate the annual time series of demographic indicators required by the CCMPP.

B. ESTIMATING TOTAL FERTILITY, AGE-SPECIFIC FERTILITY AND THE SEX RATIO AT BIRTH

In the *2022 Revision*, Bayesian hierarchical models were used to estimate the annual time series of total fertility, age-specific fertility and the sex ratio at birth from 1950 through 2021 for all countries. These models incorporated available empirical evidence from vital statistics, population censuses and demographic surveys. The data used and model specifications for each indicator are described below.

1. Data availability

The preferred source of data on fertility is counts of live births, by age of mother, from a system of civil registration with national coverage and a high level of completeness (United Nations, 2014a). In cases where the registration of births is deficient or lacking, fertility estimates are typically obtained through sample surveys. Demographic sample surveys may provide estimates of fertility by asking women detailed questions to obtain their complete childbearing histories, or just summary information about the total number of children ever born. Current global survey programmes collecting detailed birth histories include the Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS)[9]. Separate from the global programmes, some countries field their own national demographic surveys and a few have established sample vital registration systems. Population censuses serve as additional sources of information on fertility through questions about the number of children ever born. Moreover, the census population counts themselves can be used to estimate total fertility by the "reverse survival" method (Moultrie and others, 2013).[10] For most countries, recent direct or indirect information on fertility was available to inform the *2022 Revision*. Among the 236 countries or areas with 1,000 inhabitants or more in 2021, all but 32 had available data on fertility collected in 2017 or later. For 28 countries, the most recent data were collected between 2012-2016, and only for 4 the most recent national data were from 2010 (Eritrea, Micronesia (Fed. States of), South Sudan) and 2009 (Syrian Arab Republic). The metadata

---

[7] See DataPortal open API user guide (https://population.un.org/dataportal/about/dataapi) for R and Python tutorials and technical documentation.

[8] See DemoData open API documentation (https://popdiv.dfs.un.org//Demodata/swagger/ui/index#) and DDSQLtools R package (Riffe and others, 2022b) to query empirical data for selected locations and indicators using R.

[9] Fertility estimates from some other international survey programs were also considered, for example the Performance Monitoring and Accountability (PMA) surveys. Other international survey programs that provided fertility estimates in decades prior to 2010 included the World Fertility Survey (WFS), the Contraceptive Prevalence Surveys (CPS), the Reproductive Health Surveys (RHS), and the Pan-Arab Project for Family Health (PAPFAM).

[10] For the 2022 Revision, the reverse survival method was implemented using the fertestr package for R (Lima and Monteiro da Silva, 2021).

associated with the *2022 Revision*, available online, provides further details about the specific fertility data that were used for each country[11].

2. *Total fertility*

Total fertility is the mean number of children a woman would have by age 55 if she survived to age 55 and were subject, throughout her life, to the age-specific fertility rates observed in a given year. It is expressed as the number of children per woman. For the *2022 Revision*, an annual time series of total fertility from 1950 to 2021 was estimated for each country using a Bayesian hierarchical model, built on the theoretical model used by the United Nations to model fertility change. That model takes into account the biases and uncertainty associated with empirical estimates from different types of data sources, direct and indirect estimation methods, and other factors that contribute to systematic biases and non-sampling errors (Liu and Raftery, 2020). Estimates were computed using an updated version of bayesTFR (Ševčíková and others, 2022a). The data used by the model to estimate and correct for biases are country specific. As a baseline reference the model uses either the estimates from the previous revision of the *World Population Prospects* or some other data source(s) deemed unbiased by the analyst. The model takes into account two types of data characteristics: (1) several time-invariant categories that describe the type of data source (e.g., census, survey, vital registration), the type of estimation method (e.g., recent births, birth histories, adjusted fertility using P/F ratio method, own-children or reverse survival estimates, etc.), and the corresponding education level for estimates based on the reverse survival of enrolled school children , and (2) several time-dependent covariates such as the number of years of recall lag for retrospective estimates, the proportion of live births registered for vital statistics, the school enrolment rate for indirect estimates from education statistics, and the proportion of deaths due to conflicts or natural disasters one year prior.

Fertility from vital registration were used only for country-years with at least 60 per cent completeness of birth registration (Preston, 1984). Fertility time series for countries with at least 98 per cent completeness of birth registration since 1950 were treated as unbiased.

For each country, the median estimate of total fertility was based on a sample of 2,000 trajectories of the model fitted to the observed data after taking into account the various types of biases. For selected countries and periods, additional adjustments to the posterior distributions returned by the model were applied to constrain the median estimate to reflect the fluctuations in the sizes of specific birth cohorts as enumerated in successive population censuses.[12]

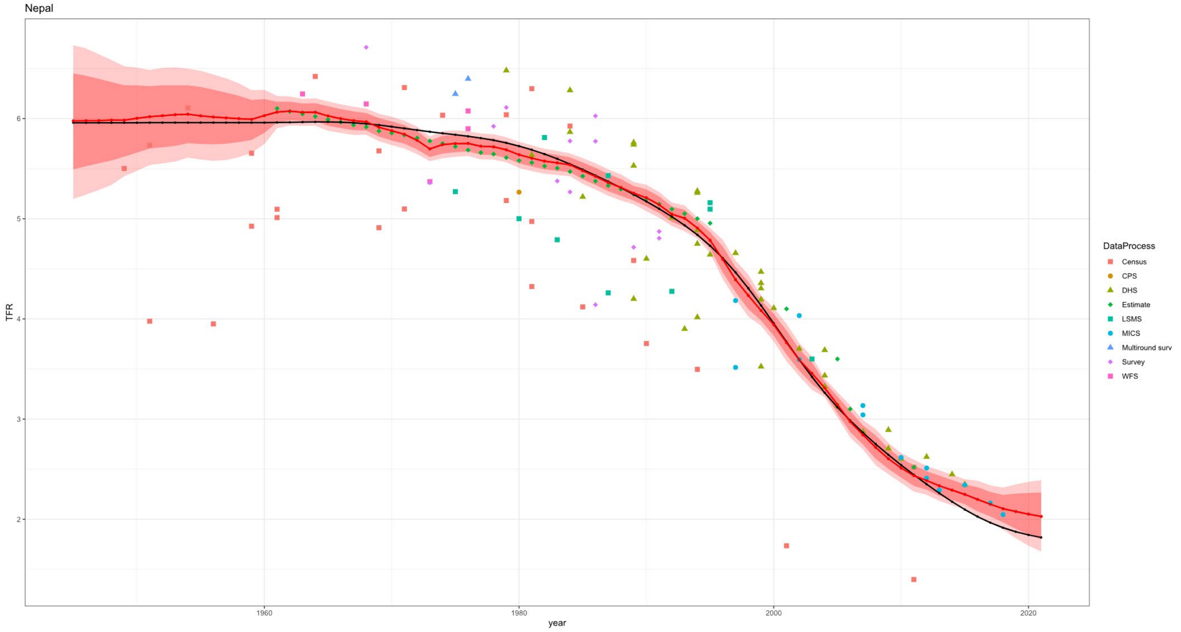
The results of the total fertility estimation for Nepal are shown in figure I.3. The shapes represent the cloud of empirical data points from censuses and surveys, the red line traces the annual time series of total fertility estimates for the *2022 Revision*, the red shaded areas represent the 80 and 95 per cent uncertainty intervals surrounding those estimates, and the black line shows the annually interpolated total fertility estimated for the *2019 Revision*.

---

[11] https://population.un.org/wpp/Download/Metadata/Documentation/

[12] The adjustment for a country and time period corresponds to the ratio between the unadjusted median TFR and adjusted median TFR, and is applied to each TFR probabilistic trajectory for the corresponding country and period.

Figure I.3
Total fertility estimation for Nepal, 1950 to 2021



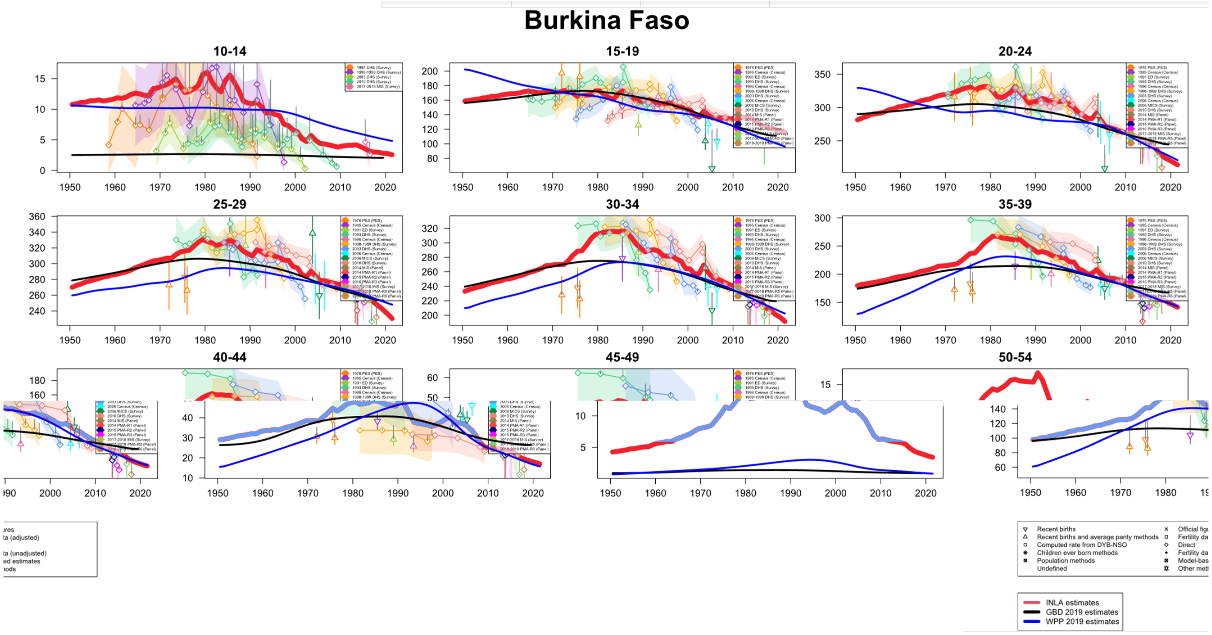
3. *Age-specific fertility*

Age-specific fertility rates (ASFR) describe the number of births per woman at each age. For the *2022 Revision*, ASFR was estimated by single year of age from 10 years to 54 years. Three main steps were implemented to derive ASFR estimates for each country.

First, for each five-year age group from 15 to 49 years, the logit-scaled fertility rate was estimated through a Bayesian hierarchical time series model fit to empirical estimates of the fertility rate from vital statistics and demographic surveys, and additionally considering the level of female educational attainment and the total fertility rate (Chao, 2022). As for the total fertility, age-specific fertility from vital registration was used only for country-years with at least 60 per cent completeness of birth registration, and rates were adjusted by the reciprocal of the proportion of registered births (Preston, 1984).

For each country, the median estimate was based on a sample of 10,000 trajectories of the model fitted to the observed data after taking into account the various types of biases. Most countries had little, if any, empirical data for age groups 10-14 and 50-54, thus the estimation process for these ages additionally assumed a correction with neighbouring age groups (e.g., to estimate fertility rates for ages 10-14, the model predictions for ages 15-19 were used as covariates, and to estimate fertility rates for ages 50-54 the model predictions for ages 45-49 were used as covariates). Model estimates of fertility rates for each five-year age group for Burkina Faso are shown in figure I.4.

Figure I.4
Estimation of age-specific fertility rates for Burkina Faso, 1950 to 2021



Once the full annual time series of fertility rates by five-year age group of mothers was obtained through the modelling process, a second step was implemented to graduate those rates to single year of age via the Calibrated Spline (CS) method (Schmertmann, 2014). It identifies a smooth curve of single-year ASFR based on fit to the five-year fertility rates as well as similarity to known single-year fertility rates. For the *2022 Revision*, the Population Division assembled a set of empirical single-year fertility rates, representing a diverse range of fertility age patterns, to calibrate the CS model. That set included fertility rates by single year of age from vital statistics disseminated through the Human Fertility Database, EuroStat vital statistics, and the Human Fertility Collection. These sources provided more than 4,000 time series of single-age fertility rates for 71 countries, covering ages 12 to 54 years and time periods from 1891 to 2018. In addition, the calibration data set included 451 full birth history time series compiled from demographic surveys, including the Demographic and Health Surveys, Multiple Indicator Cluster Surveys, World Fertility Surveys, and others (Schoumaker, 2013)[13], as well as 72 series of single-age fertility rates from 30 Health and Demographic Surveillance System sites[14]. These supplementary data came from 108 countries, including many in sub-Saharan Africa and Central and Southern Asia that otherwise would not be represented in the calibration given that they lack reliable vital registration data. Prior to their use in calibrating the CS model, single-age fertility rates from surveys were smoothed via a principal component analysis and cubic spline interpolation (Pantazis and Clark, 2018; Schoumaker, 2020). For each country, graduation models were fit to the range of 5-year age groups used for the input empirical fertility rates for each country (15 to 49 years, 10 to 49 years, or 10 to 54 years, based on data availability and reliability). Results provided single-age fertility rates for ages 12 through 54. For the subset of countries with high completeness of birth registration and high-quality empirical time series of single age fertility rates, empirical age distributions were used in lieu of graduated age patterns. The metadata associated with the *2022 Revision*, available online, provides further details about the graduation model used for each country.[15]

---

[13] Rates were computed using the tfr2 stata module for the period spanning 10 years before each survey.

[14] Rates were computed using public use microdata available from the INDEPTH-iSHARE repository (https://www.indepth-ishare.org/) and processed with the tfr2 module for Stata.

[15] https://population.un.org/wpp/Download/Metadata/Documentation/

The third and final step in estimating ASFR entailed adjusting the graduated rates, as needed, for consistency with the total fertility in each year. That is, the single-year ASFR in each year were proportionally adjusted such that the sum over age of the single-year ASFR was equal to the total fertility in each period.

4. Sex ratio at birth

The sex ratio at birth (SRB) is defined as the ratio of male to female live births and, in most populations, is fairly stable within the range of 1.03 to 1.07, with some small variations by ethnicity (Chahnazarian, 1988; Dubuc and Coleman, 2007; Garenne, 2002, 2008; Graffelman and Hoekstra, 2000; James, 1984, 1985, 1987; Kaba, 2008; Ruder, 1985; Marcus and others, 1998; Mathews and Hamilton, 2005; Visaria, 1967). In some populations, however, the observed SRB is well above this range because of sex-selective abortion, driven by the concomitant preference for sons over daughters, along with readily available technology of prenatal sex determination, and fertility decline. For the *2022 Revision*, SRB for all countries was estimated for 1950 to 2021 and projected from 2022 to 2100 using a Bayesian hierarchical time series mixture model (Chao and others, 2019, 2021). The model takes into account the stochastic variation in empirical time series of SRB, as well as the uncertainty associated with SRB estimates.

C. ESTIMATING MORTALITY RATES AND LIFE TABLES

Whereas the *2022 Revision* used a common approach across all countries to estimate the key indicators of fertility required for the CCMPP, the methods used to estimate mortality and life tables varied across countries depending on the type and quality of available empirical data. These methods can be described according to two main types: "empirical" and "model based." The empirical approach was used for countries with reliable information to describe sex- and age-specific mortality rates from vital registration or estimates across a substantial part of the estimation period from 1950 to 2021. The model-based approach was used for countries that lacked sufficient information for the empirical approach. The metadata associated with the *2022 Revision*, available online, provides further details about the data and approach used to estimate mortality rates and life tables for each country. [16]

1. Estimation for countries with long historical series of high-quality vital rates ("empirical")

For 113 countries, mortality rates derived from vital registration or estimates were deemed of sufficient quality and reliability to use to estimate the time series of sex- and age-specific mortality rates. The sources of empirical information on sex- and age-specific mortality are described in table I.2. The Human Mortality Database supplied 5,150 country-years of data, comprising close to half (44 per cent) of the empirical series incorporated in the *2022 Revision*. Another 5,079 country-years (43 per cent) came from deaths reported through vital registration systems. The remaining 13 per cent of empirical mortality data were obtained from other collections of estimates or vital registration.

To estimate a full annual time series of mortality rates by sex and single year of age from 1950 to 2021, analysts variously implemented the following procedures, depending on the specifics of the data availability and quality for each country:

a) Adjust under-five mortality rates for consistency with the estimates published by IGME in 2021 (United Nations. Interagency Group for Child Mortality Estimation, 2021)

---

[16] https://population.un.org/wpp/Download/Metadata/Documentation/

b) Adjust mortality rates according to the estimated completeness of adult vital registration in each year.
c) Smooth empirical mortality rates over time by computing a moving average with 3-, 5- or 7-year windows.
d) If empirical series is abridged, graduate to single year of age using the lt_abridged2single() function of the DemoTools R package (Riffe and others, 2022a).
e) Interpolate across any gaps in the time series using the Limited Lee-Carter method (Li and Lee, 2004) implemented through the interp_lc_lim() function of the DemoTools package.
f) Extrapolate back to 1950 or forward to 2021, as needed, using the Lee-Carter method adapted for non-sequential or sparse data.
g) Adjust old-age mortality using an extrapolation law (e.g., Kannisto, Gompertz, Makeham) or in relation to mortality rates estimated in the Human Mortality Database.
h) Smooth the time series over age-period or age-period-cohort.
i) Extend to open ended age group 130+ using the DemoTools life table function, which in turn utilized the MortalityLaws R package.
j) Add any crisis mortality impacts (see section I.C.3).

Table I.2
Country-years of empirical data for sex- and age-specific mortality rates, by data source and data process

Data Source	Data Process	Country-years	Per cent
Human Mortality Database	Estimate	5,150	43.86
Vital registration	Vital registration	5,079	43.25
EuroStat	Vital registration	416	3.54
Human Lifetable Database	Estimate	277	2.36
Other estimates	Estimate	190	1.64
UN Demographic Yearbook	Vital registration	177	1.51
Other vital registration	Vital registration	127	1.08
Sample registration System	Vital registration	88	0.75
World Health Organization Database	Estimate	82	0.70
Global Burden of Disease 2016	Vital registration	78	0.66
LAMBdA 2019	Estimate	78	0.66

2. *Estimation for countries with sparse or deficient mortality data ("model-based")*

For 124 countries, empirical mortality rates by sex and age were too sparse or of insufficient quality to estimate the complete annual time series of mortality rates. Instead, model life tables were used to estimate the mortality rates by single year of age across the full age range from 0 to 130+ and for years 1950 through 2021. These models require one or more mortality indicators as inputs to match a mortality level and age pattern. Each model life table requires at minimum one parameter that describes the mortality rate among children (e.g., the under-five mortality rate) or overall (e.g., the life expectancy at birth). An additional parameter that describes mortality among adults is useful to further inform the choice of a model that best describes the true mortality age pattern in a given country and year, especially when levels and trends for children and adults change differently over time. In order to supply the parameters needed to identify appropriate model life table age patterns of mortality, complete annual time series of child and adult mortality from 1950 to 2021 were estimated for each country.

a. Mortality at ages under 5

Similar to estimates of fertility, estimates of child mortality, measured by the probability of dying between birth and age five, can be derived from direct or indirect questions in surveys or censuses when reliable data from civil registration are not available. For child mortality, the available information is largely up to date. Among the 236 countries or areas with 1,000 inhabitants or more in 2021, the most recent available child mortality data referred to 2017 or later for 195 countries, 2012 to 2016 for 24 countries and 2007 to 2011 for another 8 countries. Three locations lacked child mortality data after 2006 (Gibraltar, Northern Mariana Islands, Wallis and Futuna Islands), and six locations had no child mortality data at all over the period 1950 to 2021 (Bonaire, Sint Eustatius and Saba; Guernsey, Jersey, Saint Helena, Tokelau, Western Sahara).

However, despite the availability of recent data in the vast majority of countries, the quantity and consistency of data available to cover the entire estimation period from 1950 to 2021 varied greatly across countries. In preparing estimates of child mortality for the *2022 Revision*, the Population Division coordinated closely with the United Nations Inter-agency Group for Child Mortality Estimation[17] (IGME), which is led by UNICEF.

b. Mortality between ages 15 and 60

Compared to information on fertility and child mortality, information on adult mortality was sparser, more likely to be outdated, or, for a few countries, lacking altogether. Estimates of adult mortality were derived from complete data on registered deaths by age and sex whenever possible. In other cases, analysts evaluated data from incomplete registration; from questions on household deaths by age and sex, usually for a 12-month period before a census or survey; or from questions on the survival of the siblings of respondents in demographic surveys. Among the 236 countries or areas with 1,000 inhabitants or more in 2021, the most recent available adult mortality data referred to 2017 or later for 165 countries, 2012 to 2016 for 17 countries, and 1998 to 2011 for 9 countries. No empirical data on adult mortality were available for seven locations (Bonaire, Sint Eustatius and Saba; Guernsey, Jersey, Monaco, Saint Helena, Tokelau, Western Sahara).

A Bayesian hierarchical model was used to estimate, for each sex, the probability of dying between ages 15 and 60 years (Chao, 2022). Observed adult mortality was modelled on the logit scale to ensure that its value was bounded between 0 and 1. In addition to the empirical observations of adult mortality, the model took into account the prevalence of HIV infection, the coverage of antiretroviral therapy and the under-five mortality rate. For the under-five mortality rate, the model considered a non-linear regional effect on the associations between child and adult mortality. This approach facilitated estimation of adult mortality for countries with limited or no empirical observations by assuming that that the associations between child and adult mortality were similar to that observed in neighbouring countries. For countries with vital registration statistics, only years with at least 60 per cent completeness of death registration were included in the analysis, and rates were adjusted by the reciprocal of the proportion of registered deaths (Preston, 1984). For each country, the median estimate was based on a sample of 10,000 trajectories of the model fitted to the observed data after taking into account the various types of biases. By default, data points for years in which significant mortality crises occurred (crude death rates due to mortality crises of 5 or more deaths per 1000 persons) were excluded, and the model was fitted on the remaining data. Crisis mortality was added back by age and sex when computing life tables (see section I.C.3). As with the models

---

[17] The IGME database, including the complete set of available empirical data used to construct the latest global estimates of under-five mortality, is available at www.childmortality.org.

previously described for total fertility, age-specific fertility and the sex ratio at birth, the adult mortality models model the measurement error to reflect the uncertainty resulting from the survey sampling design for data from surveys and censuses and stochastic uncertainty from administrative records for vital registration data, as well as non-sampling errors that may arise due to non-response, recall bias, or data input errors.

c. Model mortality patterns

Analysts selected from several types of model life table patterns in order to estimate sex- and age-specific mortality rates. For 59 of the 124 countries for which model-based patterns were used, analysts drew from the Coale-Demeny or United Nations families of model life tables (Coale and others, 1983; Coale and Guo, 1989; United Nations, 1982), which the Population Division extended to advanced life expectancies (United Nations, 2011) and graduated to single year of age (see annex). The number and type of mortality indicators used to match the model life table patterns depended on the quality of empirical mortality indicators available for each country. For 11 countries, the model life tables were matched to the under-five mortality rate alone. For 17 countries, the models were matched to two parameters: under-five mortality and the probability of dying between ages 15 and 60. For another 16 countries, the models were matched to three parameters: infant mortality, under-five mortality, and the probability of dying between ages 15 and 60. For the remaining 15 countries – mostly those with very small populations – the time series of child and adult mortality were not reliable or stable enough to inform mortality age patterns, so the models were instead matched to estimates of the life expectancies at birth, by sex.

For 43 countries, the mortality age patterns were modelled using the Logistic-Quadratic (LogQuad) relational life table approach (Wilmoth and others, 2012), with both child and adult mortality parameters as inputs. This method was implemented using procedures available in the DemoTools R package. First an abridged life table was estimated using the lt_model_lq() function and then that life table was graduated to single year of age using the lt_abridged2single() function.

d. Special considerations for countries highly affected by HIV and AIDS

The general approach described above for deriving estimates and projections of mortality is not appropriate for countries whose recent mortality patterns have been significantly affected by the HIV and AIDS epidemic. The particular dynamic of HIV and AIDS and the severity of its outcome require explicit modelling of the epidemic. Unlike other infectious diseases, HIV has a very long incubation period during which an infected person is mostly symptom-free but still infectious. Also, unlike many other infectious diseases, individuals do not develop immunity, but, in the absence of treatment, almost always die as a consequence of their compromised immune system. Another reason for an explicit modelling of the HIV and AIDS is the avalanche-like process of the infection spreading through a population and the particular age pattern of infection exhibited. The additional deaths due to HIV and AIDS occur predominately among adults in their reproductive ages and, consequently, distort the usual U-shaped age profile of mortality. This atypical age pattern cannot be found in the model life tables that are available to demographers (Heuveline, 2003).

The *2022 Revision* made explicit modelling assumptions to incorporate the demographic impact of the HIV and AIDS epidemic on the mortality age patterns for 21 countries that had experienced generalised HIV epidemics (table I.3). The approach made us of a singular value decomposition (SVD-Comp) model (Clark, 2019) that was calibrated to a reference set of life tables that represented the relationship between summary indicators of child and adult mortality, adult HIV prevalence, the coverage of ART, and the mortality pattern across the full age range (Houle and others, 2022). Specifically, the reference data set combined the set of empirical life tables from countries with high-quality historical mortality data (such as the HMD) with a collection of simulated life tables computed using the model developed by the UNAIDS Reference Group on Estimates, Modelling and Projections (Stanecki and others, 2012; Stover and others, 2012; Stover and others, 2014). The simulated life tables represented a range of values for sex-specific adult HIV prevalence and coverage of antiretroviral therapy.

Table I.3

HIV prevalence rates and ART coverage among adults aged 15-49 years in 2019 for countries for which explicit modelling of HIV and AIDS was employed in the *2022 revision* (percentages)

	Adult HIV prevalence (percentage)		*Adult ART coverage (percentage)*	
Country	*Male*	*Female*	*Male*	*Female*
Botswana	16.5	25.1	70.7	93.2
Cameroon	2.0	4.2	56.2	67.1
Central African Republic	2.8	4.2	33.8	53.5
Congo	1.8	4.4	23.4	26.7
Côte d'Ivoire	1.5	3.3	53.5	70.9
Equatorial Guinea	6.0	9.0	18.4	51.8
Eswatini	18.0	35.6	90.3	99.8
Gabon	2.0	5.1	51.9	52.9
Guinea-Bissau	2.6	4.1	21.6	55.5
Kenya	3.2	5.8	64.9	80.4
Lesotho	17.9	27.9	57.3	70.6
Liberia	1.2	1.9	20.9	42.9
Malawi	7.0	10.8	66.8	86.9
Mozambique	9.5	15.2	46.3	67.4
Namibia	8.4	14.5	76.0	89.4
Rwanda	1.9	3.2	85.0	91.4
South Africa	12.9	25.0	62.8	74.9
Uganda	4.3	7.1	76.5	90.6
United Republic of Tanzania	3.6	6.0	63.2	83.2
Zambia	8.9	14.0	78.7	90.4
Zimbabwe	10.1	80.2	15.4	89.2

Source: UNAIDS (2019) (unpublished tabulations made available in June 2020).
See also: https://population.un.org/wpp/Download/Files/4_Metadata/WPP2022_F01_LOCATIONS.XLSX

3. *Accounting for excess mortality due to crises*

The 1x1 framework adopted for the *2022 Revision* necessitated a reassessment of the demographic impact of the various crisis that have occurred around the world over the period from 1950 to 2021. The Population Division re-evaluated all empirical data points to identify whether and how crisis effects were reflected in the estimates. Altogether the mortality effects of almost 7,000 crisis-years were identified and accounted for in producing the annual time series of estimated mortality rates. Types of crises include conflicts and battles, mass killings, flooding, cyclones, epidemics, earthquakes, the COVID-19 pandemic, famines, droughts and tsunamis

Empirical mortality rates by age and sex from vital registration were used to estimate mortality during crisis-affected periods if two conditions were met: (1) 100 per cent of deaths were registered; and (2) no smoothing over time was applied to the data input to or output from the empirical estimation process described in section I.C.1.

For the remaining countries estimates of excess mortality by age and sex due to crises or shocks was added on top of the sex- and age-specific mortality rates estimated through the processes described in sections I.C.1 and I.C.2. The approach relied on two sets of information: (1) annual time series of total estimates of deaths by type of mortality crisis for each country or area, and (2) distributions by age and sex of crisis deaths by type of mortality crisis based on some model assumptions.

For the first set of information, the Population Division consolidated global datasets that described the number of deaths due to: (1) conflicts, including wars, mass killings (including genocides), battle deaths, etc. and (2) natural disasters, such as floods, cyclones, epidemics, earthquakes, famines, droughts and tsunamis. Table I.4 provides a summary of the major data sources used. Other sources were also considered[18]. From the consolidated data, estimates of the number of deaths from each crisis event by country and year were computed, with associated uncertainty bounds[19]. Various analytical methods were applied to reconcile overlaps across different data sources, gaps and discontinuities due to changes in definitions or territorial boundaries of countries, non-annual reference periods, and sources that provided a broad range of crisis-related deaths rather than a point estimate, among other challenges.

Annual time series of excess mortality due to crises were compiled for 6,945 location-years over the period 1950 to 2021 (representing about 41 percent of all 237 countries or areas over the 71 years). The distribution of location-years by major type of mortality crises is as follows:

- Conflicts and Battle deaths: 2,355 location-years (171 locations)
- Mass killings (including genocide): 95 location-years (18 locations)
- Floods: 2,323 location-years (162 locations)
- Cyclones: 1,605 location-years (169 locations)
- Epidemics (not including HIV/AIDS and COVID-19): 1,988 location-years (152 locations)
- Earthquakes: 1,143 location-years (124 locations)
- COVID-19: 431 location-years (218 locations)
- Famines/Droughts: 160 location-years (32 locations)
- Tsunami: 45 location-years (25 locations)

The mortality effects of conflicts and natural disasters tend to be most acute in countries that lack high-quality vital registration. Moreover, crises sometimes disrupt normal death registration processes such that estimates of crisis deaths are not available by age and sex. For the second set of information required to estimate sex- and age-specific crisis mortality rates, a literature review was conducted to inform a set of model age-sex patterns of crisis deaths by type of event. These model patterns were used to distribute the total deaths due to each crisis by sex and age.

---

[18] The list of supplementary sources includes: Altez and Revet (2005); Arnold (2019); Devereux (2000); Doocy and others (2013); Gráda (2007; 2009); Harff (2017); Hunter College (2018); IHME (2020); Kane (1988); Kishore and others (2018); Li and Yang (2005); (2019); Rummel (1999); Santos-Lozada and Howard (2018); Silva and Ball (2006); Valentino (2004);World Peace Foundation and Tufts University (2020); Yang (2013); Zwierzchowski and Tabeau (2010).

[19] It is worth noting that for various types of crises many locations experience more than one of these events in a given year, especially in respect to the impact of natural disasters. Therefore, one crisis-year for a given location corresponds to the sum of all deaths attributed to a specific type of crisis during that calendar year (e.g., 6453 people died in India in 2013 due to five floods).

Table I.4
Global databases on mortality crises

Type of events	Name	Unit of measure	Timeframe	Geographic coverage	Type of estimates	Periodic updates
Natural disasters	**EM-DAT** / The International Disaster Database[20]	Country-event	1900-2021	Worldwide	Point estimates	Weekly
COVID-19	European Centre for Disease Prevention and Control - Data on 14-day notification rate of new COVID-19 cases and deaths (**ECDC**)[21]	Country-week-event	2020-2021	Worldwide	Point estimates	Weekly
COVID-19	World Mortality Database (**WMD**)[22]	Country-week/month-event	2020-2021	Worldwide	Point estimates	Daily
COVID-19	World Health Organization (**WHO**) - Excess mortality associated with COVID-19[23]	Country-year-age-sex-event	2020-2021	Worldwide	Low, high and point estimates	Twice yearly
Cholera (epidemics)	World Health Organization (**WHO**)[24]	Country-year-event	1949-2016	Worldwide	Point estimates	Yearly until 2016
Conflicts and genocides	CSP/INSCR. Political Instability Task Force (**PITF**) - State Failure Problem Set: Internal Wars and Failures of Governance, 1955-2018[25]	Country-year-event	1956-2018	Worldwide	Intervals only. No point estimates.	Yearly until 2019
Conflicts	UCDP Georeferenced Event Dataset (**GED**) Global version 21.1[26]	Country-year-event	1946-2020	Worldwide	Low, high and point estimates	Yearly in June
Battles	UCDP/PRIO Armed Conflict Dataset (**ACD**) version 21.1[27]	Country-year-event	1946-2020	Worldwide	Intervals only. No point estimates.	Yearly in June
Battles	PRIO Battle Deaths Dataset (**BDD**), version 3.1.[28]	Country-year-event	1946-2008	Worldwide	Low, high and point estimates	No planned update
Conflicts and battles	Armed Conflict Location & Event Data Project (**ACLED**)[29]	Country-day-event	1997-2021	Selected regions	Point estimates	Daily

To develop the model age-sex patterns of crisis mortality, the Population Division and UNICEF assembled a comprehensive database of age-sex distributions of crisis death rates. Sources included crisis mortality studies, as well as empirical data from population surveys and death registration. Average relative risks of mortality by age and sex were estimated for nine categories of crisis events (battle deaths, conflicts, genocide (including mass killings), cyclones, earthquakes, epidemics, famine/droughts, floods, Tsunami). Age-sex mortality distributions were compiled for 159 crisis events in 54 countries: 40 conflicts, 4

---

[20] https://public.emdat.be/
[21] https://www.ecdc.europa.eu/en/publications-data/data-national-14-day-notification-rate-covid-19
[22] https://raw.githubusercontent.com/akarlinsky/world_mortality/main/world_mortality.csv
[23] https://www.who.int/data/stories/global-excess-deaths-associated-with-covid-19-january-2020-december-2021
[24] https://apps.who.int/gho/data/node.main.176?lang=en
[25] http://www.systemicpeace.org/inscrdata.html
[26] https://ucdp.uu.se/downloads/index.html#ged_global
[27] https://ucdp.uu.se/downloads/index.html#armedconflict
[28] http://www.systemicpeace.org/inscrdata.html
[29] https://acleddata.com/data-export-tool/

genocides, 3 cyclones, 32 earthquakes, 29 epidemics, 32 famines, 10 floods and 9 tsunamis from 74 data sources covering the period 1348-2019, with 64 per cent since 1950 and 37 per cent since 2000. Statistical models (Seemingly Unrelated Regression with bootstrap resampling) were fitted to these empirical series to derive a standard set of age-sex distributions for nine types of crisis events.

The analytical strategy used to incorporate the impact of each mortality crisis in the *2022 Revision* was aligned with the approaches used by the UN-IGME[30] and WHO/GBD[31] to account for mortality crises and shocks:

1. For each type of major event, use the total number of deaths (and lower/upper bound for probabilistic methods) attributable to the specific type of crisis.
2. Compute the overall crisis crude death rate for this type of crisis using the total population.
3. Apply the model-based age-sex mortality rates for this type of crisis (in standard population) to the associated population by age-sex for this year and get a total crisis death rate for above age-specific death rates in target population.
4. Compute an adjustment factor to match actual crisis death rate (i.e., ratio of the crisis CDR from step 2 by crisis CDR from step 3) to factor the difference of population age distributions between the target location and the standard population used to compute the model-based mortality pattern.
5. Rescale the model-based age-sex mortality rates for this type of crisis by applying the adjustment factor from step 4 to get the age-sex specific death rates (and uncertainty) for this type of crisis in target population.
6. Repeat the process from steps 1 to 5 for each type of mortality crisis occurring during a given period of time.
7. Aggregate the excess mortality rates by age-sex from the various types of mortality crises (using the results from step 6).
8. Add excess mortality rates (from step 7) to normal background mortality rates by age-sex.
9. Graduate into single age the mortality pattern by abridged age group (from step 8) using a piecewise cubic Hermite interpolating polynomial function.

4. *Accounting for excess mortality due to the COVID-19 pandemic*

At the time the *2022 Revision* was finalised, the COVID-19 pandemic was ongoing. Moreover, the incomplete data in many countries on the mortality levels and patterns experienced during the pandemic-affected years was incomplete. Consequently, there was great uncertainty surrounding the impact of the pandemic around the world. On 5 May 2022, the World Health Organization published estimates of "excess mortality" by country for the period from 1 January 2020 through 31 December 2021. For many countries, these estimates indicated sizable increases in deaths associated with the pandemic, including those directly attributable to the virus itself as well as those attributable to other causes but that would not have occurred without the detrimental effects of the pandemic on healthcare systems and patient access to care. In other countries where the spread of COVID-19 was limited due to lockdowns or other measures, some potential causes of death had been reduced (e.g., those related to air pollution, traffic injuries or infectious diseases like influenza), resulting in fewer deaths than would have been expected without the pandemic (Knutson and others, 2022; Karlinsky and Kobak, 2021).

---

[30] https://childmortality.org/wp-content/uploads/2021/12/UNICEF-2021-Child-Mortality-Report.pdf

[31] https://www.who.int/docs/default-source/gho-documents/global-health-estimates/ghe2019_life-table-methods.pdf?sfvrsn=c433c229_5

For most countries, to account for the excess mortality (positive or negative) related to the COVID-19 pandemic sex- and age-specific excess mortality rates during 2020 and 2021 were computed from the WHO's estimates of excess deaths by sex and age. These rates were then added to the baseline mortality rates estimated for 2020 and 2021 in the absence of a pandemic, consistent with the approach taken for other mortality crises.

D. ESTIMATING THE 1950 BASE POPULATION AND POPULATION BENCHMARKS

Recent population counts are critical for obtaining accurate estimates of population size and its composition by age and sex. The principal data source used for this purpose is the population census. Following the *UN Principles and Recommendations on Population and Housing Censuses* (United Nations, 2017b) most countries conduct a census about once per decade. Altogether, more than 1,750 censuses have been conducted worldwide since the 1950s, providing a wealth of data for the analysis and monitoring of population change.

In some countries, population registers based on administrative data systems are sufficiently well developed to serve as a basis for population estimates.

1. *Data availability*

At the global level, population data from censuses or registers referring to 2017 or later were available for 127 countries or areas, representing 54 per cent of the 237 countries or areas included in this analysis. For 45 countries or areas, the most recent available population count was from the period 2012-2016, and for another 50 locations from the period 2007-2011. For the remaining 15 countries or areas, the most recent available census data were from before 2007. These 15 countries (with date of last census) were Lebanon (1932), Afghanistan (1979), Democratic Republic of the Congo (1984), Eritrea (1984), Somalia (1987), Uzbekistan (1989), Iraq (1997), Central African Republic (2003), Haiti (2003), Syrian Arab Republic (2004), Yemen (2004), Cameroon (2005), Nicaragua (2005), Libya (2006), Nigeria (2006).

2. *Protocol for evaluation and adjustment of census populations*

Even the highest-quality population censuses may suffer from data quality problems that require some correction or adjustment to accurately represent the population size and age structure. Common data issues associated with censuses include under- or over-enumeration, age misstatement, including, for example, a digit preference for ages ending in zero or five, and the under-enumeration of very young children. To address these common errors in a systematic and standardized way, the Population Division developed and implemented a new protocol for the evaluation and adjustment of population census counts by age and sex. The main steps of that protocol are summarised below.

a. *Data series priorities*

For any given population census, there are often multiple sources of data available that detail the census population counts by age and sex. These may include census results reported to the Demographic Yearbook of the United Nations, tabulations published by National Statistical Offices, counts from microdata archived in the IPUMS collection, or other sources. The Population Division developed a series of procedures to standardize the census population information to the data structures required for the CCMPP workflow and to select the preferred data series from the available choices. In brief, the criteria prefer, in order of priority: counts disaggregated by single year of age over abridged age groups; higher data reliability assessment; *de* *facto* population over the *de jure*; a higher open-ended age group; official statistics reported to the Demographic Yearbook; and a more recent data source.

b. Coverage adjustments

When a population census does not cover the full territory of the population referenced for a country or area in the *World Population Prospects*, a coverage adjustment is required. This adjustment was implemented via a single adjustment factor that was multiplied by the census population counts by age and sex. Examples include the historical censuses of Pakistan, which were adjusted upwards to account for the population residing in the Pakistani-administered parts of Jammu and Kashmir, and the 1975 census of Yemen, which was adjusted to additionally include the population of South Yemen.

c. Under- or over-enumeration adjustments

Post-enumeration surveys, conducted following a population census, provide essential information on the degree and patterns of enumeration errors and facilitate a post-adjustment to correct for those errors (United Nations, 2010). Of the 1,758 census populations by age and sex referenced for the *2022 Revision*, 310 had associated post-enumeration survey results available, and 120 of them had some demographic evaluation covering altogether covering 130 countries between 1946 and 2019. These data formed the basis of a model to predict enumeration adjustments and patterns by sex and age for the remaining censuses.

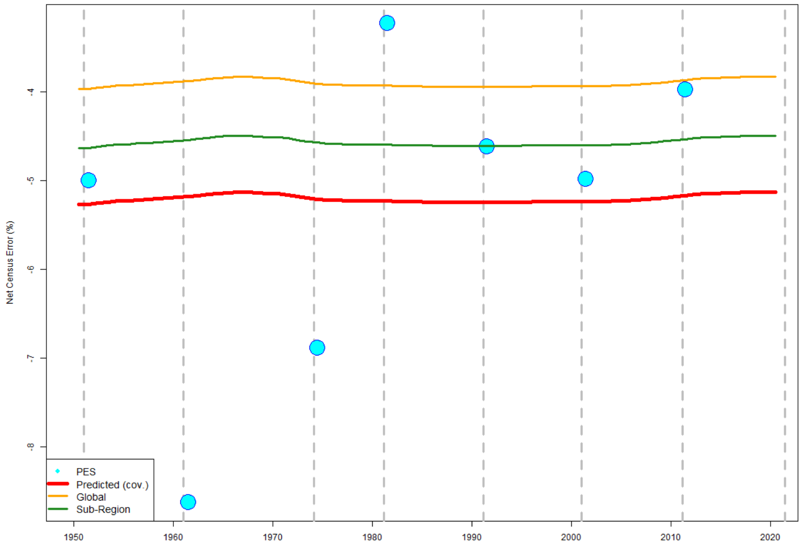
First, the overall net enumeration error was modelled as a linear function of the average number of years of education by sex, GDP (Institute for Health Metrics and Evaluation, 2020) and the under-five mortality level (both in log scales), and whether the assessment comes from a PES or demographic analysis. These data were fitted using a multilevel linear mixed-effects model that takes into account the regional and sub-regional geographical hierarchy used by the United Nations. This approach used a mixture of available data (variable number of observations by country and between regions covering different time periods) predicting overall net enumeration errors for countries and time periods without PES while controlling for various country characteristics.

Based on the set of time-dependent covariates, several time series of expected net enumeration errors were predicted for each country. Figure I.5 plots results for Bangladesh. The respective years with censuses are plotted with vertical grey dash lines and the PES estimates are shown as blue circles. The predicted (or expected) net census error is shown for (1) the country-specific expected values as the bold red line, and only as baseline reference for informative purpose for (2) the UN sub-region as the green line, and (3) the overall global model (i.e., world) as the yellow line.

Information on sex-specific net census errors was available for about 100 censuses. To leverage these data, a second model was estimated building on the first model of overall net census errors, this time to fit the sex-specific differences and to predict them for all countries from 1950 to 2021. The functional form is similar to the first model, but the overall net enumeration error was included as an additional covariate.

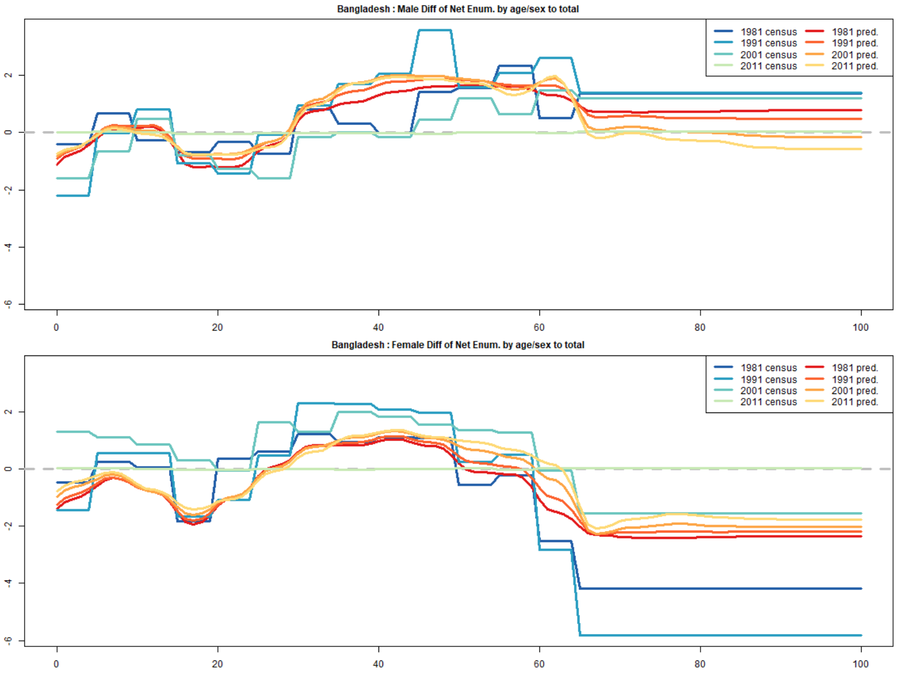
For 56 censuses across 28 countries, net census errors disaggregated by both sex and age were available. A third model was fitted to these data to predict net census errors by sex and age for all countries from 1950 to 2021. This model was sex-specific, with the same covariates as, the first model, but with an age interaction, as well as the overall net census error and the sex-specific difference. The initial predicted values for abridged age groups were smoothed using a spline function to obtain the values by single ages.

Figure I.5
Observed and predicted PES net census errors for Bangladesh, 1950 to 2021



In figure I.6, the patterns of deviation between the overall PES net enumeration error and the age and sex net enumeration errors are shown as blue/green lines, and the predicted model values as red/yellow lines for the respective censuses with available PES results. Reported PES results for some censuses referenced broad age groups, thus the age distributions were first standardized into single age distributions assuming uniform assumptions within each age group (shown as extended horizontal blue lines in the plots below).

Figure I.6
Difference in net census error by sex and age for Bangladesh, 1981-2011 censuses



d. Age misstatement adjustments

The degree to which age misstatement affects census population counts varies considerably across countries and time periods. Such errors might reflect a preference for a certain digit (e.g., ages ending in zero or five) that produces a "heaping" of population counts at specific parts of the age range. Many censuses also exhibit evidence of age understatement or exaggeration, particularly at older ages. A number of methods are available to demographers to assess the degree of age heaping and smooth accordingly. In its protocol, the Population Division considered the Bachi index (for counts by single year of age) or the age ratio score (for counts by five-year age group), together with the average level of education completed by adults in the population, to determine the degree of smoothing over age to apply via a moving average. Age heaping assessments and smoothing were performed separately for child and adult ages and the resulting series joined post-adjustment. When the census data series was grouped by five-year age group, the adjusted, smoothed series was ultimately graduated to single year of age using a monotonic spline. Where necessary, counts were redistributed to open-ended age group 105+ using the OPAG function of the DemoTools R package, which applied the life table estimated for the country and census year as a stable standard.

e. Missing children adjustments

It is quite common that young children are systematically under-enumerated in censuses to a substantially greater extent than other age groups. To detect such under-enumeration and adjust accordingly, the protocol considered the estimated fertility and mortality rates, together with the enumerated and adjusted counts of women of reproductive age, to predict the number of children that the census would be expected to capture. This step was implemented using the basepop_five() function of the DemoTools R package, with the returned counts of children by age graduated to single years via a monotonic spline.

3. Estimating the 1950 base year population

The approach taken to estimate the 1950 base year population for each country depended on the type and quality of census data available in or around that period of history. For countries with a high-quality census between 1945 and 1950, those counts were projected forward to 1 January 1950. For some of those without a pre-1950 census but with a high-quality census between 1950 and 1965, the earliest available high-quality census was back-projected to 1 January 1950. For many countries with a high-quality benchmark population estimate for the base year 1950 (e.g., HMD), that estimate was adopted for the base year. For the remaining countries, the base population was adapted from the *2019 Revision* of the *World Population Prospects* 1950 population estimate, shifted to 1 January, graduated to single year of age, and adjusted, as necessary, for consistency with the updated revision of the demographic components of population change.

E. ESTIMATING NET INTERNATIONAL MIGRATION

When a person moves from one country to another, that person is an emigrant from the country of origin and an immigrant to the country of destination. International migration is ideally studied as the flow of people moving between countries. In practice, however, data on international migration flows exist for only a small number of countries. Therefore, international migration in the *2022 Revision*, as well as in previous ones, was incorporated as net migration only. Net migration—the difference between the number of immigrants arriving in and the number of emigrants leaving from a particular country during a certain period of time—shows the net effect of international migration on the size and composition of the population in both country of origin and destination. In other words, the net international migration indicator in the *World Population Prospects* is not based on, nor does it allow for, a disaggregation of arriving immigrants and departing emigrants. In countries where the number of immigrants equals the number of emigrants, net migration will amount to zero even if immigration and emigration levels for that country are significant.

In preparing trends in international migration, attention was given to official estimates of net international migration or its components (immigration and emigration), to information on labour migration or on international migration flows recorded by receiving countries, to data about refugee (and asylum-seeker) stocks and flows prepared by the Office of the United Nations High Commissioner for Refugees (UNHCR)[32], and to estimates of stocks of foreign-born persons prepared by the Population Division of UN DESA[33]. Given the absence of empirical data on inflows and outflows of international migrants, it was difficult to produce comprehensive and consistent estimates of net migration over time. Therefore, in many cases, net international migration was estimated as the residual not accounted for by natural increase between successive census enumerations, after the protocol adjustments for net coverage errors and data quality issues. This approach computes the difference between the growth in population as recorded in successive censuses (total increase) and the growth implied by estimated levels of fertility and mortality (natural increase).

Strategies to define the sex and age patterns of net international migration vary according to the country context and time period. Given the limited empirical data available, model age patterns of migration were applied to estimate net international migration for many country-years (Rogers and Castro, 1981). The simplified models used in the *World Population Prospects*, implemented using the mig_un_fam() function of the DemoTools R package, include: a "family" model characterized by fairly even proportions of male and female migrants, a concentration of migrants in the working ages, but sizable numbers at childhood and older ages as well; a "male labour" model dominated by migration of males of working age; and a "female labour" model dominated by migration of females of working age. Alternatively, for many other country-years, a "population distribution" pattern was applied, in which the sex-age distribution of net migration is assumed identical to the sex-age distribution of the population. For countries and periods over which the residual migration methods returned reliable results by age and sex, those residual sex-age distributions were applied to estimated totals of net migration to derive estimates of net international migration by age and sex.

For a subset of countries with very high-quality empirical data with respect to both population and the components of demographic change[34], a new approach was implemented to estimate net international migration by age and sex for the *2022 Revision*. The Bayesian population reconstruction method (Wheldon and others, 2013) simultaneously estimates population counts, vital rates and net international migration, by age and sex, together with the uncertainty surrounding those estimates. It takes all inputs required CCMPP, plus the benchmark populations by sex and single year of age. It is similar to the CCMPP in that the output includes age- sex-specific estimates of the populations at each of the years after the baseline year, up to the end of the estimation period. However, Bayesian population reconstruction is a probabilistic method that yields a joint posterior probability distribution over the output populations and the input

---

[32] For refugee statistics from the Office of the United Nations High Commissioner for Refugees (UNHCR), see https://www.unhcr.org/refugee-statistics/

[33] For estimates of international migration flows and stocks of foreign-born from the United Nations, see https://www.un.org/development/desa/pd/content/international-migrant-stock

[34] Albania, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Denmark, France, Germany, Greece, Israel, Japan, Latvia, Lithuania, Malta, Netherlands, Republic of Moldova, Sweden, and United Kingdom.

quantities, thereby accounting for measurement error. Full technical details can be found in Wheldon and others (2013, 2015; 2016).

For the *2022 Revision*, Bayesian population reconstruction was used only to produce estimates of net international migration for the chosen subset of countries. The initial estimates of fertility, mortality, and populations were constructed from all available data sources in the same manner as described above for all countries. The initial estimates of net international migration were autocorrelated processes centred at zero, restricted such that the values did not exceed plus-or-minus ten per cent of the population size. The medians of the marginal Bayesian posterior distributions for net international migration by age and sex were selected as the final estimates and then input to the CCMPP. For some countries with available data, direct estimates of net international migration were used as reference values to assess the general plausibility of the estimates returned by the reconstruction.

As a final step, net migration balancing was carried out to ensure that at the global level the sum of all net international migration flows equalled zero for each year of the estimation period. Balance was achieved by applying small adjustments to the net international migration estimates for countries where such estimates were highly uncertain.

II. THE PREPARATION OF POPULATION PROJECTIONS

In the *2022 Revision*, the future population of each country was projected beginning from 1 January 2022. To project the population forward until 2101, various assumptions were made regarding future trends in fertility, mortality and international migration. Probabilistic methods were used to project future fertility and mortality levels, specifically to derive trajectories of total fertility and life expectancy at birth. In addition, a number of different projection scenarios were produced to convey the sensitivity of the projections to changes in the underlying assumptions. The following sections summarize the assumptions used for each scenario and the associated projection methods.

A. PROJECTING THE MEDIUM FERTILITY SCENARIO

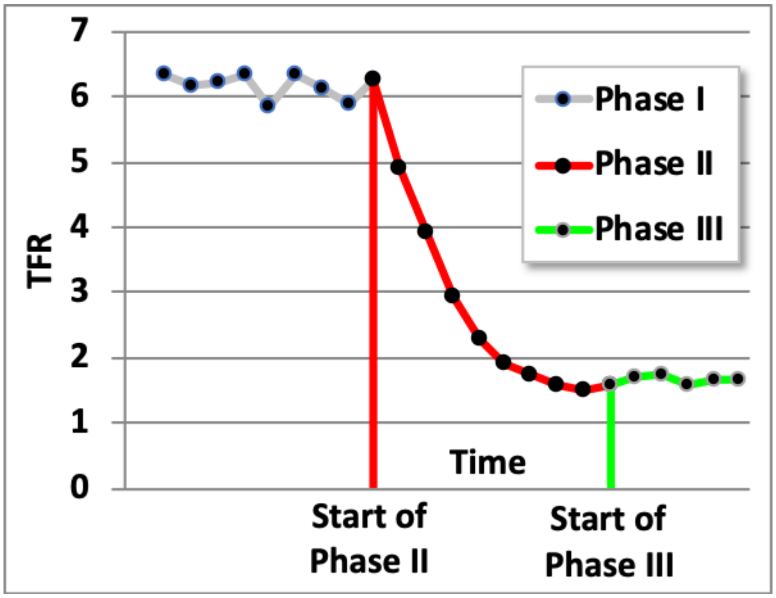
As part of its work on probabilistic projections, the Population Division has also published the 80 and 95 per cent prediction intervals of future fertility levels, along with the median trajectory. The median trajectory constitutes the medium-fertility assumption.

The *2022 Revision* of the *World Population Prospects* also includes several scenarios with different fertility assumptions: (1) medium-fertility assumption; (2) high-fertility assumption; (3) low-fertility assumption; (4) constant-fertility assumption; (5) instant-replacement assumption; (6) an instant-replacement zero migration scenario, which additionally assumes zero net international migration; and (7) a momentum scenario which has a different treatment of the mortality assumptions as compared to the instant-replacement zero migration scenario. In preparing the different scenarios, making the medium-fertility assumption is the most significant first step.

The *2022 Revision* used probabilistic methods for projecting total fertility that were first employed in the *2010 Revision* (Alkema and others, 2011; Raftery and others, 2009) and updated in subsequent revisions (Raftery and others, 2014a; United Nations, 2014b, 2015, 2017c). The method utilizes the fertility levels and trends estimated for the *2022 Revision* for all countries of the world for the period 1950 to 2021.

Projections of future country-specific fertility levels are based in the demographic transition theory. Overall, there is a consensus that the historical evolution of fertility includes three broad phases: (i) a high-fertility, pre-transition phase (phase I), (ii) a fertility transition phase (phase II), and, (iii) a low-fertility, post-transition phase (phase III). Figure II.1 illustrates the three phases of fertility transition. For each country, the start of phase II was determined by examining the maximum total fertility during the estimation period from 1950 to 2021. Countries where this maximum was less than 5.5 births per woman were deemed to have entered phase II prior to 1950. All other countries were deemed to have entered phase II in the period of their local maximum. To find the end of phase II, and thus the beginning of phase III, first the TFR is averaged over 5-year time periods. Then for each country the time period is identified where the first two successive increases were observed, after the level of the averaged TFR had fallen below 2 births per woman. If no such increase was observed, a country was deemed to still be in phase II in 2021. If such increase was observed in the last time period, phase III is assumed to start in 2022. Otherwise, it is assumed that the country's phase III has started at the midpoint of such time period. Based on the most recent population and demographic data available, it was determined that all countries had begun or already completed their fertility transition, being in either phase II or phase III. Thus, fertility transition in these two phases were modelled separately, while phase I was not modelled in the *2022 Revision*.

Figure II.1
Schematic phases of the fertility transition (live births per woman)



Phase I: High-fertility, pre-transition phase. Not modelled.

Phase II. Fertility-transition phase, modelled by double-logistic function using a Bayesian hierarchical model.

Phase III. Low-fertility, post-transition phase, modelled with a first-order auto-regressive time series model, AR(1), in a Bayesian hierarchical framework.

Source: (Alkema and others, 2011).

While the process of fertility decline differs across countries, a common general pattern has been observed. Overall, the pace of fertility decline is usually fastest just after the onset of that decline. The pace typically slows as fertility falls to "intermediate" levels, and slows further still as it approaches the replacement level. Variations to this general pattern have been observed, associated with the pace of fertility decline both at the beginning and at the end of the fertility transition. Empirical evidence of this pattern opened the door to first predict the pace of fertility decline at different fertility levels as an intermediate step towards projecting future levels of fertility, rather than directly projecting future levels of fertility alone (United Nations, 2006).

The probabilistic framework for projecting total fertility, first applied in the *2010 Revision*, consists of two separate processes:

The first process models the sequence of change from high to low fertility (phase II of the fertility transition). For countries that are undergoing a fertility transition, the pace of the fertility decline is divided into a systematic decline and various random distortion terms. The pace of the systematic decline in total fertility is modelled as a function of its level, based on a double-logistic decline function. The parameters of the double-logistic function were estimated using a Bayesian hierarchical model, which resulted in country-specific distributions for the parameters of the decline. These distributions are informed by historical trends within the country as well as the variability in historical fertility trends of all countries that have already experienced a fertility decline. This approach not only takes into account the historical experience of each country, but also to reflects uncertainty about future fertility decline based on the past experience of other countries at similar levels of fertility. Under the model, the pace of decline and the limit to which fertility was able to decline in the future varied for each projected trajectory. The model is hierarchical because in addition to the information available at the country level, a second level that is the global experience of all countries is also used to inform the statistical distributions of the parameters of the double-logistic function. This is particularly important for countries at the beginning of their fertility transition because limited information exists on the pace of their fertility decline. For these countries, the fertility projections are informed mainly by the world's experience and the variability in trends experienced in other countries at similar levels of fertility in the past.

Once projected fertility reaches phase III (figure II.1), the second component of the projection procedure implements a time series model to further project fertility, assuming that the fertility level would approach and, in the long run, fluctuate around an ultimate country-specific level. That level is determined for each country by a Bayesian hierarchical model (Raftery and others, 2014a) informed by empirical evidence from low-fertility countries that have experienced fertility increases from a sub-replacement level. In the *2022 Revision*, 48 countries or areas[35] had entered phase III by 2021. Thus, future long-run fertility levels in the *2022 Revision* are country-specific, accounting for the country's own historical experience and also informed by statistical distributions that incorporate the empirical experience of all low-fertility countries that have already experienced a recovery from sub-replacement fertility levels. The world mean parameter for the country-specific asymptotes was restricted to a fertility level no greater than 2.1 births per woman.[36] The model was fitted on all locations with more than 90,000 inhabitants in 2021, and smaller locations with less than 90,000 inhabitants are treated as supplementary locations (i.e., their experience did not inform the world distribution or other locations).

A long-term assumption of a fertility increase in low-fertility countries (phase III) is supported by the experience of many countries in Europe and East Asia (Goldstein and others, 2009; Caltabiano and others, 2009; Myrskyla and others, 2009; Sobotka, 2011; Bongaarts and Sobotka, 2012; Myrskylä and others, 2013; Sobotka and Beaujouan, 2014). However, such an increase is not universal (Billari, 2018; Reher, 2019). For countries that have experienced extended periods of low fertility with no empirical indication of an increase in fertility, fertility was projected to continue at low levels over the near future. This assumption is supported by research on the "low fertility trap hypothesis", observed among some low-fertility countries in Europe (Lutz, 2007; Lutz and others, 2006) and East Asia (Jones and others, 2008; Frejka and others, 2010; Basten, 2013).

To construct projections for all countries still in phase II, the Bayesian hierarchical model was used to generate 250,000[37] double-logistic curves for all countries that have experienced a fertility decline (figure II.2), representing the uncertainty in the double-logistic decline function of those countries[38]. This sample of double-logistic curves was then used to calculate 2,000 total fertility projections for all countries that had not reached phase III by 2021. For each trajectory at any given time, the double-logistic function provides the expected decrement in total fertility in relation to its current level. A distortion term was added to the expected decrement to reflect the uncertainty inherent in the estimated model of fertility decline.

In historical revisions of the *World Population Prospects*, up to and including the *2010 Revision*, projections assumed a long-run fertility level of 1.85 children per woman. In subsequent revisions, including the *2022 Revision*, the projected level of total fertility has been allowed to fall below that threshold, reflecting uncertainty with regard to the historic minimum level of fertility at the end of phase II

---

[35] The 2022 revision of WPP was informed by the experience of 48 countries or territories (with 90,000 inhabitants or more in 2021) that had entered phase III: Armenia, Australia, Austria, Barbados, Belarus, Belgium, Bulgaria, Canada, China (including Hong Kong SAR, Macao SAR, Taiwan Province of China), Cuba, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Guernsey, Hungary, Ireland, Italy, Japan, Jersey, Latvia, Lithuania, Luxembourg, Malta, Netherlands, North Macedonia, Norway, Poland, Republic of Moldova, Romania, Russian Federation, Serbia, Singapore, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States of America, Viet Nam.

[36] While the asymptote does not have an explicit lower bound, it does implicitly because any given total fertility trajectory is restricted not to be smaller than 0.5 child.

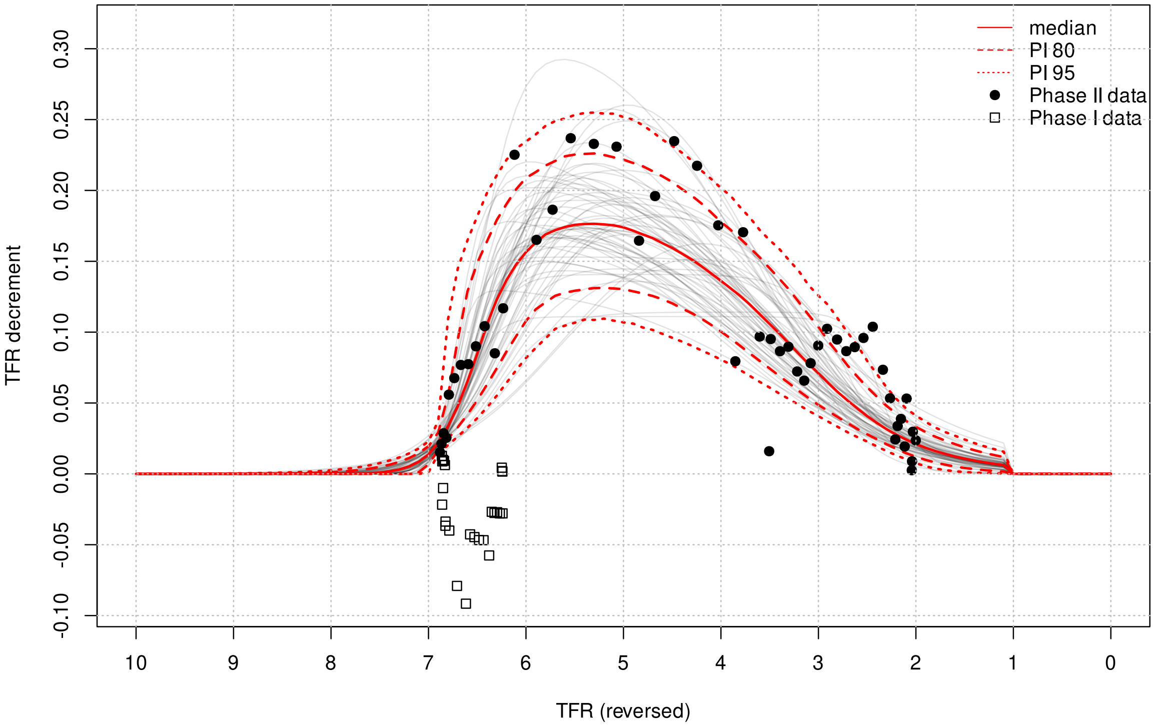
[37] Actually, ten Markov chain Monte Carlo (MCMC) simulations are run in parallel to find the various combinations of parameters with 25,000 iterations performed for each simulation, and the first 2,000 iterations for each simulation are discarded as burn-in trials so that the effect of initial values on the final results is minimized.

[38] Graphs of this double-logistic curve are available online at: https://population.un.org/wpp/Graphs/Probabilistic/FERT/CHG/50.

before the start of a recovery as part of phase III. The pace of fertility change, the level of fertility, as well as the timing of the end of phase II and the start of phase III, varies for each of the 2,000 projected fertility trajectories for a country that had not reached phase III by 2021. Future trajectories consist of a combination of cases with total fertility in phase II or III, until eventually all trajectories are in phase III. For countries that were already in phase III by 2021, the time series model for that phase was used directly. The unweighted mean value for the world distribution based on the 48 countries or areas that have entered phase III is 1.62 children per woman in 2100 while the 95 per cent prediction interval ranges between 1.50 and 1.75.

Figure II.2

Total fertility annual decrements by level of fertility and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part) (live births per woman)



Note: Observed annual decrements by level of total fertility (TFR) are shown as black dots for those that occurred since the start of Phase II (decline), and as empty black squares for those that occurred before the start of Phase II. For clarity, only 60 of the 250,000 calculated trajectories are shown here. The median projection is depicted by the solid red line, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

The probabilistic projections of total fertility have been computed using "bayesTFR" (Ševčíková and others, 2022a; Ševčíková and others, 2011) an open-source and portable software implementation based on the R statistical language, and the full dataset used for the *2022 Revision* (United Nations, 2022).

The median of these 2,000 trajectories was used as the medium fertility scenario projection in the *2022 Revision*. To express the uncertainty surrounding future trends in fertility, 80 and 95 per cent prediction intervals were also calculated (figure II.3). Additional tables[39] and graphs[40] are available online for all

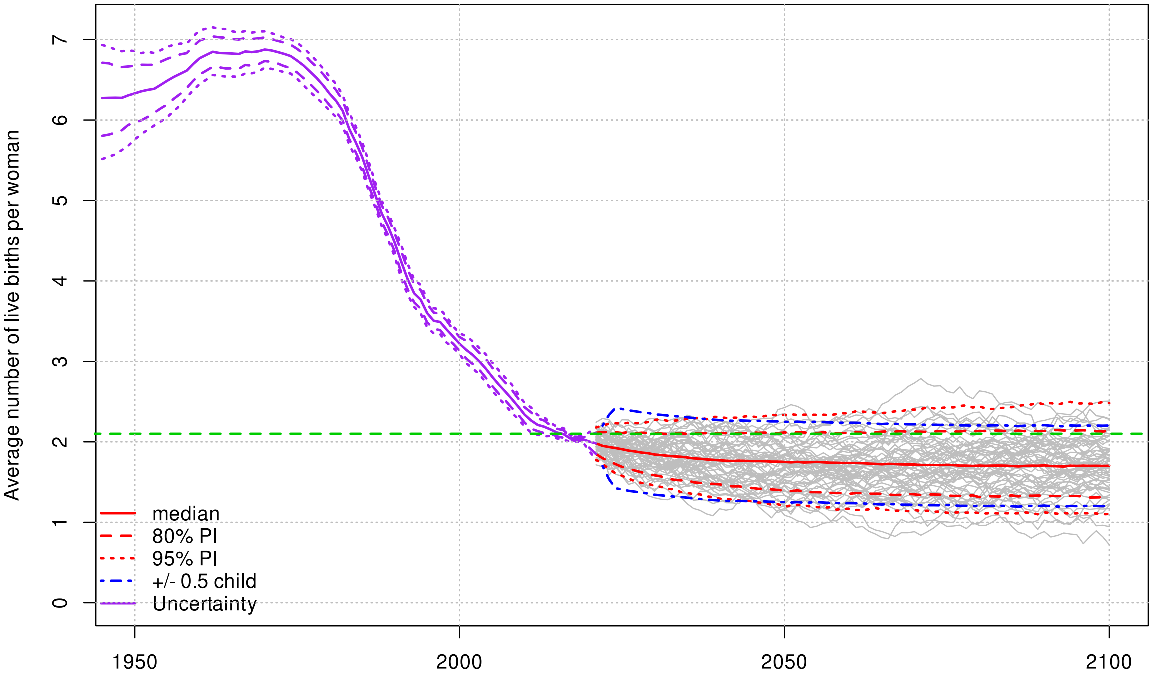
---

[39] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online tables of stochastic projections of total fertility: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp/Download/Probabilistic/Input/.

[40] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online plots of projections of total fertility: median, 80 and 95 per cent prediction intervals, high and low WPP fertility scenarios; see https://population.un.org/wpp/Graphs/Probabilistic/FERT/TOT/50.

countries. For countries that had not reached phase III by 2021, the projected median trajectory reflects the uncertainty as to when the fertility transition will end and at what level.

Figure II.3
Estimates and projected probabilistic trajectories of total fertility, Bangladesh, 1950-2100 (live births per woman)



Note: For clarity, only 60 of the 2,000 calculated trajectories are shown here for the period 2022 to 2100. The median estimate is depicted by the solid purple line, and by the solid red line for the projections, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted purple lines for the estimation period, and red lines for the projection period, respectively. The high- and low-fertility scenarios of the *2022 Revision* correspond to the plus or minus 0.5 births around the median trajectory, shown here as blue dashed lines. The replacement-level of 2.1 births per woman is plotted as green horizontal dashed line for reference purposes only.

The fertility projections produced in the *2022 Revision* have been informed by historical trends in fertility and reflect an implicit assumption that the conditions facilitating fertility decline will persist in the future. Should massive efforts to scale up family planning information, supplies and services be realized, then the median fertility projections may be too high. Conversely, should prevailing conditions underlying fertility decline deteriorate (for example, if there is a slowdown in modern contraceptive method uptake or a persistent or resurgent desire for early marriage and large families), then the median projected levels of fertility in this revision may be too low.

B. PROJECTING AGE PATTERNS OF FERTILITY

Once the path of future total fertility was determined, age-specific fertility rates by mothers' single year of age were calculated. For some low-fertility countries with mean age at childbearing greater than 32 years in 2021 or with an age pattern of fertility that is very dissimilar from the global norm[41], the projected age patterns of fertility pattern were held constant at those estimated for 2021. For all other countries, age-

---

[41] Countries or areas for which projected PASFR was held constant at the 2021 pattern include: Andorra, Bermuda, China, Hong Kong SAR, China, Macao SAR, Guadeloupe, Ireland, Kosovo (under UNSC res. 1244), Kyrgyzstan, Luxembourg, Mongolia, Republic of Korea, San Marino, Spain and Switzerland.

specific patterns of fertility were projected based on country-specific trends in the estimation period, leading towards a global model age pattern of fertility[42] (Ševčíková and others, 2016). The projection method was implemented on the proportionate age-specific fertility rates (PASFR) by mothers' single year of age from 10 to 54.

The final projection of the PASFR for each age group is a weighted average of two preliminary projections:

- A first preliminary projection, assuming that the PASFRs converge to the global model pattern, and
- A second preliminary projection, assuming that the observed national trend in PASFRs continues indefinitely.

The method was applied to each of the trajectories that constituted the probabilistic projection of the total fertility rate of each country, based on the estimated PASFRs for 1950-2021 from the *2022 Revision*. In examining the resultant mean age at childbearing (MAC), it was found that the mean values, rather than the median values, of generated PASFRs produced a smoother trend line for most countries.

It was assumed that the transition in each trajectory from the observed national trend to the global model age pattern of fertility was dependent on (a) the timing of when the country entered phase III of the fertility transition, and on (b) whether the projected fertility for a given period is higher than the ultimate TFR (2100) in the medium scenario projection (Ševčíková and others, 2016).

Out of 20 major methods to project fertility by age, this overall approach has been confirmed to be one of the four best performing methods (Bohk-Ewald and others, 2018) with the greatest accuracy to predict completed cohort fertility (i.e., how many children will be born on average by women over their entire reproductive lifetime).

C. PROJECTING THE MEDIUM MORTALITY SCENARIO

Assumptions for the projection of mortality are specified in terms of life expectancy at birth by sex. As part of the probabilistic population projections, the Population Division publishes 80 and 95 per cent prediction intervals for future levels of life expectancy at birth, along with the median trajectory derived from a statistical model describing mortality change over time. The median trajectory provides the mortality trend used in the high-, medium- and low-, instant-replacement-fertility, instant-replacement-zero-migration, and zero-migration scenarios. As in previous revisions, life expectancy was generally assumed to rise over the projection period.

The *2022 Revision* used probabilistic methods for projecting life expectancy at birth, including the modifications that were made in the implementation of the models in the *2017 Revision* (Castanheira and others, 2017; United Nations, 2017c).

---

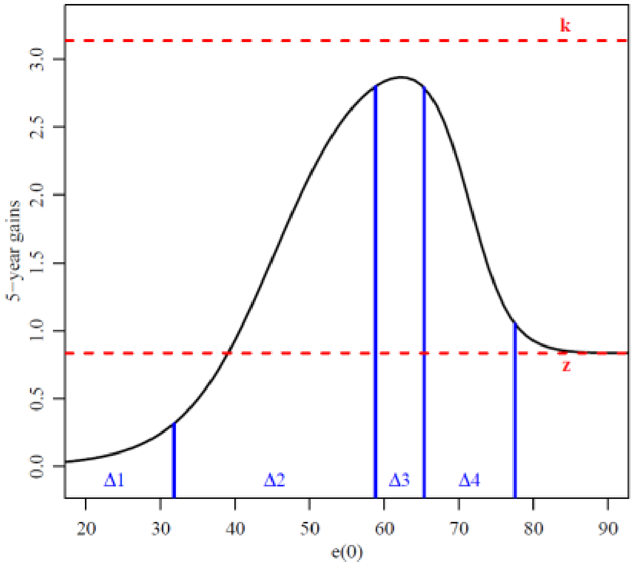
[42] The global model pattern in the *2022 Revision* is based on the unweighted average of the proportionate distribution of the age-specific fertility rates mothers' single year of age for the following low fertility countries or areas that (a) have reached phase III; (b) display childbearing patterns with a mean age at childbearing of 30 years or above in 2021; and (c) are not among the countries for which projected PASFR was held constant: Australia, Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Japan, Jersey, Lithuania, Netherlands, Norway, Slovenia and Sweden.

1. *Projecting female life expectancy at birth*

The probabilistic methods used in the *2022 Revision* for projecting life expectancy at birth comprise two separate models. The first model depicts the gradual increase over time in female life expectancy at birth (Raftery and others, 2013). In this model, the transition from high to low levels of mortality is divided into two phases, each of which are approximated by a logistic function that models the gains in life expectancy (figure II.4).

Figure II.4

Phases of the mortality transition: gains in life expectancy at birth by level of life expectancy at birth (years)



Source: Raftery and others (2013).

Note: The deltas (Δ) in the figure represent changes in the magnitude of 5-year gains against increases in life expectancy at birth.

The first phase, modelled through the first two delta terms in figure II.4, consists of the initial slow growth in life expectancy associated with the diffusion of improved hygiene and nutrition, followed by a period of accelerated improvement, especially in the mortality of infants and children, associated with social and economic development accompanied by interventions in public health and basic medical care, including infant feeding, water and sanitation, and childhood immunization programmes. The second phase, modelled through the third and fourth delta terms in figure II.4, begins once the easiest gains, mainly from fighting infectious diseases that often strike in childhood, have been achieved. The second phase is characterized by a combination of continued gains from defeating infectious diseases across the age range and from combating non-communicable diseases that strike primarily at older ages. Given the greater challenges in preventing deaths from non-communicable diseases and the lower payoff in years of life expectancy gained that result from saving the life of an older person as compared to that of a child, the rise of life expectancy is slower in the second phase (Fogel, 2004; Riley, 2001).

For all countries undergoing a mortality transition, the pace of improvement in life expectancy at birth described by the model is composed of two parts, which are depicted by a systematic decline term and a random distortion term:

- First, the pace of the systematic gains in life expectancy at birth is modelled as a function of the level of life expectancy, based on a double-logistic improvement function developed in earlier revisions of *World Population Prospects* (United Nations, 2006). The parameters of the double-logistic function were estimated on the basis of the observed gains in female life expectancy from 1950 until 2019 for each country[43], using a Bayesian hierarchical model that yields country-specific distributions for all estimated parameters and for future trends in life expectancy. The model is hierarchical because, in addition to the information available for a particular country, a second level of information derived from the average global experience is used to inform the estimation of each country-specific double-logistic curve.

- Second, given the estimated double-logistic curve for a particular country or area, each projected value of life expectancy at time t+1, the next year of projection period, was derived using a random walk with drift (Raftery and others, 2013), where the drift parameter, which specifies the pace of change over time, was taken from the estimated country-specific double-logistic function.

Under these conditions, the pace of improvement and the asymptotic limit to future gains in female life expectancy vary for each projected trajectory, but ultimately are informed and constrained by the finding that the rate of increase of maximum female life expectancy over the past 150 years has been approximately linear (Oeppen and Vaupel, 2002; Vaupel and Kistowski, 2005), albeit at a slower pace after female life expectancy at birth in the vanguard countries started to exceed 75 years in the 1960s (Vallin and Meslé, 2009). Additional evidence used to guide decisions about the future rate of increase of life expectancy at birth included information on the historic increase of the maximum recorded age at death for women, or the maximum observed female lifespan, among countries with high life expectancies and reliable data on mortality at very old ages. Maximum recorded female age at death in countries such as Sweden and Norway has been increasing at a steady pace of about 1.25 years per decade since around 1970 (Wilmoth and others, 2000; Wilmoth and Robine, 2003; Wilmoth and Ouellette, 2012). Since the increase in average lifespan cannot exceed the increase in maximum lifespan indefinitely, the historic pace of increase in the observed maximum lifespan of women from selected countries was used to set the value of the model parameter that helps to determine the asymptotic average rate of increase in female life expectancy.[44]

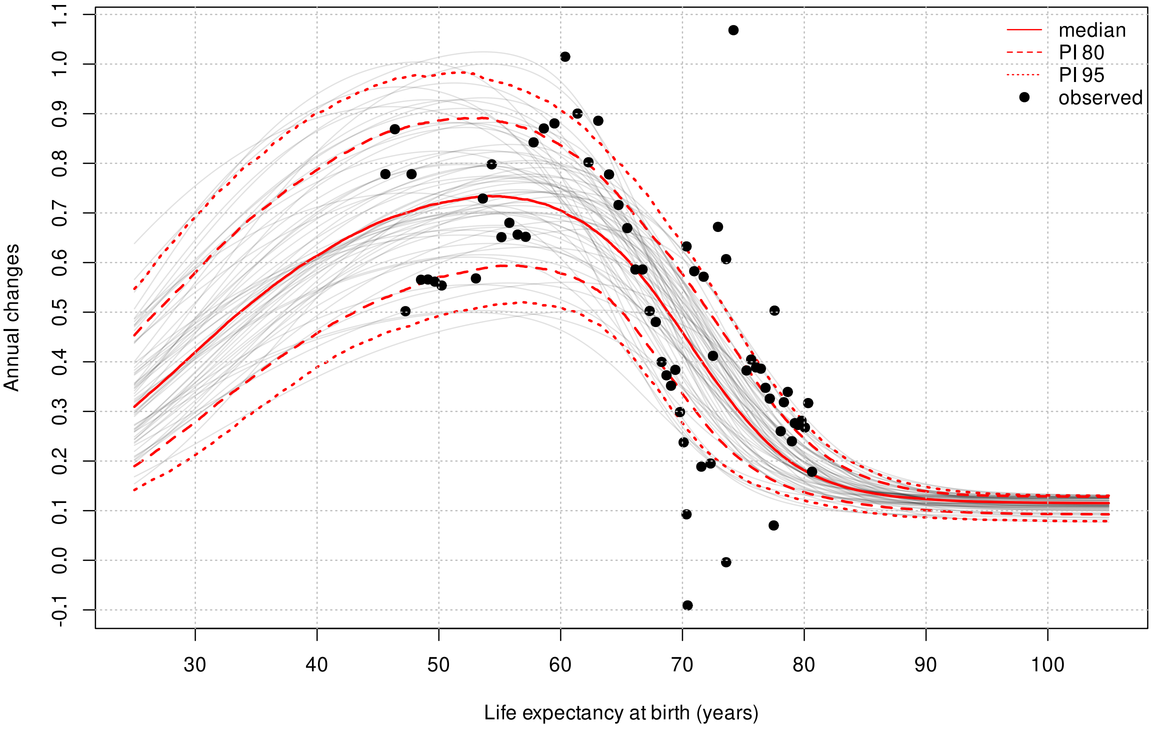
---

[43] Life expectancies in the years 2020 and 2021 were highly affected by the COVID-19 pandemic, thus estimates for these years have been excluded from the model for all countries.

[44] Following the notation used in Raftery and others (2013), to obtain a posterior median of the annual gain in life expectancy of around 0.125 year, the parameter constraining the maximal value of the asymptote of the double-logistic curve at high levels of life expectancy was set to 0.1326, both for the global parameter (z) and for each country-specific parameter (zc), during both the estimation and subsequent use of the collection of country-specific double-logistic curves.

Figure II.5

Female gains in life expectancy at birth by level of life expectancy at birth and prediction intervals of estimated double-logistic curve, China (years)



Note: The observed yearly gains by level of life expectancy at birth (e(0)) are shown by black dots. For ease of viewing, only 60 of the 800,000 simulated trajectories are shown here. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

To construct projections of female life expectancy at birth for all countries, the Bayesian hierarchical model was used to generate 800,000[45] double-logistic curves for each country or area (figure II.5), representing the uncertainty in the estimated curve describing the country-specific relationship between the current value of life expectancy and the pace of increase in life expectancy[46]. The model was fitted on all locations with more than 90,000 inhabitants in 2021, and smaller locations with less than 90,000 inhabitants were treated as supplementary locations (i.e., their experience did not inform the world distribution or other locations).

A systematic sampling of double-logistic curves was then used to calculate 10,000 projected values of life expectancy at birth for each country or area in each time period. All the probabilistic projections of female life expectancy at birth were computed using "bayesLife" (Ševčíková and others, 2022e), an open-source and portable software implementation based on the R statistical language, and the full dataset used for the *2022 Revision* (United Nations, 2022). The transition from 5-year periods to annual time periods necessitated some changes to the implementation of the life expectancy projections, including a new criteria

---

[45] Actually, ten Markov chain Monte Carlo (MCMC) simulations were run in parallel to find the various combinations of parameters with 80,000 iterations performed for each simulation, and the first 2,000 for each simulation were discarded as burn-in trials so that the effect of initial values on the final results is minimized.

[46] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York. Online plots of double-logistic curves depicting annual gains in female life expectancy at birth, estimated using a Bayesian hierarchical model (BHM): median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp20/Graphs/Probabilistic/EX/CHGFEM/156.

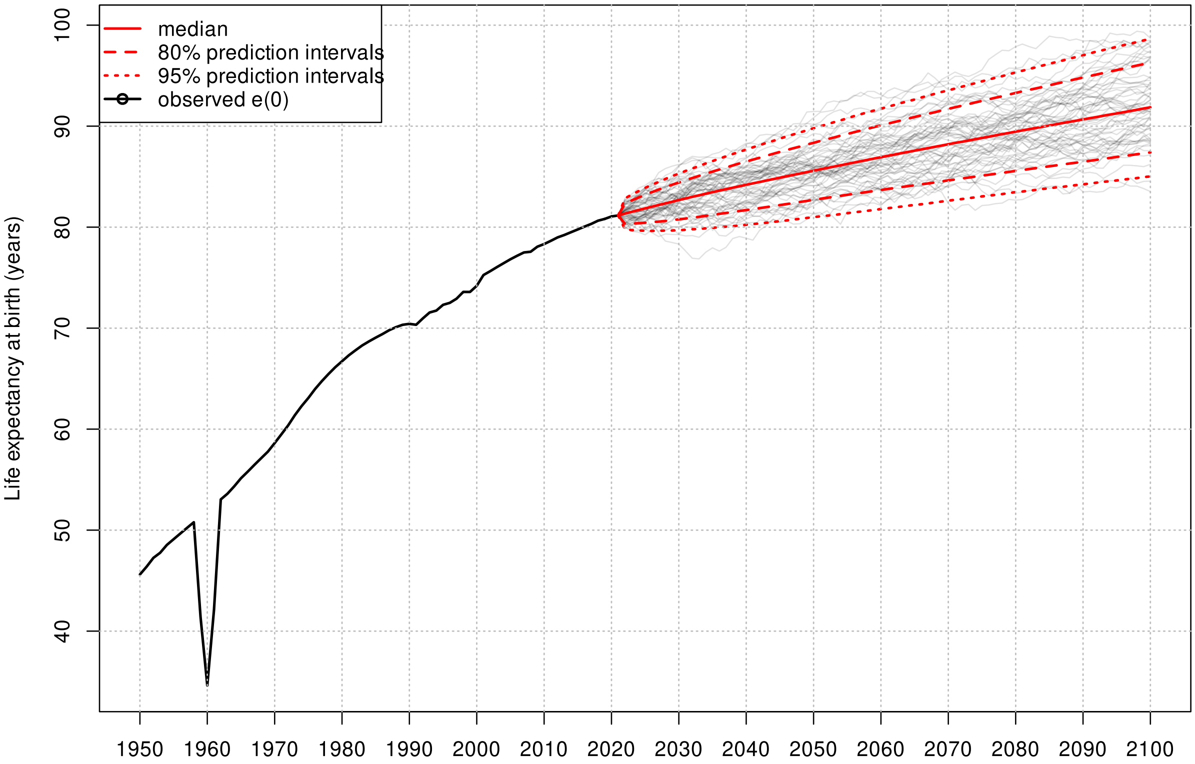
for annual outliers of ± 5 years, and a new set of default global priors estimated jointly as follows (assuming U_z=0.1326 and the sum of deltas is equal to 86):

Table II.1
Global default set of parameters for the female life expectancy at birth double-logistic estimation

	Δ_1	Δ_2	Δ_3	Δ_4	k	z
a_i	13.218	40.912	9.462	22.104	2.748	0.627
δ_i	12.231	7.839	13.784	5.628	2.768	0.071
τ_i	19.157	22.410	14.867	21.518	2.768	0.265

The median of these 10,000 trajectories was used as the standard mortality projection of the *2022 Revision*. To evaluate the uncertainty of future trends in female life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.6). Additional tables[47] and graphs[48] for all countries are available online.

Figure II.6
Estimates and projected probabilistic trajectories of female life expectancy at birth, China, 1950-2100 (years)



NOTE: For ease of viewing, only 60 trajectories of the 10,000 simulated trajectories are shown here for 2022 to 2100. The median trajectory is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines respectively.

---

[47] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. Online tables of probabilistic projections of female life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp20/Download/Probabilistic/Input/.

[48] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York. Online plots of probabilistic projections of female life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp20/Graphs/Probabilistic/EX/Female/156.

2. *Modelling the gap between female and male life expectancy*

The second model used for projecting future mortality trends addresses the gap between female and male life expectancy at birth. Results obtained using the model of the sex-gap in life expectancy were combined with those from the model of female life expectancy in order to derive projections of male life expectancy. In other words, projected values of male life expectancy were obtained by subtracting the projected gap from the projected value of female life expectancy. The application of this approach took into account the correlation between female and male life expectancies, and the existence of outlying data points during periods of crisis or conflict (Raftery and others, 2014b).

The gap in life expectancy at birth between females and males was modelled using an autoregressive model with female life expectancy serving as a covariate. A large body of literature exists on biological, behavioural and socioeconomic factors underlying the gap in life expectancy between women and men (Oksuzyan and others, 2008; Rogers and others, 2010; Trovato and Heyen, 2006; Trovato and Lalu, 1996, 1998). Recent trends provide evidence of a narrowing in the sex gap for almost all high-income countries (Glei and Horiuchi, 2007; Meslé, 2004; Oksuzyan and others, 2008; Pampel, 2005). The pattern of decline in the sex gap at high levels of life expectancy, which has been observed for high-income countries and for some emerging economies, was assumed to apply in the future to other countries as well. Such trend does not seem implausible given the diffusion of effective public health and safety measures and medical interventions (Vallin, 2006; Bongaarts, 2009). In effect, the projection model used by the United Nations implies, on the basis of past experience in countries from across the world, that the future sex gap is expected to widen when life expectancy is low but will tend to narrow once female life expectancy reaches about 75 years. In the current implementation of the model, this narrowing is assumed to continue until female life expectancy attains a threshold value set equal to 86 years. This specification brought about some convergence in male and female values of life expectancy at birth within the projection interval for some countries. For projected levels of female life expectancy at or above the highest values observed to date (about 86 years), the sex gap was modelled as constant with normally distributed distortions because little information on the determinants of changes in the gap exists at these high ages and beyond.

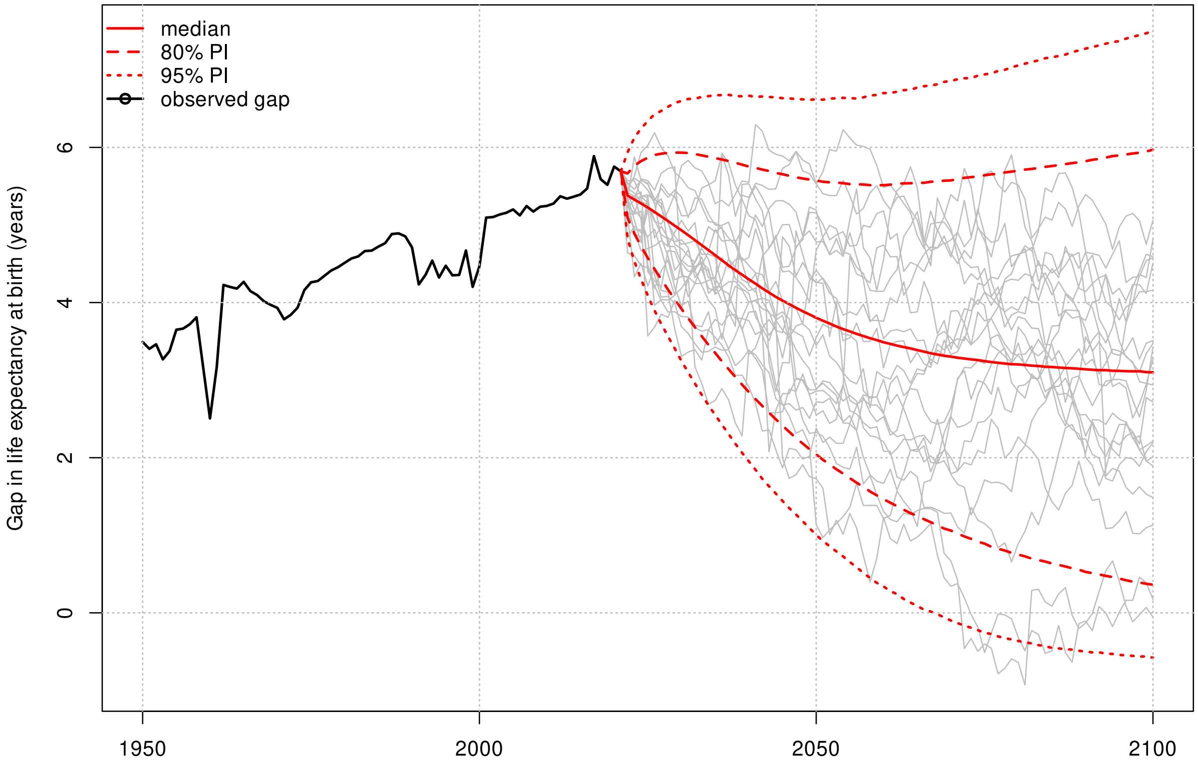
To systematically produce joint probabilistic projections of female and male life expectancy, a large number of future trajectories for the gap in life expectancy was simulated. To construct projections of male life expectancy at birth, the autoregressive model of the sex gap in life expectancy was used to generate 10,000 trajectories of the gap for each country (figure II.8), representing the uncertainty in the projected future gap. Then, each simulated value of the sex gap was subtracted from its paired value of female life expectancy to generate the corresponding projected value of male life expectancy. Graphs of the sex gap trajectories for all countries are available online[49].

---

[49] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online plots of female-male gap in life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp/Graphs/Probabilistic/EX/FMGAP/156.

Figure II.7

Estimates and projected probabilistic trajectories of gap between female and male life expectancy at birth, China, 1950-2100 (years)



NOTE: For clarity, only 60 trajectories of the 10,000 calculated are shown here for 2022 to 2100. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively.

As in the *2019 Revision* (United Nations, 2019b), the *2022 Revision* includes historical data for periods prior to 1950 for several countries in the dataset used to estimate the coefficients of the sex gap model. The minimum and maximum bounds of the gap were set at -1 and 18, respectively[50]. The sample of gender gap trajectories was then used to calculate 10,000 male life expectancy projections for each country. All the computation for the probabilistic projections of male life expectancy at birth were performed using the open source “bayesLife” R package (Ševčíková and others, 2022e).

The median of these projections was used as the standard mortality projection in the *2022 Revision*. To evaluate the uncertainty of future trends in male life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.8). Additional tables[51] and graphs[52] for all countries are available online.

---

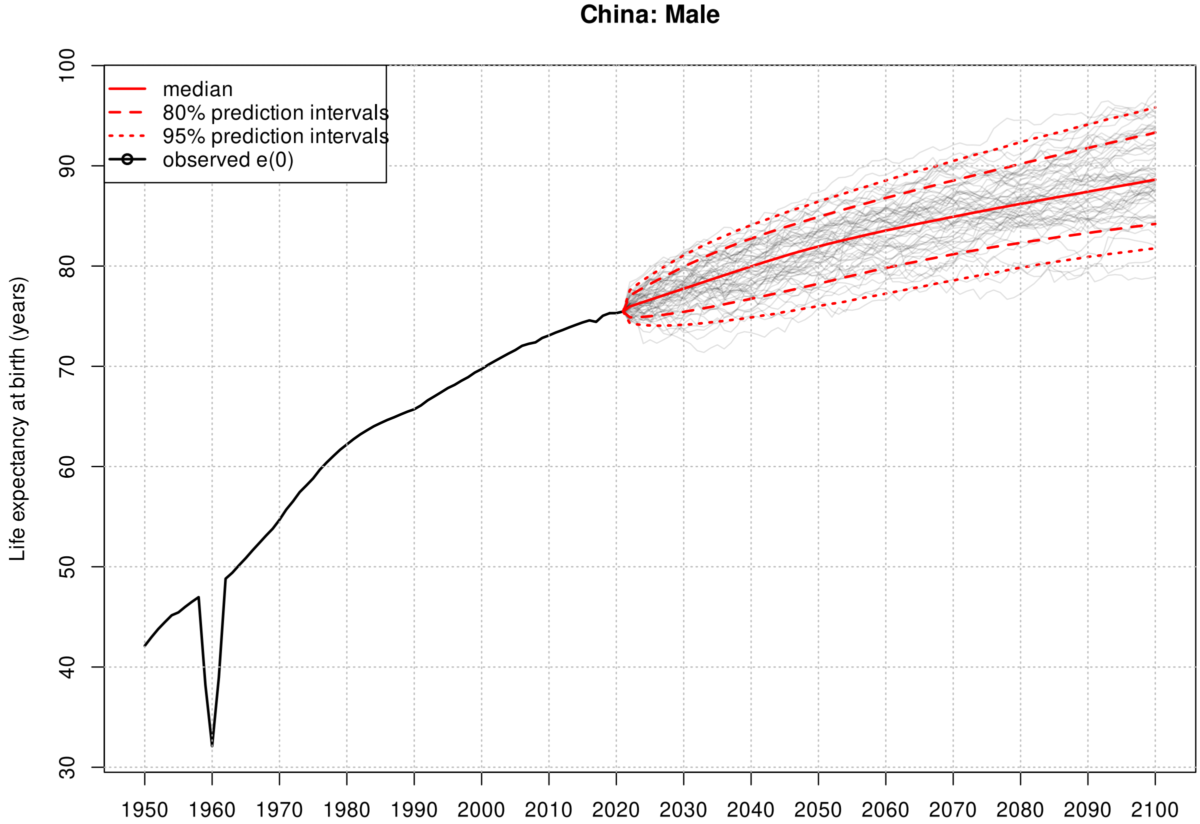
[50] Maximum female life expectancy for male projections handled by the first equation (parameter M in Equation (1) in Raftery and others (2014b)) is 84 for the data used for estimation with 3 degrees of freedom to deal with the heavy tail of the t-distribution due to more outliers with the use of annual time series instead of 5-year period averages as in previous revisions.

[51] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online tables of probabilistic projections of male life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp/Download/Probabilistic/Input/.

[52] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online plots of probabilistic projections of male life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp/Graphs/Probabilistic/EX/Male/156.

Figure II.8

Estimates and projected probabilistic trajectories of male life expectancy at birth, China, 1950-2100 (years)



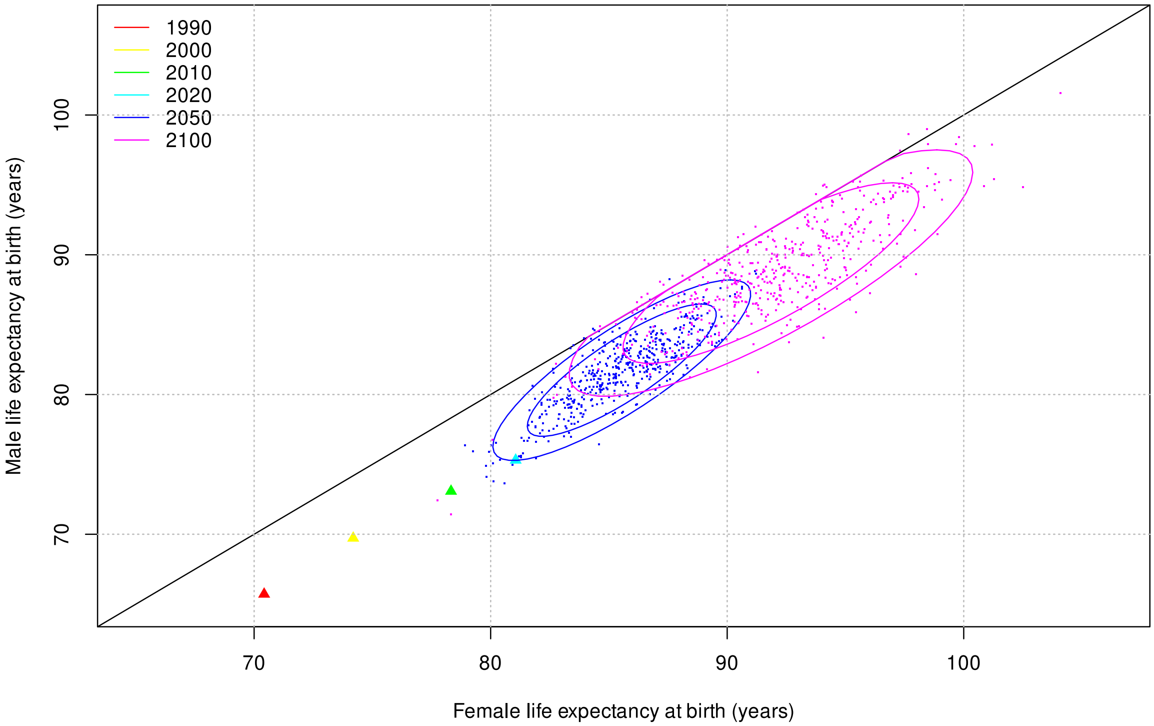
NOTE: For clarity, only 60 trajectories of the 10,000 calculated are shown here for 2022 to 2100. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively.

The relationship between probabilistic projections of male and female life expectancy at birth for selected projection periods can be summarized through scatter plots showing a subsample of 500 probabilistic trajectories of life expectancy at birth for males and females (figure II.9). The 80 and 95 per cent prediction intervals are shown as ellipses. The diagonal line represents equal male and female life expectancies. Graphs of the distributions of life expectancy by sex for all countries are available online.[53]

---

[53] United Nations, Department of Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. New York: United Nations. Online plots of Comparison between probabilistic projections of male and female life expectancies at birth for selected projection periods: 80 and 95 per cent prediction intervals; see https://population.un.org/wpp/Graphs/Probabilistic/EX/FMCOMP/156.

Figure II.9
Comparison of probabilistic projections of female and male life expectancies at birth, selected periods, China (years)



NOTE: The figure shows the relationship between probabilistic projections of male and female life expectancies at birth for 1990, 2000, 2010, 2020, 2050 and 2100, computed on the basis of estimates from the *2022 Revision* of the *World Population Prospects*. For ease of viewing, only 500 of the 10,000 projected trajectories are shown here for each sex.

3. *Special considerations for countries affected by HIV and AIDS*

The *2022 Revision* took the same approach as the *2019 Revision* to project the life expectancy at birth of countries affected by the HIV and AIDS epidemic. For the 58 countries or areas having ever experienced adult HIV prevalence of one per cent or more among males or females during the period 1980 and 2021, the levels of life expectancy at birth were projected using the existing Bayesian probabilistic life expectancy projection methods (Ševčíková and others, 2022e) extended to account for past and expected levels and trends in HIV prevalence and adult antiretroviral therapy (ART) coverage (Godwin and Raftery, 2017). The latest epidemiological data for these countries referred to the period 1980-2019 (UNAIDS, 2019). The projection assumptions for the future course of the HIV and AIDS epidemic were similar as in previous revisions: the *2022 Revision* assumed that the HIV prevalence rate observed in 2019 would decline by 2100 to about one-tenth of its value, following an exponential decay function. Coverage of ART was projected to reach 90 per cent in 2050 if it was below 85 per cent in 2019 or to reach 95 per cent if it was above 85 per cent in 2019; it remained constant thereafter until 2100. All computations for the probabilistic projections of life expectancy at birth for HIV and AIDS countries were performed using the open source “bayesLifeHIV” R package (Ševčíková and others, 2022b).

4. *Adjustments for future mortality improvements for selected countries or areas*

The approach to project life expectancy described above worked well for the majority of countries that have experienced normal or typical improvements in survival since the 1950s. But some countries stood out either because of much faster or much slower improvements than those experienced by other countries. Countries that experienced much faster gains in life expectancy since the 1950s, or over segments of the estimation period, tend to be those where low life expectancy remains relatively low. In some of these countries, a relatively fast decline in child mortality in the latter part of the estimation period contributed to an unreasonably optimistic projection of the life expectancy at birth. Conversely, for several countries that experienced periods of stagnating mortality in the estimation period, the standard model described above produced unreasonably pessimistic projections of life expectancy. In both cases, adjustments were made such that the four parameters of the double logistic function responsible for future gains for each country were informed by the experience of the leading countries in its respective region.

The countries to which adjustments were applied are listed in table II.2 together with the respective values used as priors for each adjusted parameter[54]. In cases of too-optimistic projections of life expectancy, this approach was used to temper unreasonably high values over the long term and thus avoid implausible outcomes or crossovers in the long-term projections (i.e., countries that were lagging in the recent observation period becoming leaders by 2100). In cases of too-pessimistic projections of life expectancy, this approach was used to provide further guidance on the trajectory of long-term potential gains, assuming that, in the long run, these countries would gradually catch up with the more advanced countries in their region.

Table II.2

Countries for which adjustments were made to the default mortality projection trajectory in the 2022 Revision

A. Countries with projected life expectancies that were deemed too high	Upper bound for country-specific priors of the double-logistic parameters			
Country or area	Δ_{c3}	Δ_{c4}	k^c	z^c
1. Afghanistan	11.77	18.46	0.7440	0.1225
2. Andorra	14.54	20.82	0.6283	0.1235
3. Angola	11.82	17.40	0.4796	0.1200
4. Benin	13.60	20.51	0.4813	0.1226
5. Bolivia (Plurinational State of)	13.36	19.72	0.4756	0.1227
6. Botswana	12.88	19.93	0.5057	0.1227
7. Brunei Darussalam	14.04	20.38	0.8943	0.1222
8. Burkina Faso	13.75	20.52	0.4813	0.1226
9. Burundi	12.92	19.97	0.4666	0.1224
10. Cambodia	13.13	20.19	0.7324	0.1228
11. Cameroon	13.25	20.26	0.6448	0.1226
12. Central African Republic	13.25	20.26	0.4392	0.1226
13. Chad	12.61	19.42	0.3547	0.1200
14. Côte d'Ivoire	13.49	20.55	0.4813	0.1226
15. Dem. Rep. of the Congo	13.25	20.26	0.4578	0.1226
16. Ecuador	13.54	20.34	0.6795	0.1230

---

[54] Following the formal notation of Raftery and others (2013), country-specific priors were specified for the first set of countries for the upper bound of the Δ_{c3}, Δ_{c4}, k^c and z^c double-logistic parameters while for the second set of countries, the lower bound were used for these parameters. In general, the upper quartile of the distribution of these parameters for the best performers in each region was used to inform other countries.

A. Countries with projected life expectancies that were deemed too high	Upper bound for country-specific priors of the double-logistic parameters			
Country or area	Δ_{c3}	Δ_{c4}	k^c	z^c
17. El Salvador	12.87	19.44	0.8060	0.1219
18. Equatorial Guinea	13.25	20.26	0.4392	0.1226
19. Falkland Islands (Malvinas)	13.54	18.98	0.6807	0.1233
20. French Polynesia	13.67	20.88	0.3975	0.1243
21. Gabon	12.34	18.03	0.7681	0.1226
22. Gambia	13.36	20.43	0.6885	0.1226
23. Guadeloupe	13.95	21.09	0.3975	0.1242
24. Guatemala	12.87	19.44	0.5693	0.1219
25. Guinea	13.60	20.38	0.4268	0.1226
26. Guinea-Bissau	13.75	20.41	0.4813	0.1226
27. Lao People's Dem. Republic	12.51	19.35	0.5824	0.1203
28. Madagascar	13.94	20.44	0.5260	0.1228
29. Malawi	13.83	20.36	0.6627	0.1227
30. Maldives	14.04	19.21	1.0165	0.1230
31. Mali	12.93	19.64	0.5417	0.1200
32. Martinique	13.95	21.09	0.3975	0.1241
33. Monaco	14.12	21.68	0.8398	0.1243
34. New Caledonia	13.67	20.88	0.3975	0.1240
35. Nicaragua	12.87	19.44	0.7092	0.1219
36. Niger	12.77	18.70	0.4430	0.1200
37. Peru	13.48	18.67	0.5169	0.1228
38. Republic of Korea	14.15	22.45	0.8398	0.1243
39. Réunion	13.95	21.09	0.3975	0.1236
40. Sierra Leone	13.75	20.40	0.4344	0.1227
41. Timor-Leste	13.13	20.19	0.6593	0.1229
42. Wallis and Futuna Islands	13.67	20.02	0.3975	0.1227
43. Western Sahara	13.32	19.95	0.7335	0.1202

B. Countries with projected life expectancies that were deemed too low	Lower bound for country-specific priors of the double-logistic parameters			
Country or area	Δ_{c3}	Δ_{c4}	k^c	z^c
1. Belize	10.29	16.38	0.8636	0.1031
2. Bermuda	10.83	16.43	0.9339	0.1050
3. Dominica	10.98	17.70	1.3365	0.1071
4. Faeroe Islands	10.67	16.68	0.8748	0.1060
5. Gibraltar	10.72	18.18	0.7984	0.1068
6. Hungary	10.59	15.72	1.3854	0.1078
7. Jersey	10.59	16.82	0.6014	0.1053
8. Kenya	10.44	16.50	0.4739	0.1030
9. Liechtenstein	11.31	17.64	0.4483	0.1118
10. Nauru	10.79	16.92	0.3854	0.1070
11. Pakistan	11.47	17.17	1.0098	0.1079

A. Countries with projected life expectancies that were deemed too high	Upper bound for country-specific priors of the double-logistic parameters			
Country or area	Δ_{c3}	Δ_{c4}	k^c	z^c
12. Palau	10.79	16.92	0.3854	0.1070
13. Philippines	11.15	17.03	1.6162	0.1103
14. Romania	10.58	16.17	1.3854	0.1078
15. Serbia	11.19	17.19	0.8540	0.1085
16. Sudan	11.07	16.92	1.0438	0.1080
17. United States Virgin Islands	10.83	16.48	1.6952	0.1027
18. Viet Nam	11.32	17.59	1.6162	0.1103

5. *Special considerations in the context of the COVID-19 pandemic*

The impacts of the COVID-19 pandemic, which caused reductions in life expectancies across much of the world in 2020 and 2021, necessitate a modified approach to the short-term projections of life expectancy. At the time the *2022 Revision* was finalized, the mortality impacts of COVID-19 were receding in many countries, especially those where large proportions of the population were vaccinated against the virus. For these countries, it was assumed that the life expectancy at birth would return to pre-pandemic trajectory in 2022. In countries where the mortality impacts of COVID-19 were especially large or where vaccination rates were low, it was assumed that future life expectancies would continue to be affected by COVID-19 in 2022 or later, before eventually returning to the respective country-specific pre-pandemic trajectories.

The number of years to recovery to the expected pre-pandemic levels was determined for each country following these set of criteria:

Table II.3

Assumptions used to estimate the number of years to pre-pandemic mortality levels

Change in life expectancy at birth in 2020 compared to 2018-2019 baseline	*Change in life expectancy at birth in 2021 compared to 2018-2019 baseline*	*COVID-19 vaccine coverage (1 or more doses) as of mid-May 2022*	*Number of years to return to pre-pandemic levels*	*Assumed year to return to pre-pandemic levels*
Decline	More Decline	Less than 25 %	3	2025
Decline	More Decline	25-49 %	2	2024
Decline	More Decline	50 % or more	1	2023
Decline	Decline	Less than 25 %	2	2024
Decline	Decline	25-49 %	1	2023
Decline	Decline	50 % or more	0	2022
Decline	Partial recovery	Less than 25 %	2	2024
Decline	Partial recovery	25-49 %	1	2023
Decline	Partial recovery	50 % or more	0	2022
Decline	Recovery		0	2022
No Decline	Decline	Less than 25 %	2	2024
No Decline	Decline	25-49 %	1	2023
No Decline	Decline	50 % or more	0	2022
No Decline	No Decline		0	2022

For these countries, the values of life expectancy at birth projected for between 2022 and 2024 were adjusted by blending the most recent observed trend up to 2021 with the unadjusted model prediction for 2022-2024 based on the pre-pandemic levels and trends (i.e., information for 2020-2021 was excluded). A spline interpolation was constrained on these three periods to predict respectively the values for 2022-2024. All probabilistic trajectories were proportionately adjusted to reflect these values in the median trajectory for each country.[55]

D. PROJECTING AGE PATTERNS OF MORTALITY

Once the path of future life expectancy was determined, mortality rates by single year of age and sex were calculated, consistent with the projected life expectancy at birth for each year. The specific approach employed to project sex- and age-specific mortality for each country depended on the type and quality of empirical information used to estimate the age pattern of mortality for recent periods:

a) Model life tables (MLT)

For eight countries or areas, projected sex-specific mortality rates were obtained from an underlying model life table matched to the projected life expectancy at birth. Model patterns were selected from the set of model life tables extended to a maximum life expectancy at birth of 100 years (Li and Gerland, 2011)[56]. The Coale-Demeny North family of model life tables was used for Gibraltar and Isle of Man. The Coale-Demeny West family was used for Falkland Island (Malvinas), Guernsey, Holy See, Jersey, and Liechtenstein. The UN Far Eastern family was used for Wallis and Futuna Islands.

b) Modified Lee-Carter method (LC)

For 25 countries with high-quality information on mortality age patterns[57], sex- and age-specific mortality rates were projected by extrapolating country-specific historical trends using the modified Lee-Carter method constrained to the projected life expectancy at birth (Li and others, 2013). This method selects appropriate increases in the level parameter (k_t) for each year of the projection with the age pattern (a_x) based on the average of 2015 through 2019 and smoothed over age. The age pattern of mortality improvement (b_x) gradually changes by level of mortality to reflect a deceleration of mortality decline at younger ages and an acceleration at old ages.

c) Pattern of mortality decline method (PMD)

The remaining 204 countries or areas had some recent and reliable empirical information on mortality age patterns, but without the quality or time-coverage needed for the modified Lee-Carter method to yield stable results (Gu and others, 2017). For these countries, projected sex- and age-specific mortality rates were obtained from a model of the typical age-specific patterns of mortality improvement given the level of life expectancy at birth. This model was calibrated to the range of country experiences represented in the HMD (Andreev and others, 2013)[58]. For each country, the model was fit to the mortality pattern of a recent year or years that was not impacted by COVID-19 or other crisis mortality, smoothed over age as warranted.

---

[55] The adjustment for a country and time period corresponds to the ratio between the unadjusted median life expectancy at birth and adjusted median life expectancy at birth, and is applied to each life expectancy at birth probabilistic trajectory for the corresponding country and period.

[56] The last available entry in the revised system of model life tables of 100.0 years of life expectancy, for both males and females, is not meant to represent a ceiling for human longevity.

[57] Including Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, United Kingdom, and United States of America.

[58] Available demographic data have permitted reliable estimation of the patterns of mortality improvement only up to 75-80 years of e0 for males, and 80-85 years for females. For extrapolating patterns of mortality improvement into higher levels of life expectancy at birth, smoothed linear trends were extrapolated for levels of life expectancy at birth up to 105-110 years of age.

> To impose some structure on the projected mortality patterns over the long-term projection horizon, those obtained from the PMD model were blended gradually towards a model life table age pattern of mortality matched to the projected life expectancy at birth. The Coale-Demeny West family of model life tables was used for 142 countries, the Coale-Demeny North family for 50 countries, and the UN Far Eastern family for 12 countries.

Where necessary, projected mortality age patterns were constrained below age 60 to avoid implausible cross-over between male and female mortality patterns, especially at very high levels of projected life expectancies. An open source implementation of these three projection methods is available through the "MortCast" R package (Ševčíková and others, 2022c; Ševčíková and others, 2016).

For the 116 countries expected to continue to experience mortality impacts of the COVID-19 pandemic in 2022 or beyond, additional steps were implemented to blend the mortality age pattern projected for the COVID-19 recovery period into the longer-term post-COVID projected mortality rates. First, the PMD method was used to project the age pattern of mortality based on the mortality rates estimated for 2021. These COVID-affected projected rates were then blended with the mortality rates that were projected based on the pre-COVID mortality, such that the weight given to the COVID-affected mortality schedules decreases with time.

E. INTERNATIONAL MIGRATION IN THE MEDIUM SCENARIO

International migration is the component of population change that is most difficult to project. Data on past trends are often sparse or incomplete. Moreover, the movement of people across international borders, which is often a response to rapidly changing economic, social, political and environmental factors, is an erratic process. In some instances, both the volume and direction of international migration have changed significantly within a short period of time. Some countries that historically have been primarily countries of origin have become countries of destination of international migrants, and vice versa. Any long-range assumption about future trends in international migration is virtually guaranteed to prove incorrect. Given that migration flows to and from most countries tend to be small relatively to the size of the total population, these errors are not expected to substantially influence the population projections. But for those countries where international migration has been or will become a dominant factor in demographic change, the assumption applied in the projection can be highly consequential.

The basic approach for formulating future net international migration assumptions is straight-forward for most countries. For any given country, a distinction was made between international migration flows and the movement of refugees. For most countries, the level of net international migration projected for the *2022 revision* was identical or very similar to that projected for the *2019 revision*. For countries for which the level of net international migration projected in the *2022 Revision* was changed from the *2019 Revision*, it was assumed that levels estimated for the period prior to the start of the COVID-19 pandemic (i.e., pre-2020), if stable, would continue through the remainder of the century. The government's views on international migration as well as estimates of undocumented and irregular migration flows affecting a country were also considered. Regarding the movements of refugees, it was assumed in general that approximately two-thirds of refugees would return to their country of origin within five years.

Usually, migration assumptions are expressed in terms of the net number of international migrants. The distribution of international migrants by sex and age was established on the basis of what was known about the recent sex- and age-patterns of net international migration for each country. For most countries, model patterns (including the family, male labour, female labour, and population distribution patterns described in section I.E) were used to distribute the projected net number of migrants by sex and age.

For some countries where the direction of net international migration changes over age (e.g., where there is net emigration of young adults who leave for education or employment and a net immigration of older persons following retirement) model age patterns do not adequately represent the most likely future age distributions of international migration. In these instances, the projected sex- and age pattern of net international migration is represented by the average distribution estimated over the period 2011 to 2021, smoothed over age using a simple moving average. This approach was used for 12 countries or areas: Aruba, Belarus, Bulgaria, Comoros, Czechia, Dominica, Estonia, France, Kenya, Mexico, Puerto Rico and Viet Nam.

For several countries of the Gulf region where demographic change is dominated by the flows of temporary labour migrants, including Bahrain, Oman, Qatar and the United Arab Emirates, an effort was made to model the return flow of those migrants, taking into account their ageing.

As with estimates, net migration balancing was carried out for projections as a final step to ensure that at the global level the sum of all net international migration flows equalled zero for each year of the projection period.

F. TEN PROJECTION SCENARIOS

The *2022 Revision* includes ten deterministic projection scenarios that illustrate the impact of differing assumptions from the medium scenario (table II.4). Five of those scenarios differ only with respect to the level of fertility, that is, they share the same assumptions with respect to sex ratio at birth, mortality and international migration. The five fertility scenarios are: medium, low, high, constant-fertility and instant-replacement-fertility. A comparison of the results from these five scenarios allows an assessment of the effects that different fertility assumptions have on other demographic parameters.

Under the high scenario, fertility is projected to remain 0.5 births above the fertility in the medium scenario over the entire projection period except for the initial years. To create a smooth transition between levels observed for the baseline period (2021) and future levels within the high scenario, fertility for the high scenario was assumed to be 0.25 births higher in the first five years of the projection (2022-2026) compared to the baseline, 0.4 births higher in the second five years of the projection (2027-2031), and 0.5 births higher thereafter. Thus, starting in 2032, fertility in the high scenario was assumed to be 0.5 births higher than that of the medium scenario. In other words, a country with a total fertility rate of 2.1 births per woman in some time period under the medium scenario would have a total fertility of 2.6 births per woman in the high scenario.

Under the low scenario, fertility is projected to remain 0.5 births below the fertility in the medium scenario over most of the projection period. To ensure a smoother transition between the baseline period (2021) and the low scenario, fertility in the low scenario is initially 0.25 births lower in the first five years of the projection (2022-2026), 0.4 births lower in the second five years of the projection (2027-2031), and 0.5 births lower thereafter. By 2032, fertility in the low scenario is therefore half a child lower than that of the medium scenario. That is, countries reaching a total fertility rate of 2.1 births per woman in the medium scenario have a total fertility rate of 1.6 births per woman in the low scenario.

As the name implies, under the constant-fertility scenario, fertility in all countries remains constant at the level projected for 2022.[59] Meanwhile, mortality and migration assumptions are the same as those in the medium fertility scenario.

Under the instant-replacement scenario, for each country, fertility is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2022. Fertility varies over the remainder of the projection period in such a way that the net reproduction rate always remains equal to one ensuring, over the long run, the replacement of the population.[60] Mortality and migration assumptions are the same as those in the medium fertility scenario.

Table II.4
Projection scenarios in terms of assumptions for fertility, mortality and international migration

Projection scenarios	*Assumptions*		
	Fertility	*Mortality*	*International migration*
Medium	Medium*	Medium*	Medium
High fertility	High	Medium	Medium
Low fertility	Low	Medium	Medium
Constant-fertility	Constant as of 2022	Medium	Medium
Instant-replacement-fertility	Instant-replacement as of 2022	Medium	Medium
Constant-mortality	Medium	Constant as of 2022	Medium
No change	Constant as of 2022	Constant as of 2022	Medium
Zero-migration	Medium	Medium	Zero from 2022
Instant replacement zero-migration	Instant-replacement as of 2022	Medium	Zero from 2022
Momentum	Instant-replacement as of 2022	Constant as of 2022	Zero from 2022

* Based on the median probabilistic projection.

In addition to the five fertility scenarios, a constant-mortality scenario, a zero-migration scenario, an instant replacement zero-migration scenario, and a “no change” scenario, that is, both fertility and mortality are kept constant, have been computed. The constant-mortality scenario and the zero-migration scenario both use the medium-fertility assumption, while the instant replacement zero-migration scenario uses the instant replacement fertility assumption. The constant-mortality and no change scenarios have the same international migration assumption as the medium scenario. Consequently, the results of the constant-mortality scenario can be compared with those of the medium scenario to assess the effect that changing mortality has on population size and composition. Similarly, the zero-migration scenario differs from the medium scenario only with respect to the underlying assumption regarding international migration. Therefore, the zero-migration scenario allows for an assessment of the effect that non-zero net migration has on various population size and composition. When compared to the medium scenario, the no change scenario sheds light on the effects that changing fertility and mortality have on the results obtained.

---

[59] In previous revisions of the World Population Prospects, this variant has held fertility constant at the level of the last estimate. For the 2022 Revision, the last estimate refers to the year 2021, during which fertility in many countries was influenced by factors related to the COVID-19 pandemic. Rather than carry forward pandemic-affected fertility levels, the constant-fertility assumption in the 2022 Revision holds fertility constant at the first projected level for 2022.

[60] Mortality levels are also taken into account while measuring the replacement level.

A final scenario, called "momentum" illustrates the impact of age structure on long-term population change (United Nations, 2017a). This scenario combines elements of three scenarios: the instant-replacement-fertility scenario, the constant-mortality scenario, and the zero-migration scenario.

G. POPULATION PROJECTION METHOD

Population projection was carried out using the same CCMPP engine as for estimates, described in section I.A of this report.

Two types of population projections were included in the *2022 Revision*: a deterministic version and a probabilistic version.

a) In the deterministic versions, the population was projected using the trajectories of fertility, mortality and net international migration described in the previous section. Computations for geographic aggregates and other country-groupings were carried out as described in section I.A of this report.

b) The probabilistic version extended the deterministic medium scenario by incorporating uncertainty about future changes in fertility and mortality. For each country, 2,000 population projections were computed from 2022 to 2100, each one using a projected trajectory of total fertility rates and a projected trajectory of life expectancy in the country sampled from the predictive distribution of these quantities. The various population and demographic indicators, including vital events and vital rates, were computed for each trajectory, and summarized through 80 and 95 per cent prediction intervals. All computations were done using the open source "bayesPop" R package updated to work with single years of age and one-year periods of time (Ševčíková and others, 2022d; Ševčíková and Raftery, 2016). These probabilistic projections do not incorporate uncertainty about future net international migration, for reasons outlined above, nor do they take into account the uncertainty in the baseline population or mortality rates, but in the *2022 Revision* they incorporate the uncertainty in past fertility estimates. Computations for geographic aggregates and other country groupings were first performed at the trajectory level, and the aggregated results of the 2,000 trajectories of population and vital events used to derive summary statistics. Between-country correlations not captured by the Bayesian hierarchical projection model for total fertility are incorporated into the final projected trajectories for each country using the method described in Fosdick and Raftery (2014) through a set of time invariant covariates, that is, whether the countries are contiguous, whether they were colonized by the same country after 1945, and whether they are located in the same continental region. For mortality, the modelling approach used (Raftery and others, 2013; Raftery and others, 2014b; Godwin and Raftery, 2017) does not require additional provisions for between-country correlations in life expectancy.

ANNEX

Methodological note on extrapolation and graduation of model life table reference data:

1) Extrapolation to life expectancies at birth up to 115 years

In 2010, in preparation for an extended projection horizon to the year 2100 in the 2012 revision of the World Population Prospects, the United Nations Population Division extrapolated the set of Coale-Demeny and United Nations abridged model life tables to life expectancies at birth up to 100 years (Li and Gerland, 2011)[61].

Since then, with the adoption of Bayesian methods for projecting the life expectancies at birth, there is a need to extrapolate the model life table patterns even further in order to accommodate the more extreme values of that can arise with many thousands of projected trajectories of e0 over an 80-year horizon. Thus in preparation for the *2022 Revision* of the *World Population Prospects*, the Coale-Demeny and United Nations abridged Model Life Table patterns were extrapolated to life expectancies at birth up to 115 years[62].

Extrapolation was carried out for each model life table family by fitting a limited Lee-Carter forecast (using the interp_lc_lim() function of the DemoTools package for R) to the abridged set model life table patterns associated with life expectancies of 90, 92.5, 95, 97.5 and 100 years. The resulting set of extrapolated life tables have life expectancies at birth ranging from 102.5 years to 115 years, in increments of 2.5 years. Taken together with the previous set of abridged model patterns to life expectancy 100 years, these life tables form smooth mortality surfaces by age and sex and e0 levels.

2) Graduation to single year of age

For the *2022 Revision*, the Population Division transitioned from the historical practice of estimating population and demographic rates for five-year age groups and five-year periods of time to single year age groups and one-year periods of time. This “one-by-one” framework necessitated model life table patterns that correspond to single years of age.

Each of the abridged model life tables described above was graduated to single years of age using the lt_abridged2single() function of the DemoTools package for R. This function, in turn, called the pclm() function of the ungroup package to return single-age mortality rates (${}_1m_x$) by splitting the ${}_nd_x$ life table deaths, offset by ${}_nL_x$ life table person-years of exposure. For ages 110 through 130, the ${}_1m_x$ were modelled by fitting a Kannisto function to the 1mx of the oldest 20 ages returned by the pclm() function. The resulting model life tables by single year of age have life expectancies at birth that are very close to, though not identical, to their abridged counterparts.

---

[61] https://www.un.org/development/desa/pd/data/model-life-tables

[62] The tools used for graduation to single year of age presently do not permit extensions beyond 115 years of life expectancy at birth. In general, the pclm model cannot converge at such low levels of mortality.

REFERENCES

Alkema, L., and others (2011). Probabilistic projections of the total fertility rate for all countries. *Demography*, vol. 48, No. 3, pp. 815-39. doi: 10.1007/s13524-011-0040-5.

Altez, R., and S. Revet (2005). Contar los muertos para contar la muerte: discusión en torno al número de fallecidos en la tragedia de 1999 en el estado Vargas–Venezuela. *Revista geográfica venezolana*, vol. 46, No., pp. 21-43.

Andreev, K., and others (2013). Patterns of Mortality Improvement by Level of Life Expectancy at Birth. Annual Meeting of the Population Association of America, New Orleans, LA.

Arnold, C. (2019). Death, statistics and a disaster zone: the struggle to count the dead after Hurricane Maria. *Nature*, vol. 566, No. 7742, pp. 22-26. doi: 10.1038/d41586-019-00442-0.

Basten, S.A. (2013). *Re-Examining the Fertility Assumptions for Pacific Asia in the UN's 2010 World Population Prospects*. Barnett Papers in Social Research, No. 2013/1, Oxford, UK, University of Oxford.

Billari, F.C. (2018). A “Great Divergence” in Fertility? In *Low Fertility Regimes and Demographic and Societal Change*, edited by Jr Dudley L. Poston, pp. 15-35. Cham: Springer International Publishing.

Bohk-Ewald, C., and others (2018). Forecast accuracy hardly improves with method complexity when completing cohort fertility. *Proceedings of the National Academy of Sciences*, vol. 115, No. 37, pp. 9187-9192. doi: 10.1073/pnas.1722364115.

Bongaarts, J. (2009). Trends in senescent life expectancy. *Population Studies*, vol. 63, No. 3, pp. 203-213. doi: 10.1080/00324720903165456.

Bongaarts, J., and T. Sobotka (2012). A demographic explanation for the recent rise in European fertility. *Popul Dev Rev*, vol. 38, No. 1, pp. 83-120. doi: 10.1111/j.1728-4457.2012.00473.x.

Caltabiano, M., and others (2009). Lowest-Low Fertility: Signs of a recovery in Italy? *Demographic Research*, vol. 21, No. 23, pp. 681-718. doi: 10.4054/DemRes.2009.21.23.

Castanheira, H., and others (2017). *A Sensitivity Analysis of the Bayesian Framework for the Projections of Life Expectancy at Birth*. UN Population Division, Technical Paper, No. 2017/7, New York, United Nations.

Chahnazarian, A. (1988). Determinants of the sex ratio at birth: review of recent literature. *Social biology*, vol. 35, No. 3-4, pp. 214-235.

Chao, F. (2022). *Estimating age-sex-specific adult mortality and age-specific fertility rate in the World Population Prospects: A Bayesian modelling approach*. UN Population Division, Technical Paper, No. forthcoming, New York, United Nations.

Chao, F., and others (2019). Systematic assessment of the sex ratio at birth for all countries and estimation of national imbalances and regional reference levels. *Proceedings of the National Academy of Sciences*, vol. 116, No. 19, pp. 9303-9311.

__________ (2021). Global estimation and scenario-based projections of sex ratio at birth and missing female births using a Bayesian hierarchical time series mixture model. *The Annals of Applied Statistics*, vol. 15, No. 3, pp. 1499-1528.

Clark, S.J. (2019). A general age-specific mortality model with an example indexed by child mortality or both child and adult mortality. *Demography*, vol. 56, No. 3, pp. 1131-1159.

Coale, A.J., and others (1983). *Regional model life tables and stable populations*. 2nd ed, *Studies in population*. New York: Academic Press.

Coale, A.J., and G. Guo (1989). Revised Regional Model Life Tables at Very Low Levels of Mortality. *Population Index*, vol. 55, No. 4, pp. 613-643.

Committee for the Coordination of Statistical Activities (2020). Report of the Committee for the Coordination of Statistical Activities: Note by the Secretary-General. 2021 Statistical Commission, Fifty-second session (1–3 and 5 March 2021). New York, 16 December 2020, United Nations.

Devereux, S. (2000). *Famine in the twentieth century*. Working Paper, No.

Doocy, S., and others (2013). Mortality following the Haitian earthquake of 2010: a stratified cluster survey. *Population health metrics*, vol. 11, No. 1, pp. 1-9. doi: 10.1186/1478-7954-11-5.

Dubuc, S., and D. Coleman (2007). An increase in the sex ratio of births to India‐born mothers in England and Wales: evidence for sex‐selective abortion. *Population and Development Review*, vol. 33, No. 2, pp. 383-400.

Fogel, R.W. (2004). *The escape from hunger and premature death, 1700-2100 : Europe, America, and the Third World*, *Cambridge studies in population, economy, and society in past time*. Cambridge ; New York: Cambridge University Press.

Fosdick, B., and A. Raftery (2014). Regional probabilistic fertility forecasting by modeling between-country correlations. *Demographic Research*, vol. 30, No. 35, pp. 1011-1034. doi: 10.4054/DemRes.2014.30.35.

Frejka, T., and others (2010). East Asian childbearing patterns and policy developments. *Popul Dev Rev*, vol. 36, No. 3, pp. 579-606. doi: 10.1111/j.1728-4457.2010.00347.x.

Garenne, M. (2002). Sex ratios at birth in African populations: A review of survey data. *Human Biology*, vol., No., pp. 889-900.

__________ (2008). Poisson variations of the sex ratio at birth in African demographic surveys. *Human Biology*, vol. 80, No. 5, pp. 473-482.

Glei, D.A., and S. Horiuchi (2007). The narrowing sex differential in life expectancy in high-income populations: effects of differences in the age pattern of mortality. *Population Studies*, vol. 61, No. 2, pp. 141-59. doi: 10.1080/00324720701331433.

Godwin, J., and A.E. Raftery (2017). Bayesian projection of life expectancy accounting for the HIV/AIDS epidemic. *Demographic Research*, vol. 37, No., pp. 1549-1610. doi: 10.4054/DemRes.2017.37.48.

Goldstein, J.R., and others (2009). The End of “Lowest‐Low” Fertility? *Population and Development Review*, vol. 35, No. 4, pp. 663-699. doi: 10.1111/j.1728-4457.2009.00304.x.

Gráda, C. (2009). *Famine : a short history*. Princeton, New Jersey; Oxford: Princeton University Press.

Gráda, C.Ó. (2007). Making famine history. *Journal of economic Literature*, vol. 45, No. 1, pp. 5-38.

Graffelman, J., and R.F. Hoekstra (2000). A statistical analysis of the effect of warfare on the human secondary sex ratio. *Human Biology*, vol. 72, No. 3, pp. 433-445.

Gu, D., and others (2017). *Projecting Age-sex-specific Mortality: A Comparison of the Modified Lee-Carter and Pattern of Mortality Decline Methods*. UN Population Division, Technical Paper, No. 2017/6, New York, United Nations.

Harff, B. (2017). No lessons learned from the Holocaust? Assessing risks of genocide and political mass murder since 1955. In *Genocide and Human Rights*, pp. 329-345. Routledge.

Heuveline, P. (2003). HIV and population dynamics: a general model and maximum-likelihood standards for east Africa. *Demography*, vol. 40, No. 2, pp. 217-45. doi: 10.1353/dem.2003.0013.

Houle, B., and others (2022). Application of a Singular Value Decomposition-Based Factorization and Parsimonious-Component Model of Mortality to HIV Epidemics in Africa. PAA 2022 Annual Meeting. Atlanta, GA, PAA.

Hunter College (2018). *Puerto Rico post-Maria report*. Edited by CUNY. New York, NY: Centro de Estudios Puertorriqueños.

Institute for Health Metrics and Evaluation (2020). Global Burden of Disease Study 2019 (GBD 2019). University of Washington. Available from http://www.healthdata.org/gbd. Accessed 10 Oct. 2020.

International IDEA (2020). Voter Turnout Database.

James, W.H. (1984). The sex ratios of black births. *Annals of human biology*, vol. 11, No. 1, pp. 39-44. doi: 10.1080/03014468400006871.

__________ (1985). The sex ratio of Oriental births. *Annals of human biology*, vol. 12, No. 5, pp. 485-487. doi: 10.1080/03014468500008041.

__________ (1987). The human sex ratio. Part 1: A review of the literature. *Human biology*, vol. 59, No. 5, pp. 721-752.

Jones, G., and others (2008). *Ultra-low fertility in Pacific Asia: trends, causes and policy issues*: Taylor & Francis US.

Kaba, A.J. (2008). Sex ratio at birth and racial differences: why do black women give birth to more females than non-black women? *African journal of reproductive health*, vol. 12, No. 3, pp. 139-150.

Kane, P. (1988). *Famine in China, 1959-61 : demographic and social implications*. Basingstoke [etc.]: Macmillan.

Karlinsky, A., and D. Kobak (2021). Tracking excess mortality across countries during the COVID-19 pandemic with the World Mortality Dataset. *Elife*, vol. 10, No., pp.

Kishore, N., and others (2018). Mortality in puerto rico after hurricane maria. *New England journal of medicine*, vol. 379, No. 2, pp. 162-170. doi: 10.1056/NEJMsa1803972.

Knutson, V., and others (2022). Estimating Global and Country-Specific Excess Mortality During the COVID-19 Pandemic. *Annals of Applied Statistics*, vol. (submitted), No. arXiv:2205.09081, pp.

Li, N., and P. Gerland (2011). Modifying the Lee-Carter Method to Project Mortality Changes up to 2100. Annual Meeting of the Population Association of America, Washington, DC, 1 April 2011.

Li, N., and others (2013). Extending the Lee-carter method to model the rotation of age patterns of mortality decline for long-term projections. *Demography*, vol. 50, No. 6, pp. 2037-51. doi: 10.1007/s13524-013-0232-2.

Li, W., and D.T. Yang (2005). The great leap forward: Anatomy of a central planning disaster. *Journal of Political Economy*, vol. 113, No. 4, pp. 840-877.

Lima, E.E.C., and J.H.C. Monteiro da Silva (2021). fertestr: demographic tools for the assessment of fertility and parity data. Available from https://github.com/josehcms/fertestr. Accessed 21 Sept. 2021.

Liu, P., and A.E. Raftery (2020). Accounting for uncertainty about past values in probabilistic projections of the total fertility rate for most countries. *The annals of applied statistics*, vol. 14, No. 2, pp. 685-705. doi: 10.1214/19-aoas1294.

Lutz, W. (2007). The Future of Human Reproduction: Will Birth Rates Recover or Continue to Fall? *Ageing Horizons*, vol., No. 7, pp. 15–21.

Lutz, W., and others (2006). The Low Fertility Trap Hypothesis: Forces that May Lead to Further Postponement and Fewer Births in Europe *Vienna Yearbook of Population Research*, vol. 4, No. Postponement of Childbearing in Europe, pp. 167-192. doi: 10.1553/populationyearbook2006s167.

Marcus, M., and others (1998). Changing sex ratio in the United States, 1969–1995. *Fertility and sterility*, vol. 70, No. 2, pp. 270-273. doi: 10.1016/s0015-0282(98)00149-6.

Mathews, T., and B.E. Hamilton (2005). Trend analysis of the sex ratio at birth in the United States. *National vital statistics reports*, vol. 53, No. 20, pp. 1-17.

Max Planck Institute for Demographic Research (Germany), and others (2020). Human Life Table Database.

Max Planck Institute for Demographic Research (Germany), and Vienna Institute of Demography (Austria) (2020). Human Fertility Collection. Germany and Austria.

__________ (2021). Human Fertility Database. Germany and Austria.

Meslé, F. (2004). Gender gap in life expectancy: the reasons for a reduction of female advantage. *Revue d'Epidémiologie et de Santé Publique*, vol. 52, No. 4, pp. 333-52. doi: 10.1016/s0398-7620(04)99063-3.

Moultrie, T.A., and others (2013). Tools for Demographic Estimation. In: International Union for the Scientific Study of Population. http://demographicestimation.iussp.org/.

Myrskylä, M., and others (2013). New Cohort Fertility Forecasts for the Developed World: Rises, Falls, and Reversals. *Population and Development Review*, vol. 39, No. 1, pp. 31-56. doi: 10.1111/j.1728-4457.2013.00572.x.

Myrskyla, M., and others (2009). Advances in development reverse fertility declines. *Nature*, vol. 460, No. 7256, pp. 741-3. doi: 10.1038/nature08230.

Oeppen, J., and J.W. Vaupel (2002). Demography. Broken limits to life expectancy. *Science*, vol. 296, No. 5570, pp. 1029-31. doi: 10.1126/science.1069675.

Oksuzyan, A., and others (2008). Men: good health and high mortality. Sex differences in health and aging. *Aging Clinical and Experimental Research*, vol. 20, No. 2, pp. 91-102. doi: 10.1007/bf03324754.

Palloni, A., and others (2021). Latin American Mortality Database (LAMBdA). Madison: University of Wisconsin.

Pampel, F. (2005). Forecasting sex differences in mortality in high income nations: The contribution of smoking. *Demographic Research*, vol. 13, No. 18, pp. 455-484. doi: 10.4054/DemRes.2005.13.18.

Pantazis, A., and S.J. Clark (2018). A parsimonious characterization of change in global age-specific and total fertility rates. *PloS one*, vol. 13, No. 1, pp. e0190574. doi: 10.1371/journal.pone.0190574.

Preston, S. (1984). The Use of Direct and Indirect Techniques for Estimating the Completeness of Death Registration Systems. In *Data bases for mortality measurements*, edited by United Nations, pp. 66-76. New York.

Preston, S.H., and others (2001). *Demography : measuring and modeling population processes*. Malden, MA: Blackwell Publishers.

Raftery, A., and others (2009). White Paper: Probabilistic Projections of the Total Fertility Rate for All Countries for the 2010 World Population Prospects. Expert Group Meeting on Recent and Future Trends in Fertility, New York, NY, 2-4 December 2009.

Raftery, A.E., and others (2014a). Bayesian Population Projections for the United Nations. *Statistical Science*, vol. 29, No. 1, pp. 58-68. doi: 10.1214/13-STS419.

Raftery, A.E., and others (2013). Bayesian probabilistic projections of life expectancy for all countries. *Demography*, vol. 50, No. 3, pp. 777-801. doi: 10.1007/s13524-012-0193-x.

Raftery, A.E., and others (2014b). Joint Probabilistic Projection of Female and Male Life Expectancy. *Demographic Research*, vol. 30, No. 27, pp. 795-822. doi: 10.4054/DemRes.2014.30.27.

Reher, D.S. (2019). The Aftermath of the Demographic Transition in the Developed World: Interpreting Enduring Disparities in Reproductive Behavior. *Population and Development Review*, vol. 47, No. 2, pp. 475-503. doi: https://doi.org/10.1111/padr.12266.

Riffe, T., and others (2022a). DemoTools: An R package of tools for aggregate demographic analysis. Available from https://timriffe.github.io/DemoTools/.

Riffe, T., and others (2022b). DDSQLtools: wrappers for the DemoTools package to work with UNPD SQL data format. Available from https://timriffe.github.io/DDSQLtools/.

Riley, J.C. (2001). *Rising life expectancy : a global history*. Cambridge ; New York: Cambridge University Press.

Rivera, R., and W. Rolke (2019). Modeling excess deaths after a natural disaster with application to Hurricane Maria. *Statistics in medicine*, vol. 38, No. 23, pp. 4545-4554. doi: 10.1002/sim.8314.

Rogers, A., and L.J. Castro (1981). Model migration schedules. vol., No., pp.

Rogers, R.G., and others (2010). Social, behavioral, and biological factors, and sex differences in mortality. *Demography*, vol. 47, No. 3, pp. 555-78. doi: 10.1353/dem.0.0119.

Ruder, A. (1985). Paternal-age and birth-order effect on the human secondary sex ratio. *American journal of human genetics*, vol. 37, No. 2, pp. 362-72.

Rummel, R.J. (1999). *Statistics of democide : genocide and mass murder since 1900*. London: Transaction Books.

Santos-Lozada, A.R., and J.T. Howard (2018). Use of death counts from vital statistics to calculate excess deaths in Puerto Rico following Hurricane Maria. *Jama*, vol. 320, No. 14, pp. 1491-1493.

Schmertmann, C.P. (2014). Calibrated spline estimation of detailed fertility schedules from abridged data[1]. *Revista Brasileira de Estudos de População*, vol. 31, No., pp. 291-307.

Schoumaker, B. (2013). A Stata module for computing fertility rates and TFRs from birth histories: tfr2. *Demographic research*, vol. 28, No., pp. 1093-1144.

__________ (2020). Estimation of fertility rates from survey full histories and HDSS. Expert group meeting on methods for the World Population Prospects 2021 and beyond, New York, N.Y., 6-8 April 2020.

Ševčíková, H., and others (2022a). bayesTFR: Bayesian Fertility Projection. R Package and documentation version 7.1-1. Available from https://cran.r-project.org/web/packages/bayesTFR/. Accessed 24 May 2022.

Ševčíková, H., and others (2011). bayesTFR: An R package for probabilistic projections of the total fertility rate. *Journal of Statistical Software*, vol. 43, No. 1, pp. 1-29. doi: 10.18637/jss.v043.i01.

Ševčíková, H., and others (2022b). bayesLifeHIV: Bayesian Projection of Life Expectancy with HIV. R Package and documentation version 1.1-0.9001. Available from https://github.com/PPgp/bayesLifeHIV/. Accessed 11 May 2022.

Ševčíková, H., and others (2022c). MortCast: Estimation and Projection of Age-Specific Mortality Rates. R Package and documentation version 2.7-0.9001. Available from https://cran.r-project.org/web/packages/MortCast/. Accessed 10 June 2022.

Ševčíková, H., and others (2016). Age-Specific Mortality and Fertility Rates for Probabilistic Population Projections. In *Dynamic Demographic Analysis*, edited by Robert Schoen, pp. 285-310. Cham: Springer International Publishing.

Ševčíková, H., and A.E. Raftery (2016). bayesPop: Probabilistic Population Projections. *Journal of statistical software*, vol. 75, No., pp. doi: 10.18637/jss.v075.i05.

Ševčíková, H., and others (2022d). bayesPop: Probabilistic Population Projection. R Package and documentation version 9.0-1. Available from https://cran.r-project.org/web/packages/bayesPop/. Accessed 10 June 2022.

Ševčíková, H., and others (2022e). bayesLife: Bayesian Projection of Life Expectancy. R Package and documentation version 5.0-3. Available from https://cran.r-project.org/web/packages/bayesLife/. Accessed 22 March 2019.

Silva, R., and P.D. Ball (2006). *The Profile of Human Rights Violations in Timor-Leste, 1974-1999*, *A Report by the Benetech Human Rights Data Analysis Group to the Commission on Reception, Truth and Reconciliation.*: Benetech Initiative.

Sobotka, T. (2011). Fertility in Central and Eastern Europe after 1989: Collapse and Gradual Recovery. *Historical Social Research-Historische Sozialforschung*, vol. 36, No. 2, pp. 246-296.

Sobotka, T., and É. Beaujouan (2014). Two Is Best? The Persistence of a Two-Child Family Ideal in Europe. *Population and Development Review*, vol. 40, No. 3, pp. 391-419. doi: 10.1111/j.1728-4457.2014.00691.x.

Stanecki, K., and others (2012). Developments in the field of HIV estimates: methods, parameters and trends. *Sexually Transmitted Infections*, vol. 88 Suppl 2, No. Suppl 2, pp. i1-i2. doi: 10.1136/sextrans-2012-050885.

Stevens, G.A., and others (2016). Guidelines for accurate and transparent health estimates reporting: the GATHER statement. *PLoS medicine*, vol. 13, No. 6, pp. e1002056. doi: 10.1016/S0140-6736(16)30388-9.

Stover, J., and others (2014). Updates to the spectrum model to estimate key HIV indicators for adults and children. *AIDS*, vol. 28 Suppl 4, No. 4, pp. S427-34. doi: 10.1097/QAD.0000000000000483.

Stover, J., and others (2012). Updates to the Spectrum/Estimation and Projection Package (EPP) model to estimate HIV trends for adults and children. *Sex Transm Infect*, vol. 88 Suppl 2, No., pp. i11-6. doi: 10.1136/sextrans-2012-050640.

Trovato, F., and N.B. Heyen (2006). A varied pattern of change of the sex differential in survival in the G7 countries. *J Biosoc Sci*, vol. 38, No. 3, pp. 391-401. doi: 10.1017/S0021932005007212.

Trovato, F., and N.M. Lalu (1996). Narrowing sex differentials in life expectancy in the industrialized world: early 1970's to early 1990's. *Soc Biol*, vol. 43, No. 1-2, pp. 20-37. doi: 10.1080/19485565.1996.9988911.

___________ (1998). Contribution of cause-specific mortality to changing sex differences in life expectancy: seven nations case study. *Soc Biol*, vol. 45, No. 1-2, pp. 1-20. doi: 10.1080/19485565.1998.9988961.

U.S. Bureau of the Census (2020). International Data Base. International Programs Center (IPC), Population Division. Available from https://www.census.gov/programs-surveys/international-programs/about/idb.html. Accessed 18 March 2021.

UNAIDS (2019). AIDS Info Database. In *UNAIDS Data 2019.* Geneva (Switzerland): Joint United Nations Programme on HIV/AIDS (UNAIDS).

UNESCO Institute for Statistics (2020). UIS database: enrolment by level of education, and official school ages for each country.: UNESCO.

United Nations (1956). *Manual III: Methods for Population Projections by Sex and Age*. Edited by Population Division Dept. of Economic and Social Affairs. Vol. 25, *Population Studies*. New York: United Nations.

__________ (1982). *Model life tables for developing countries*. Edited by Population Division Dept. of International Economic and Social Affairs., *Population studies*. New York: United Nations.

__________ (2006). *World Population Prospects: The 2004 Revision, Volume III: Analytical Report*. No. ST/ESA/SER.A/246, New York, Department of Economic and Social Affairs, Population Division.

__________ (2010). *Post Enumeration Surveys. Operational Guidelines*. Technical Report, No., New York, United Nations.

__________ (2011). Extended Model Life Tables Version 1.3. Department of Economic and Social Affairs, Population Division. Available from https://www.un.org/en/development/desa/population/publications/mortality/model-life-tables.asp. Accessed 1 July 2019.

__________ (2014a). *Principles and Recommendations for a Vital Statistics System, Revision 3*. Edited by Statistics Division Department of Economic and Social Affairs. Rev. 3 ed, *New York, NY*. New York, NY: United Nations.

__________ (2014b). *World Population Prospects: The 2012 Revision - Methodology of the United Nations Population Estimates and Projections*. Working Paper, No. ESA/P/WP.235, New York, Population Division, Dept. of Economic and Social Affairs.

__________ (2015). *World Population Prospects: The 2015 Revision - Methodology of the United Nations Population Estimates and Projections*. Working Paper, No. ESA/P/WP.242, New York, Population Division, Dept. of Economic and Social Affairs.

__________ (2017a). *The impact of population momentum on future population growth*. Population Facts, No. 2017/4, New York, N.Y., United Nations Publications.

__________ (2017b). *Principles and Recommendations for Population and Housing Censuses, Revision 3*. No., New York, NY, United Nations, ST/ESA/STAT/SER.M/67/Rev.3.

__________ (2017c). *World Population Prospects: The 2017 Revision - Methodology of the United Nations Population Estimates and Projections*. Working Paper, No. ESA/P/WP.250, New York, Population Division, Dept. of Economic and Social Affairs.

__________ (2019a). *How certain are the United Nations global population projections?* Population Facts, No. 2019/6, New York, N.Y., United Nations Publications.

__________ (2019b). *World Population Prospects 2019: Methodology of the United Nations population estimates and projections*. Working Paper, No. ST/ESA/SER.A/425, New York, Population Division, Dept. of Economic and Social Affairs.

__________ (2020). Report of the meeting. Expert group meeting on methods for the World Population Prospects 2021 and beyond, New York, N.Y., 6-8 April 2020.

__________ (2022). wpp2022: World Population Prospects 2022: R Package and documentation version 1.0. Population Division, Dept. of Economic and Social Affairs. Available from https://github.com/PPgp/wpp2022. Accessed 11 July 2022.

United Nations. Interagency Group for Child Mortality Estimation (2021). *Levels & trends in child mortality: report 2021: estimates developed by the UN Inter-Agency Group for Child Mortality Estimation*: United Nations Children's Fund.

University of California at Berkeley (USA), and Max Planck Institute for Demographic Research (Germany) (2022). Human Mortality Database (HMD).

Valentino, B.A. (2004). *Final solutions : mass killing and genocide in the twentieth century*, *Cornell studies in security affairs*. Ithaca, N.Y: Cornell University Press.

Vallin, J. (2006). Mortality, Sex, and Gender. In *Demography : analysis and synthesis*, edited by Graziella Caselli, Jacques Vallin and Guillaume J. Wunsch, pp. 177-194. Amsterdam ;Boston: Elsevier.

Vallin, J., and F. Meslé (2009). The Segmented Trend Line of Highest Life Expectancies. *Population and Development Review*, vol. 35, No. 1, pp. 159-187. doi: 10.1111/j.1728-4457.2009.00264.x.

Vaupel, J.W., and K.G.v. Kistowski (2005). Broken Limits to Life Expectancy. *Ageing Horizons*, vol., No. 3, pp. 6-13.

Visaria, P.M. (1967). Sex ratio at birth in territories with a relatively complete registration. *Eugenics quarterly*, vol. 14, No. 2, pp. 132-142.

Wheldon, M.C., and others (2013). Reconstructing Past Populations With Uncertainty From Fragmentary Data. *Journal of the American Statistical Association*, vol. 108, No. 501, pp. 96-110. doi: 10.1080/01621459.2012.737729.

__________ (2015). Bayesian reconstruction of two-sex populations by age: estimating sex ratios at birth and sex ratios of mortality. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, vol. 178, No. 4, pp. 977-1007. doi: 10.1111/rssa.12104.

Wheldon, M.C., and others (2016). Bayesian population reconstruction of female populations for less developed and more developed countries. *Population studies*, vol. 70, No. 1, pp. 21-37. doi: 10.1080/00324728.2016.1139164.

Whelpton, P.K. (1936). An Empirical Method of Calculating Future Population. *Journal of the American Statistical Association*, vol. 31, No. 195, pp. 457-473. doi: 10.1080/01621459.1936.10503346.

WHO/UNICEF (2020). WHO/UNICEF Joint Reporting Process: Reported administrative target population, number of doses administered and administrative coverage.

Wilmoth, J., and others (2012). A flexible two-dimensional mortality model for use in indirect estimation. *Population studies*, vol. 66, No. 1, pp. 1-28.

Wilmoth, J.R., and others (2000). Increase of maximum life-span in Sweden, 1861-1999. *Science*, vol. 289, No. 5488, pp. 2366-8. doi: 10.1126/science.289.5488.2366.

Wilmoth, J.R., and N. Ouellette (2012). Maximum human lifespan: Will the records be unbroken? Stockholm, Sweden, 13-16 June, European Population Conference.

Wilmoth, J.R., and J.-M. Robine (2003). The world trend in maximum life span. In *Life Span: Evolutionary, Ecological, and Demographic Perspectives*, edited by J. R. Carey and S. Tuljapurkar, pp. 239–257. Population and Development Review.

World Bank (2018). Global ID4D Dataset 2018: Registered Population Above Cut-off Age.

World Peace Foundation, and Tufts University (2020). Mass Atrocity Endings: List of Cases. Available from https://sites.tufts.edu/atrocityendings/2017/01/30/list-of-cases/.

Yang, J. (2013). *Tombstone : the great Chinese famine, 1958-1962*. New York: Farrar, Strauss and Giroux.

Zwierzchowski, J., and E. Tabeau (2010). The 1992–95 War in Bosnia and Herzegovina: Census-based multiple system estimation of casualties' undercount. *Berlin: Households in Conflict Network and Institute for Economic Research*, vol. 539, No., pp.