BAYESIAN METHODS FOR ESTIMATING GLOBAL HEALTH INDICATORS

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A THESIS SUBMITTED
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
SAW SWEE HOCK SCHOOL OF PUBLIC HEALTH
NATIONAL UNIVERSITY OF SINGAPORE

2017

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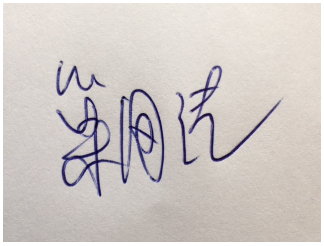
Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.



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14 August 2017

Acknowledgements

I would like to thank my supervisors Dr. Leontine Alkema and Associate Professor Alex Cook. I would like to especially thank Dr. Leontine Alkema for leading me into the world of demography, and her guidance and support. I would like to thank my main collaborators Dr. Patrick Gerland from the United Nations Population Division, Dr. Danzhen You and Lucia Hug from the UNICEF, and Jon Pederson from Fafo. I appreciate the useful comments from the Chair of my Thesis Advisory Committee Dr. Tan Chuen Seng. The contents of this thesis are much related to their contributions. I would like to dedicate this thesis to my parents and husband.

Contents

Summary

Child and maternal mortality are crucial indicators for monitoring the health status and the health care environment of populations on country-level. In the United Nations General Assembly 2015, member states across the world adopted 17 Sustainable Development Goals, which include objectives to further reduce maternal mortality and to end preventable child deaths by 2030. In order to achieve these goals effectively, it is important to monitor indicators relating to maternal and child mortality accurately. This is especially so in developing countries where the improvements of these health indicators are most needed. However, estimating the indicators relating to maternal and child mortality are fraught with challenges, mainly due to the paucity of data and the great variance of data quality across different sources.

The studies included in this thesis concern estimating and/or projecting the indicators regarding child and maternal mortality: **Chapter 2** – reporting errors in vital registration data on maternal mortality; **Chapter 3** – sex ratio at birth; **Chapter 4** – mortality for children under the age of 5 years, disaggregated by sex of children; and **Chapter 5** – mortality for children under the age of 5 years, disaggregated by household economic status.

Most of the previous studies on these topics generated results by reporting or summarizing the empirical data. Very few of them provide uncertainty intervals corresponding to the outcome of interest. Furthermore, it is difficult to validate model-based imputations or extrapolations from those previous studies since the methods were generally not reproducible and/or based on strong assumptions.

To overcome the difficulties of monitoring the indicators covered in this thesis,

context-specific Bayesian hierarchical models were developed to produce estimates and projections with uncertainty assessments. Bayesian hierarchical modeling approaches implemented in this thesis provide more objective, data-driven insights into global health indicators, in particular for countries and time periods with limited data and with poor data quality. The hierarchical structure of the model makes full use of available data by sharing the information in data-rich countries with countries without data or with limited data only. All the country-level indicators are drawn from the same distribution on regional or global level. The parameters from countries where quality data are limited are pooled toward the mean of the regional or global distribution.

The results in this thesis may be used by international agencies and local governments. These institutions can make use of these results to inform future policies and decision making for programming and services to move forward with the Sustainable Development Goals. The model and resulting estimates on sex-specific mortality for children under the age of 5 years have been used by the United Nations Inter-Agency Group for Child Mortality Estimation (consisting of United Nations Children's Fund, World Health Organization, United Nations Population Division, and the World Bank) for the update of sex-specific child mortality estimates in 2013, 2014, 2015.

List of Publications

This list summarizes the publications that have resulted from my PhD research.

1. **Chao F**, Alkema L. How informative are vital registration data for estimating maternal mortality? A bayesian analysis of WHO adjustment data and parameters. Statistics and Public Policy. 2014 Dec 22;1(1):6-18.

2. Alkema L, **Chao F**, You D, Pedersen J, Sawyer CC. National, regional, and global sex ratios of infant, child, and under-5 mortality and identification of countries with outlying ratios: a systematic assessment. The Lancet Global Health. 2014 Sep 30;2(9):e521-30.

3. (under review) **Chao F**, You D, Pedersen J, Hug L, Alkema L. A systematic assessment of national and regional under-5 mortality by economic status for low- and middle-income countries.

4. (submitted) **Chao F**, Gerland P, Cook A, Alkema L. A systematic assessment of national, regional and global levels and trends in the sex ratio at birth and scenario-based projections.

List of Abbreviations

AMFB	annual number of missing female births
CI	credible interval
CMFB	cumulative number of missing female births
CMR	child mortality rate
CV	coefficient of variation
DHS	Demographic and Health Survey
GBD	Global Burden of Disease
IMR	infant mortality rate
MCMC	Markov chain Monte Carlo
MDG	Millennium Development Goal
MICS	Multiple Indicator Cluster Survey
MMR	maternal mortality ratio
PAPCHILD	Pan Arab Project for Child Development
PAPFAM	Pan Arab Project for Family Health
PD	prenatal diagnosis
PI	prediction interval
PM	proportion of maternal deaths among all deaths to women of reproductive ages
PSU	primary sampling unit
RHS	Reproductive Health Survey
SRB	sex ratio at birth
SRS	Sample Registration System
TFR	total fertility rate
U5MR	under-5 mortality rate
UI	uncertainty interval
UN	United Nations
UNFPA	United Nations Population Fund
UNICEF	United Nations Children's Fund
UN IGME	United Nations Inter-agency Group for Child Mortality Estimation
UN MMEIG	United Nations Maternal Mortality Estimation Inter-agency Group
VR	Vital Registration
WFS	World Fertility Surveys
WHO	World Health Organization
WPP	World Population Prospect

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Chapter 1

Introduction

1.1 Research background

Global health is the area of study, research, and practice that aims to improve the health status worldwide, and to reduce disparities among and within populations [1, 2]. The study of global health covers a wide range of areas such as demography, public health, medicine, epidemiology, economics, sociology, statistics, development studies and more. Thus, research in global health can hardly be related to only one area mentioned above but rather is a combination of several areas. This thesis is most relevant to statistical demography, public health, and remotely related to economics.

There are various indicators to measure the health of populations around the world. Broadly speaking, the global health indicators fall into four main groups according to the World Health Organization (WHO) [3]: 1) health status; 2) risk factors; 3) service coverage; and 4) health systems. The indicators that this thesis will cover mainly fall under the category of health status. These indicators are:

1. Reporting errors in vital registration data on maternal mortality ratio (MMR);

2. Sex ratio at birth (SRB);

3. Infant/child/under-5 mortality rate (IMR/CMR/U5MR) disaggregated by sex;

4. Under-5 mortality rate (U5MR) disaggregated by household income status;

The definitions related to the main indicators studied in this thesis are listed in Table 1.1.

Indicator	Definition
Maternal mortality ratio (MMR)	The ratio of number of maternal deaths to every 100,000 livebirths.
Sex ratio at birth (SRB)	The ratio of number of male livebirths to number of female livebirths.
Infant mortality rate (IMR)	The probability of dying between birth and 1 year of age. Equivalently, it is the number of children dead before 1 year of age per 1000 livebirths.
Child mortality rate (CMR)	The probability of dying between 1 year of age and before 5 years of age. Equivalently, it is the number of children survived up to 1 year of age and dead before 5 years of age per 1000 survivors up to 1 year of age.
Under-5 mortality rate (U5MR)	The probability of dying between births and before 5 years of age. Equivalently, it is the number of children dead before age 5 per 1000 livebirths.

Table 1.1 **Definitions.**

In recent decades, global health studies have received much attention from and have been implemented with priority by international agencies, local governments across the world, and independent research institutes. In 2000, the United Nations (UN) gathered the leaders around the world to agree on the Millennium Development Goals (MDGs). Among the total of eight MDG targets, the target 4 (MDG 4) aimed at a two-thirds reduction in the under-5 mortality rate (U5MR) and target 5 (MDG 5) called for a three-quarters reduction in the maternal mortality ratio (MMR), with the observation period between 1990 and 2015 for both MDG 4 and MDG 5. During the period, international agencies monitored the levels of and trends in these targeted indicators like MMR and U5MR and provided evidence-based programmatic guidance, set global standards, offered technical support to member states, and supported countries to implement policies and programmes. In

particular, WHO has led the United Nations Maternal Mortality Estimation Inter-Agency Group (UN MMEIG) in monitoring and estimating the levels and trends in MMR across countries for the MDG period [4, 5]. The estimation and monitoring of U5MR for all countries during the MDG period has been carried out by the United Nations Inter-agency Group for Child Mortality Estimation (UN IGME) with the lead of United Nations Children's Fund (UNICEF) [6, 7]. Figure 1.1 and Figure 1.2 shows the MMR and U5MR estimates respectively in 2015 for all countries. By 2105, the global MMR had a 44% decline (with an 80% uncertainty interval from 34% to 49%) relative to the level in 1990 [5]. Meanwhile, the global U5MR has reduced by 53% (with a 90% uncertainty interval from 50% to 55%) since 1990 [7]. Although the progress made in reducing MMR and U5MR is impressive, the MDG targets were not achieved by 2015.

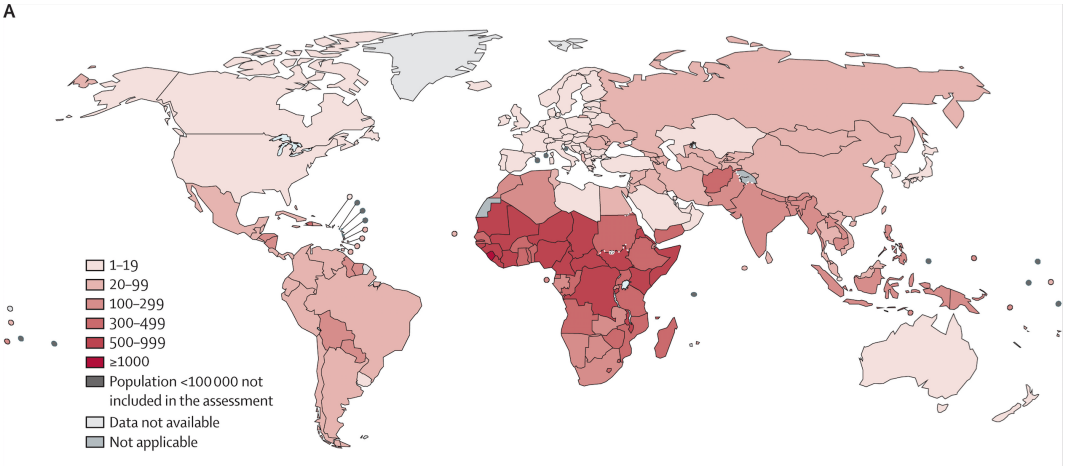

Fig. 1.1 **Maternal mortality ratio (per 100,000 livebirths) estimates in 2015 by country** (source [5]).

To continue past efforts of MDGs and to complete the unfinished MDG agenda, the former UN Secretary-General Ban Ki-moon launched the Global Strategy for Women's, Children's and Adolescents' Health, 2016–2030 [8] during the United Nations General Assembly 2015, in New York. The Strategy is a road map for the post-2015 agenda as described by the Sustainable Development Goals (SDGs) [9]. Figure 1.3 lists the SDGs. The goals of SDG set an ambitious framework that covers almost every aspect of the actions and challenges around the world. Goal 3 seeks

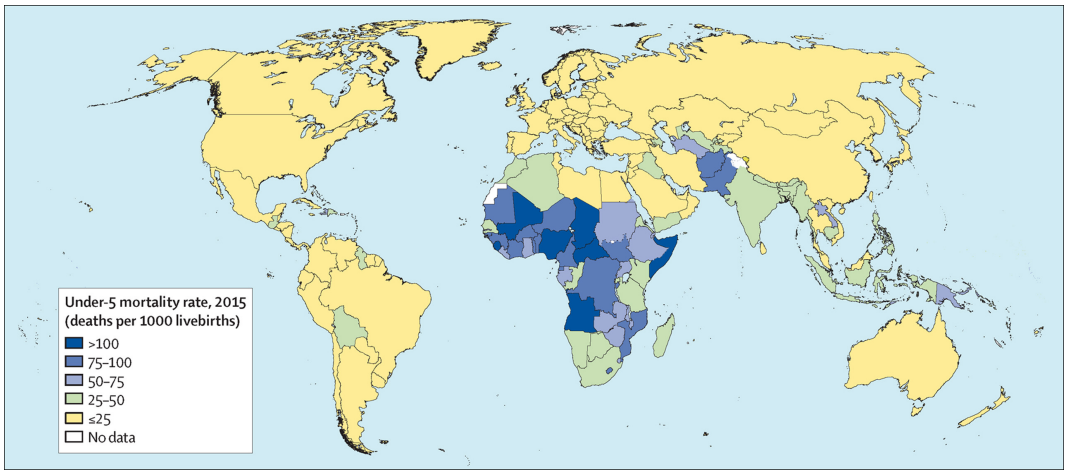

Fig. 1.2 **Under-5 mortality rate (per 1000 livebirths) estimates in 2015 by country** (source [7]).

to ensure universal health and well-being throughout the entire life span. Some of the main sub-goals aim to further reduce and end preventable deaths of women and children under 5 years of age. In order to better identify the most vulnerable and disadvantaged women and children as targeted groups, the disaggregation of national-level indicators are much in need. For instance, dividends of U5MR by household economic status can be helpful to monitor the situation of child survival by identifying the most vulnerable economic group within a country. Goal 5 calls for the end of discrimination against women and girls. The goal highlights the importance of monitoring the sex disparity of global health indicators such as SRB that measure the pre-natal sex disparity and sex-specific U5MR that inform the sex discrimination during the post-natal period.

1.2 Data used for monitoring child and maternal mortality

The data on SRB and U5MR by sex and household economic status are mainly related to information on births and mortality. On the other hand, data on maternal mortality are more related to the cause of death, and will be explained in Chapter 2.

The data sources on births and mortality are mainly vital registration (VR) sys-

Fig. 1.3 **Sustainable Development Goals.** (source `http://www.undp.org/content/undp/en/home/sustainable-development-goals.html`)

tems, surveys with full or summary birth histories, and censuses. Table 1.2 summarizes the data sources for births and mortality that were used in this thesis. For most developed countries, data from VR systems of high quality are available. Among most developing countries, VR systems are either incomplete with low coverage or of poor quality such that the data resulting from the collection system are not reliable. For many developing countries, data are collected retrospectively in surveys. Census data may also provide information on mortality or births.

1.3 Research void

Prior to the studies in this thesis, systematic analyses for the indicators focused on in this thesis were lacking. Most of the previous studies on similar topics did not use reproducible methods, nor did they have uncertainty analyses that take account of both sampling and non-sampling errors (explained in the following paragraphs). The past studies were mainly based on reporting empirical data or based on expert opinion and strong assumptions.

The challenge of monitoring these indicators mainly come from the input data. The first data issue is their paucity. Data are not available for all the country-years

Data type	Features
Vital registration (VR) system	Typically provide data on an annual basis from routine registration of births and deaths • Vital information is normally included, such as sex of birth, cause of death, etc. • MMR, SRB, U5MR can be computed directly from the data.
Surveys with full birth histories	Household surveys that are normally conducted every 5–10 years and interview females in their reproductive age. The surveys can provide data with retrospective periods from 5 to 20 years before the survey was conducted. • The entire births history of each female is recorded in detail: sex, date of birth/death, etc. • SRB, U5MR can be computed directly from the data.
Surveys with summary birth histories	Retrospective household surveys that are normally conducted every 5–10 years and interview females in their reproductive age • Ask about women the number of children ever born and children dead. • The timing of births and deaths are not recorded. • U5MR cannot be computed directly from the data. Indirect methods are used to approximate the U5MR.
Census	Usually national censuses are conducted every 5-10 years and provide information for the previous 12 or 24 months. • Some censuses collect data on summary birth history. • The number of questions asked in a census is usually limited.

Table 1.2 **Main data types used in this thesis.**

of interest. One reason for data paucity is the lack of surveys carried out in some countries or during certain periods. The other reason for lack of quality data is because of limitations of the data collection system for certain countries and periods. As shown in Figure 1.4, initially there are 38 data points on SRB available from VR and surveys in Guyana. After the we conducted the data quality check (details will be explained in Chapter 3 for SRB data), more than half of the data points were excluded from modelling due to various reasons like low data coverage, large recall bias due to long recall period.

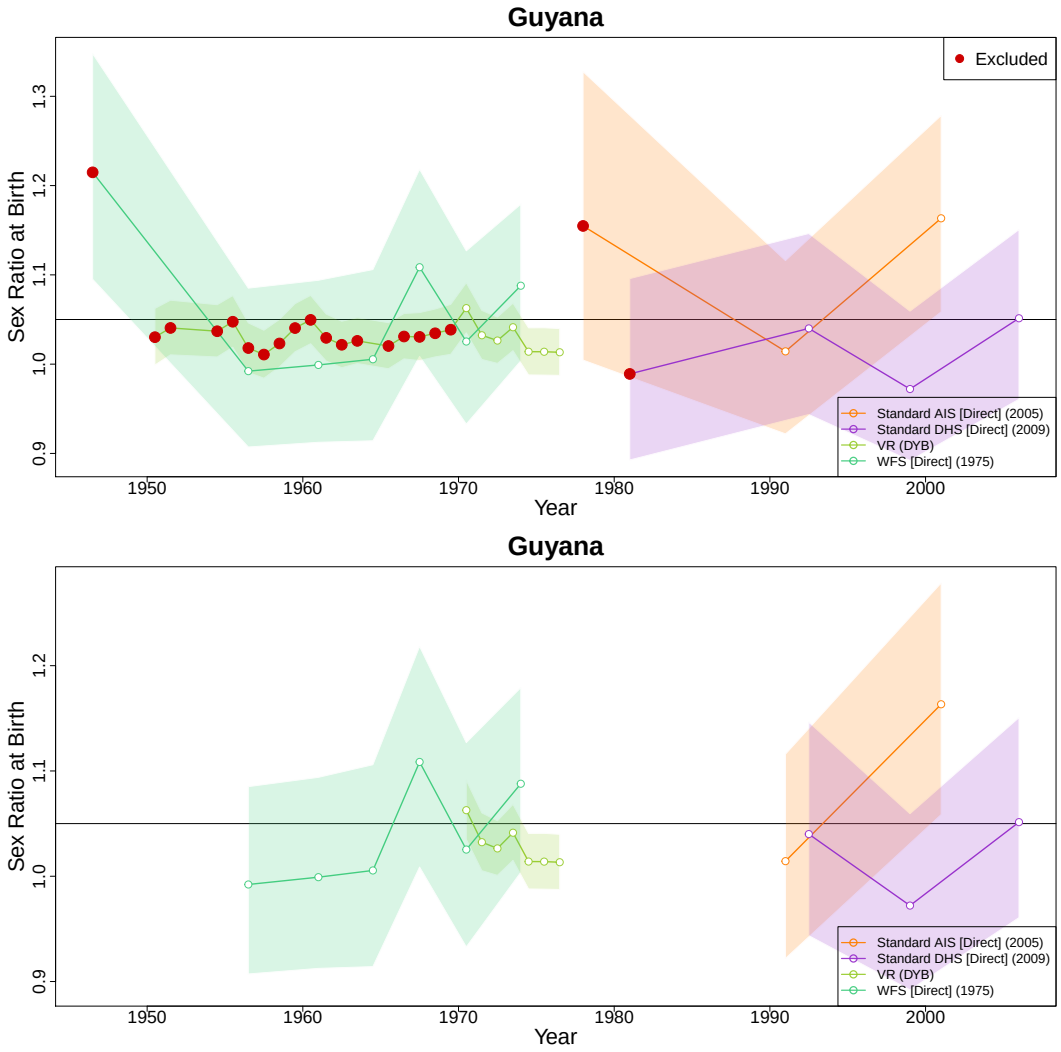

Fig. 1.4 **Data of sex ratio at birth for Guyana.** Different data series are differentiated by colors. The shades around each data series are the corresponding sampling errors (for non-VR data) or stochastic errors (for VR data). Red solid dots are excluded after data quality check. Top: all data points before exclusion. Bottom: data points included for modelling.

The second data issue is that for some data-rich populations where data come from multiple sources, the data quality may vary greatly across different types. Variations of the data quality among different types result in different sampling and non-sampling errors. The sampling error takes account of the uncertainty resulting from sampling of individual units from a population and can be evaluated statistically if the survey sampling structure is known. The non-sampling error is the result of mistakes made in implementing data collection and data processing, such as failure to locate and interview the correct household, misunderstanding of the survey questions (either by the interviewers or the respondents), and data entry errors. Non-sampling errors are impossible to avoid and difficult to evaluate statistically. The different levels of sampling and non-sampling errors may explain some of the differences in the observed values. However, they can not explain completely the differences in the levels and trends of data series from different types, and it is not obvious which data series is more accurate. Figure 1.5 shows the data points and their corresponding sampling errors used to estimate the sex ratio of IMR, which is the ratio of male IMR to female IMR, for Jordan. There are ten data series from three data types: others indirect, WFS direct, and DHS direct as stated in the plot legend. There are overlaps of the reference periods from different data series. However, the empirical data from different series do not agree with each other for the same reference period.

1.4 Method summary

The basic concepts of the statistical methods that were used in this thesis are briefly summarized here.

1.4.1 Bayesian hierarchical model

The hierarchical model was used to allow the sharing of data across country-years so that the information in data-rich countries can be used to inform those countries

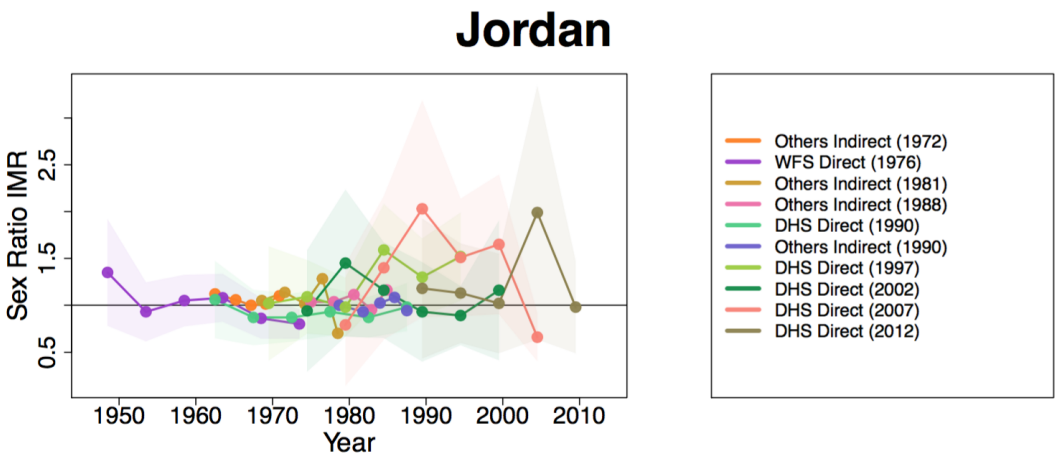

Fig. 1.5 **Data of sex ratio of infant mortality rate for Jordan.** Sex ratio of infant mortality rate (IMR) is the ratio of male IMR to female IMR. Different data series are differentiated by colors. The shades around each data series are the corresponding sampling errors.

with limited or no data. The implementation of the hierarchical structure is subjected to the model assumption that country-specific parameters are drawn from a common distribution. In general, assuming we want to estimate the country-specific parameter α_c from country c for all countries $c = 1,\ldots,C$, we have:

$$\alpha_c|\mu_\alpha,\sigma_\alpha \quad \sim \quad N(\mu_\alpha,\sigma_\alpha^2), \text{ for } c = 1,\ldots,C.$$

We model the country-specific parameters α_c and assume they all follow the same normal distribution with a global mean μ_α and a global variance σ_α^2. μ_α and σ_α^2 are usually modeled by assigning weakly informative priors such as uniform distributions to them.

To illustrate that the hierarchical model can allow information sharing among countries with different levels of data availability, assume that country $c1$ has five data points and country $c2$ has no data. The parameter α_{c1} is estimated mainly based on the five observations from country $c1$ conditioning on the sampling and non-sampling error associated with these five data points. The parameter α_{c2} is pooled towards the global mean μ_α since there is no data from country $c2$ to inform it at all. However, α_{c2} is indirectly informed by other α_c's from countries with data points.

1.4.2 Time series model

Since all the studies in this thesis are about estimation and/or projecting global health indicators across countries over time, time series models are also heavily used in this thesis to take into account the auto-correlation of the indicators over certain time span. An auto regressive model of order 1 structure, i.e. AR(1) model, is illustrated here. In general, assuming we want to estimate the time-specific parameter β_t over time points $t = 1, \ldots, T$:

$$\begin{aligned} \beta_t - \mu &= (\beta_{t-1} - \mu) \cdot \rho + \varepsilon_t, \text{ for } t = 2, \ldots, T, \\ \varepsilon_t | \sigma_\varepsilon &\sim N(0, \sigma_\varepsilon^2). \end{aligned}$$

The time-specific parameter β_t depends on the parameter from the previous time point β_{t-1}, and it fluctuates around the mean μ while ρ is the autoregressive parameter. The innovation term ε_t at time point t follows the normal distribution with standard deviation σ_ε.

Depending on the modeling purpose, parameters of the time series model can be modeled hierarchically.

1.5 Research objectives

The main objective of this thesis is to implement reproducible Bayesian models to estimate and project a set of global health indicators from multiple countries with uncertainty analyses. The researches included here provide timely model-based evidence on global health indicators which is in great need for moving forward with the SDGs.

The specific aims for each of the research topics in this thesis are summarized below and are presented in each of the subsequent chapters:

- Chapter 2 – To estimate the misclassification of maternal deaths recorded in the VR data based on an objective method. Instead of applying the same

informative distribution suggested by experts for all the country-years to account for the uncertainty of the adjustment of the misclassification errors, we aimed to construct data-driven estimates of the misclassification errors.

- Chapter 3 – To estimate and project the SRB for all countries since 1950. We aimed to compile an extensive national-level SRB database. We also aimed to quantify the deficit of female births that resulted from the past and present SRB imbalance, as well as the deficit that would result in the future under different scenarios of SRB projections.

- Chapter 4 – To estimate the sex ratio of IMR, CMR, and U5MR for all countries since 1990 and to identify country-years with outlying sex ratio.

- Chapter 5 – To estimate the U5MR by household economic status for all the low- and middle-income countries (excluding China) and to identify country-years with outlying disparities in U5MR between the rich and the poor.

Chapter 6 is a recapitulation of the major findings and contributions of the thesis. Future works are briefly discussed.

Chapter 2

Reporting errors in vital registration data on maternal mortality ratio

This work has been published as:

Chao F, Alkema L. How informative are vital registration data for estimating maternal mortality? A Bayesian analysis of WHO adjustment data and parameters. Statistics and Public Policy. 2014 Dec 22;1(1):6-18.

Contributors FC and LA designed research. FC and LA performed research. FC and LA wrote the paper.

Abstract

Monitoring maternal mortality is challenging due to fragmented data of varying quality. The maternal mortality estimates published by the World Health Organization (WHO) in 2012 included data adjustment parameters to account for these data quality issues, but there was a discrepancy between the WHO assumption about, and the observed variability in, misclassification errors in vital registration (VR) observations.

We developed a Bayesian hierarchical time series model to estimate the extent of VR misclassification errors and to provide a plausible assessment of the uncertainty associated with VR observations for countries with and without external informa-

tion on VR adjustment parameters. The resulting distribution for VR adjustments generated by the implemented Bayesian model in this study was more comparable to the observed biases than the WHO expert distribution and the model allows for estimation of VR adjustment values for any period of interest for countries with partial information on such adjustments. We also illustrated that a fully Bayesian modeling approach for estimating maternal mortality can provide more data-driven insights into maternal mortality estimates and data adjustment parameters. However, given the paucity of, and the issues with, maternal mortality data, validation of modeling assumptions and findings is challenging; more data collection and research on measuring maternal mortality and assessing data quality are needed.

keywords Autoregressive time series model; Maternal mortality; Multilevel model; Proportion of maternal deaths among all deaths to women of reproductive ages (PM); Vital registration (VR); World Health Organization (WHO).

2.1 Introduction

Maternal mortality is widely considered as a sentinel indicator of the quality of a health care delivery system and as a key indicator of population health and social and economic development [10]. Millennium Development Goal 5 (MDG 5) calls for a reduction in the maternal mortality ratio (MMR) by three quarters between 1990 and 2015. To measure progress, the World Health Organization (WHO), the United Nations Children's Fund (UNICEF), the United Nations Population Fund (UNFPA) and the World Bank published estimates of maternal mortality in 2012, referred to hereafter as the WHO estimates [11].

It is challenging to estimate maternal mortality due to the paucity of accurate data, especially in developing countries where maternal mortality is high and such estimates are most needed. The WHO estimates were based on limited data on the proportion of maternal deaths among all deaths of women of reproductive age, adjusted to account for data issues such as under-reporting, misclassification and inconsistent definitions. The adjustments and the uncertainty associated with the

adjustment were based on external data and/or expert opinion.

In this paper, we assessed the accuracy of the estimates and probability distributions used for the vital registration (VR) misclassification parameters used in the WHO modeling approach. We identified two issues: (1) it is not clear how information on varying periods for countries with information should be summarized into the periods needed for the maternal mortality estimation, and (2) for countries without additional information on the extent of misclassification of maternal deaths in the VR, the WHO expert distribution may understate uncertainty therein. To improve upon the current WHO modeling approach, we developed a Bayesian estimation approach for the VR misclassification adjustments for countries with or without additional information on the quality of the VR data. The resulting probability distribution for VR adjustments was compared to those from the WHO and adjustments published by [12], used by the Institute for Health Metrics and Evaluation for constructing global estimates of maternal mortality [13]. We also incorporated the Bayesian VR adjustment into the current WHO estimation approach and implemented a fully Bayesian maternal mortality estimation model to examine the effect of the differences in VR adjustment parameters on the maternal mortality estimates for selected countries.

The paper is organized as follows. We first summarize the WHO estimation method in Section 2.2. Then we introduce our alternative estimation approach in Section 2.3. We then present results in Section 2.4 and end with a discussion of findings.

2.2 Summary of WHO estimation method

The WHO maternal mortality estimation methods used are described in detail elsewhere [10, 11]. We summarize the method here.

The key indicator in the WHO estimation approach is the proportion of maternal deaths (PM) among all deaths of women of reproductive ages. Estimation of PM is complicated in countries with HIV/AIDS epidemics because of the difficulties

in determining whether a death of a woman who was HIV-positive and died during the maternal risk period should be counted as a maternal death. In the WHO method, the "total" PM is estimated as PM = $(1-a)\text{PM}^{na} + a\text{PM}^{a}$, where a refers to the proportion of AIDS deaths among all deaths to women of reproductive ages, PM^{na} is the non-AIDS PM (the proportion of non-AIDS maternal deaths among the total number of non-AIDS deaths of women of reproductive ages), and PM^{a} is the AIDS PM (the proportion of AIDS maternal deaths among the total number of AIDS deaths to women of reproductive ages). This paper focused on the estimation of PM^{na}, whereas PM^{a} and a are estimated from other sources and not the subject of this paper.

Let z_i denote the observed total PM for observation i. Data are available from VR systems and other sources such as household surveys (described in detail in the 2012 WHO report [11]). The WHO analysis started by carrying out an adjustment procedure resulting in an adjusted PM, denoted by y_i, which represents the proportion of non-AIDS maternal deaths among all deaths of women of reproductive ages, given by:

$$y_i = (z_i \cdot \gamma_i - s_i)q_i, \tag{2.1}$$

where s_i refers to an adjustment related to AIDS deaths and q_i refers to an adjustment for observations that reported to be pregnancy-related deaths (as opposed to maternal deaths). Parameter γ_i is an under-reporting or misclassification parameter and is determined by the data source of observation i. For VR observations, γ_i quantifies the extent to which maternal deaths have been misclassified. For example, if the observed proportion of maternal deaths among all deaths to women of reproductive ages is underestimated by 50%, $\gamma_i = 1.5$. Adjustment parameters were informed by external studies.

In the WHO approach, for countries with sufficient information from vital registration systems from 1990 to 2012, PM^{na} estimates were based on adjusted PM data. For the countries without sufficient VR information, estimates were obtained

from a multi-level model which was fitted to the adjusted data from all countries combined. The multi-level model was given by

$$\begin{aligned} \log(y_i) &\sim N(\phi_i, \sigma_i^2), \\ \phi_i &= \log(1-a_i) + \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \beta_3 x_{3,i} + \alpha^C_{c[i]} + \alpha^R_{r[i]}, \end{aligned} \tag{2.2}$$

where $\log(1-a_i)$ is an offset to remove the AIDS deaths from the denominator of the adjusted PM, x_1, x_2 and x_3 are predictors for the PM (referring to the log of the general fertility rate, the log of GDP per capita and the proportion of births with a skilled birth attendant). $\alpha^C_{c[i]}$ and $\alpha^R_{r[i]}$ refer to the country- and region-specific intercepts for the i-th observation in country $c[i]$ and in region $r[i]$ respectively. They are estimated by hierarchical models on country and region levels as following:

$$\begin{aligned} \alpha^C_j &\sim N(0, \sigma^2_{ac}), \\ \alpha^R_k &\sim N(0, \sigma^2_{ar}), \end{aligned}$$

where α^C_j is the country-specific intercept for country j that multiple observations could fall into. Similarly, α^R_k is the region-specific intercept for region k that multiple observations could fall into.

The estimates of the non-AIDS PM, i.e. PM^{na}, is based on the fitted model Eq.(2.2) when using the mean of the adjustment parameter distribution (explained below in Eq.(2.3)) to compute the input y_i. The estimates of PM^{na} is computed by the estimated $\exp\{\phi_i\}/(1-a_i)$. The uncertainty assessment of the resulting PM^{na} estimates was based on repeated draws from probability distributions on the adjustment parameters, and repeated fitting of the multilevel model to the resulting sets of adjusted PM values.

The probability distribution for the i-th VR adjustment parameter γ_i was given by:

$$\gamma_i \sim \log N(\log(V_i), 0.05^2), \tag{2.3}$$

where the VR adjustment parameter γ_i follows a log-normal distribution with mean at V_i and standard deviation at 0.05. The mean value V_i was a country-specific value for a subset of countries where country-specific studies were available, while for the remaining 63 countries with VR data but without external information on the VR adjustment, $V_i = 1.5$, based on the median of reported VR adjustments in Table 2.1 from source *a* (Appendix 1 from the WHO 2012 report [11]). The standard deviation 0.05 in Eq.(2.3) was based on expert opinion, by assuming the adjustment factor γ_i falls in a range of $\pm 10\%$ of the mean V_i.

Figure 2.1 illustrates the distribution of 35 reported VR misclassification errors, or in other words, reported VR adjustment parameters, obtained from various studies in 19 countries. The data set, based on Appendix 1 from the WHO 2012 report and additional information provided by WHO analysts, is given in Table 2.1.The observed adjustments range from 0.95 (from New Zealand with observation period 2006-2008) to 2.03 (from Australia with observation period 2003-2006). The VR adjustment data are from 19 countries and 9.7 country-years of data are available for each country on average. Figure 2.2 illustrates the observed VR adjustments for all 19 countries.

Limitations of the current WHO adjustment method Country-specific observation periods for VR adjustments vary and generally do not coincide with the observation periods that are used to calculate the observed PM in the WHO multilevel model (which are generally 5-year periods). Additionally, the adjustments are often not available for the entire VR observation period. As a consequence, the WHO VR adjustments for countries with external information (the V_i's in Eq.(2.3)) are often based on partial information. The procedure to impute adjustments for missing observation years has not been formalized.

The WHO expert distribution for countries without external information on VR adjustment parameters (Eq.(2.3) when $V_i = 1.5$, the median of the reported VR adjustment values as shown in Table 2.1 source *a*) is added to Figure 2.1. A comparison of observed adjustments and the WHO expert distribution reveals that the

Country	Period	VR Adjustment	Source
Australia	1994-1996	1.23	a
Australia	1997-1999	1.80	a
Australia	2000-2002	1.97	a
Australia	2003-2005	2.03	a
Austria	1980-1998	1.61	a
Brazil	2002-2002	1.40	a
Canada	1988-1992	1.60	a
Canada	1997-2000	1.52	a
China (Taiwan)	1984-1987	1.58	a
Denmark	1985-1994	1.94	a
Denmark	2002-2006	1.04	b
Finland	1987-1994	1.03	a
France	1999-1999	1.24	a
France	2001-2006	1.21	a
Georgia	2006-2006	2.00	a
Germany	1983-2000	1.02	a
Japan	2005-2005	1.35	a
Mexico	2008-2008	1.10	a
Netherlands	1983-1992	1.34	a
Netherlands	1993-2005	1.49	a
New Zealand	2006-2007	0.95	b
Serbia	2007-2010	1.86	a
Sweden	1997-2005	1.33	a
Switzerland	1985-1996	1.25	a
United Kingdom	1988-1990	1.39	a
United Kingdom	1991-1993	1.52	a
United Kingdom	1994-1996	1.64	a
United Kingdom	1997-1999	1.82	a
United Kingdom	2000-2002	1.66	a
United Kingdom	2003-2005	1.74	a
United Kingdom	2006-2008	1.60	a
United States of America	1991-1997	1.48	a
United States of America	1995-1997	1.59	a
United States of America	1999-2002	1.50	a
United States of America	2003-2005	1.10	a

Table 2.1 **VR adjustment data set.** Sources: (a). Appendix 1 from the WHO 2012 report [11]; and (b). additional information provided by WHO.

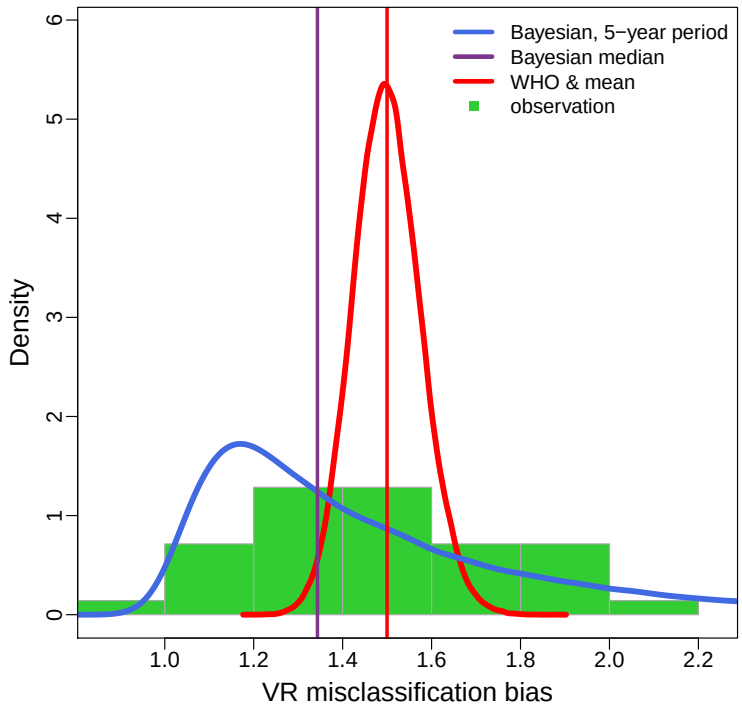

Fig. 2.1 **Observed and estimated VR misclassification biases.** Histogram of observed VR misclassification biases and density functions for the WHO and Bayesian VR adjustment for a 5-year observation in a country with no external information on the VR misclassification error.

expert distribution (the red curve) understates the variability of observed adjustment factors (green bars). Hence, if this expert distribution were used for countries where external information on VR adjustment is not available, the uncertainty in adjustments is assumed have a standard deviation at 5% (based on expert assumption) and the true underlying uncertainty would be underestimated.

2.3 Methods

This section describes the implemented estimation approach based on Bayesian models as an alternative to the WHO method. Section 2.3.1 is about estimating the VR misclassification parameters using a Bayesian modeling approach. Section 2.3.2 explains a fully Bayesian approach to estimate the VR misclassification parameter and the maternal mortality simultaneously to improve the estimates and

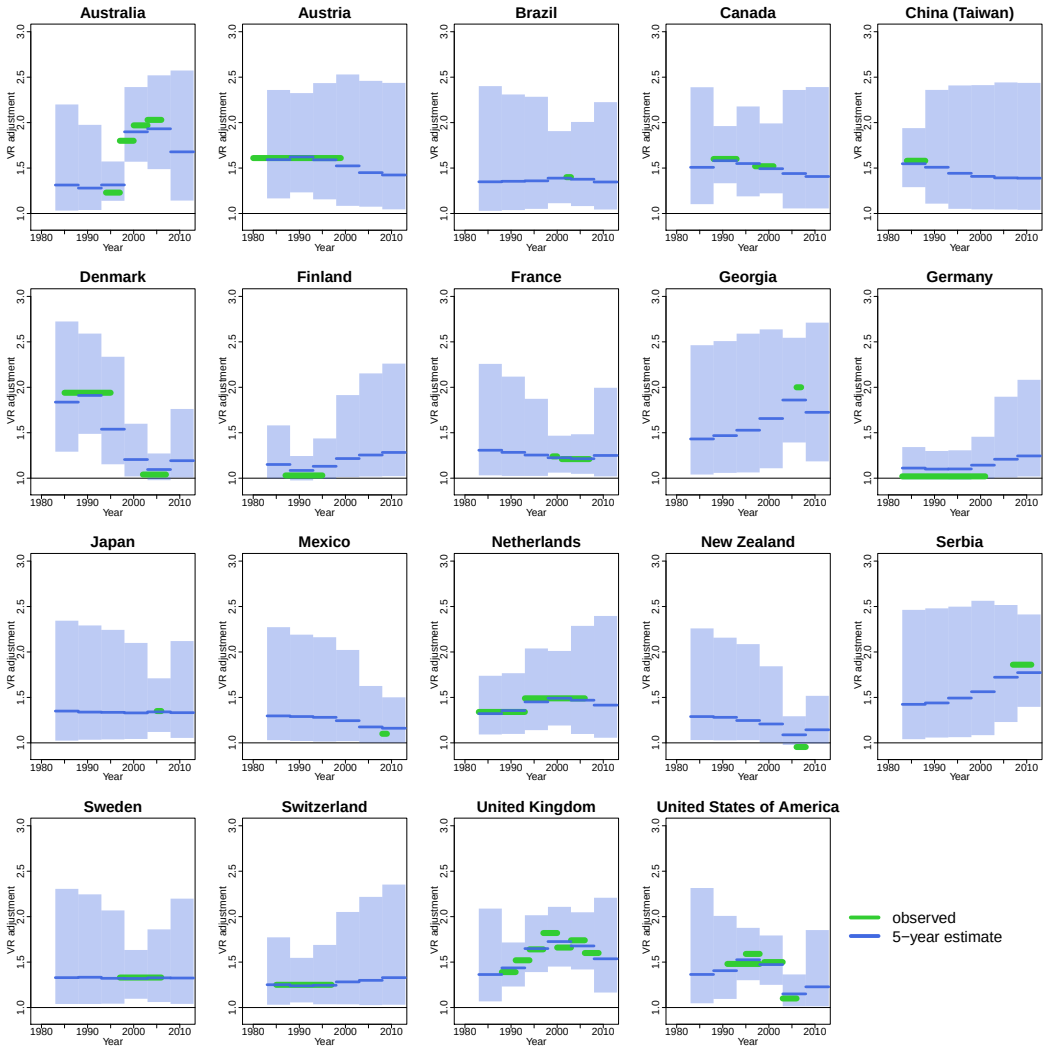

Fig. 2.2 **Observed VR adjustments and Bayesian estimates for countries with external information on VR misclassification biases.** The green line segments represent the observed VR adjustments. Bayesian posterior median estimates for the VR adjustments for 5-year periods (the default periods used in the WHO modeling approach) are added in blue and blue shades represent 95% credible bounds. The line span corresponds to the observation period.

uncertainty assessment by taking account of all available information.

2.3.1 A Bayesian model for VR misclassification parameters

To overcome the limitations of the current WHO adjustment procedure, we developed an alternative model for VR misclassification parameters that provides annual estimates of the VR adjustment parameter for all countries, based on the available data on such adjustments, to (i) impute VR adjustments for countries with external information for a subset of observation years, and (ii) provide a more plausible representation of the extent of VR misclassification bias for countries without external information.

A Bayesian hierarchical time series model is used to model the underlying true (but most often unknown) VR misclassification parameters. This type of model setup was motivated by the need (i) to deal with observation periods of varying lengths, (ii) to allow for variation in misclassification errors between countries and within countries over time (e.g., the observations in Figure 2.2 suggest that the average adjustment in the United Kingdom may be higher than in Finland or Germany, and that the adjustment has changed over time in several countries), (iii) to minimize the number of model parameters given the limited number of observed misclassification outcomes. Technical details of the model specification are discussed in the remainder of this subsection.

Let $P_{c,t}$ be the proportion of maternal deaths that are correctly reported as maternal deaths in country $c = 1,\ldots,C$ during year t, i.e., $P_{c,t} = \frac{R_{c,t}}{M_{c,t}}$, where $R_{c,t}$ is the reported number of maternal deaths for the country-year while $M_{c,t}$ is the true number of maternal deaths. The $P_{c,t}$'s were modeled with an autoregressive time series model of order one (AR(1)) with truncation:

$$\begin{aligned} P_{c,1978} &\sim TN_{[1/3,1]}\left(p_c, \frac{\sigma^2_{AR}}{1-\rho^2}\right), \\ P_{c,t} &\sim TN_{[1/3,1]}\left(p_c + \rho(P_{c,t-1} - p_c), \sigma^2_{AR}\right), \text{ for } t = 1979,\ldots,2012, \end{aligned}$$

where $TN_{[A,B]}(a,b^2)$ denotes a truncated normal distribution with mean a and vari-

ance b^2, truncated to lie between A and B, such that the proportion of correctly reported deaths is assumed to be at least 1/3. The global time series parameters are given by the autoregressive parameter $0 \leq \rho < 1$ and variance σ^2_{AR} with priors $\rho \sim U(0,1)$ and $\sigma_{AR} \sim U(0,0.5)$. The proportion of correctly reported maternal deaths fluctuates around the country-specific mean parameter p_c. This parameter is assumed to be drawn from a common truncated normal distribution,

$$p_c \sim TN_{[1/2,1]}\left(w, \sigma_p^2\right),$$

where w refers to the global mean, and σ_p^2 to the variance, with priors $w \sim U(1/2,1)$ and $\sigma_p \sim U\left(0, \frac{1/2}{\sqrt{12}}\right)$. The truncation on the country-level under-reporting means p_c's and their global mean w are based on the prior assumption that the average proportion of maternal deaths that are correctly reported in a given year is between 1/2 and 1. Similarly, the upper bound for the prior on σ_p is given by the standard deviation of a $U(1/2,1)$ distribution, based on the assumption that the country-specific p_c's are at most as spread out as this distribution.

The model has only four "global" parameters (the autoregressive parameters and the hierarchical mean and variance of the country means) but allows for differences within countries over time through the time series set-up and for differences between countries through the hierarchical model for mean reporting levels.

Inference The AR(1) model parameters were estimated using the 35 observed VR adjustments for various country-periods from Table 2.1. Let $W_{c[i],k[i]} = V_i$, the observed VR adjustment for country $c[i]$ and period $(t_{c[i],k[i]}, t_{c[i],k[i]} + T_{c[i],k[i]} - 1)$, where $T_{c,k}$ refers to the number of observation years for the k-th observation in country c. The observed VR adjustment relates to the true number of maternal and reported maternal deaths as follows:

$$W_{c,k} = \frac{\sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1}(M_{c,t} + M^*_{c,t})}{\sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1}(R_{c,t} + R^*_{c,t})},$$

where $M^*_{c,t}$ and $R^*_{c,t}$ denote reporting errors, which are assumed to be small as compared to $M_{c,t}$ and $R_{c,t}$ (i.e., the errors represent an increase or decrease in the number of (reported) maternal deaths because of misreporting of the calendar year of death). If the number of maternal deaths does not vary greatly during a VR observation period, $\frac{1}{W_{c,k}} \approx \frac{1}{T_{c,k}} \sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1} P_{c,t}$. Without additional information on the extent of the difference between $\frac{1}{W_{c,k}}$ and $\frac{1}{T_{c,k}} \sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1} P_{c,t}$, we assumed

$$\frac{1}{W_{c,k}} \sim TN_{[0,\infty)}\left(\frac{1}{T_{c,k}} \sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1} P_{c,t}, \sigma_W^2\right), \tag{2.4}$$

where $\sigma_W \sim U(0, 0.05)$, i.e., we assume that the standard deviation of the differences is at most 5%.

The effect of the VR adjustment modeling procedure on the WHO maternal mortality estimates from the multi-level model was assessed by replacing the WHO point estimates for the adjustment parameters by the posterior medians from the Bayesian VR adjustment model (obtained via Eq.(2.4) for the relevant country-periods), and similarly, by replacing the draws of the adjustment parameters from the WHO probability distributions by the posterior samples from the Bayesian VR adjustment model when carrying out the uncertainty assessment.

Model summary The Bayesian VR adjustment model is summarized as follows:

$$\begin{aligned}
P_{c,1978} &\sim TN_{[1/3,1]}\left(p_c, \frac{\sigma_{AR}^2}{1-\rho^2}\right), \text{ for } c = 1,\ldots,C,\\
P_{c,t} &\sim TN_{[1/3,1]}\left(p_c + \rho(P_{c,t-1} - p_c), \sigma_{AR}^2\right), \text{ for } t = 1979,\ldots,2012; c = 1,\ldots,C\\
p_c &\sim TN_{[1/2,1]}\left(w, \sigma_p^2\right), \text{ for } c = 1,\ldots,C,\\
w &\sim U(1/2, 1),\\
\sigma_p &\sim U\left(0, \frac{1/2}{\sqrt{12}}\right),\\
\frac{1}{W_{c,k}} &\sim TN_{[0,\infty)}\left(\frac{1}{T_{c,k}} \sum_{t=t_{c,k}}^{t_{c,k}+T_{c,k}-1} P_{c,t}, \sigma_W^2\right),\\
\sigma_W &\sim U(0, 0.05).
\end{aligned}$$

Validation Formal validation of the proposed model and sensitivity analyses of the model assumptions are challenging because of the paucity of data on VR adjustments. We compared the resulting posterior distribution for 5-year adjustments to the prior distribution to check whether unexpected findings were driven by the prior assumptions and model structure or informed by the data. We also compared the observed adjustments for the countries with external information to the adjustments that would have been obtained if the Bayesian and WHO approaches for countries without external information would have been used.

2.3.2 A Bayesian estimation model for maternal mortality

In the previous section, we proposed a Bayesian model for the VR adjustment parameters, that was fitted to observed VR adjustments and used to replace the current WHO point estimates and probability distributions to assess the effect of the VR adjustment model on the maternal mortality estimates.

Instead of "plugging in" the Bayesian estimates of the VR adjustments into the WHO maternal mortality model, alternatively, VR adjustments and maternal mortality can be estimated simultaneously. Such a combined Bayesian estimation model could provide more accurate estimates and uncertainty assessments of both VR adjustments as well as maternal mortality because all relevant information is taken into account simultaneously. For example, suppose that in a country without external information on the extent of misclassification in the VR, the VR data as adjusted by the "default" Bayesian point estimates (the estimates that would result from the model as discussed in the previous section) are far below adjusted data from alternative sources and/or the expected level based on the region and the country's predictors for PM. Such findings indicate that the extent of under-reporting in the VR may be greater than the default adjustment. When estimating the VR adjustment and PM simultaneously, the posterior distribution of the VR adjustment parameters would reflect this possibility, and higher PM point estimates and associated uncertainty bounds may be obtained.

To illustrate this approach and incorporate the estimation of adjustment parameters in the PM estimation procedure, we fitted a Bayesian model that combined the WHO multi-level model from Section 2.2 with the Bayesian VR adjustment model from Section 2.3.1. We focused our PM analysis on countries for which the maximum proportion of AIDS deaths among all deaths of women aged 15 to 49 in the population is smaller than 0.05 (102 countries, here referred to as the non-AIDS countries) and did not carry out any AIDS-related adjustments in the estimation procedure. The main reason for focusing on the non-AIDS countries was to avoid the difficulties associated with the AIDS adjustments and to discuss only one type of adjustment. Leaving out s_i from Eq.(2.1), the data model for observed PM for the non-AIDS countries is simplified as $y_i = z_i \cdot \gamma_i \cdot q_i$ such that:

$$\begin{aligned} \log(z_i) \mid \phi_i, \gamma_i, q_i, \sigma_y &\sim N(\eta_i, \sigma_y^2), \\ \alpha_j^C &\sim N(0, \sigma_{ac}^2), \\ \alpha_k^R &\sim N(0, \sigma_{ar}^2), \end{aligned}$$

where,

$$\begin{aligned} \eta_i &= \phi_i - \log(\gamma_i) - \log(q_i), \\ \phi_i &= \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \beta_3 x_{3,i} + \alpha_{c[i]}^C + \alpha_{r[i]}^R. \end{aligned}$$

Hence, ϕ_i is given by Eq.(2.2) where $a_i = 0$.

VR adjustment parameters γ_i are modeled with the Bayesian VR adjustment model as described in Section 2.3.1.

Prior distributions for the multi-level model parameters were chosen to be spread out, with the exception of the non-VR adjustment parameters that determine γ_i and q_i for non-VR observations. For these parameters, priors were based on the WHO expert distributions. Adjustment parameter $\gamma_i = \theta_s$ for observations obtained from information on sisterhood survival, and $\gamma_i = \theta_o$ for observation from other (non-VR and non-sisterhood) sources. The WHO distributions for these parameters are

identical:

$$\begin{aligned}\theta_s &\sim \log N(\log(1.1), 0.05^2),\\ \theta_o &\sim \log N(\log(1.1), 0.05^2).\end{aligned}$$

In the Bayesian model, the WHO distributions are used as priors, but truncated at 1 to avoid high posterior probabilities of values less than 1, given that those values are deemed extremely unlikely. For parameters relating to q_i, the WHO expert distributions are used as priors. All prior distributions used in the fully Bayesian model are listed in Table 2.2, together with their posterior median estimate and 95% CI. The input data are observed PM (the z_i's) for the non-AIDS countries and the observed VR adjustments for all countries (to estimate the global model parameters in the VR adjustment model).

The results from the Bayesian model were compared to the results from a modified WHO model. The modified WHO model is based on the original WHO model, but modified to leave out all AIDS adjustments (as explained for the Bayesian model) and fitted to non-AIDS countries only, such that its results were directly comparable to the results from the Bayesian model. Given that the models were fit to non-AIDS countries only, the results are for illustrative purposes only (to illustrate the insights that can be obtained from this approach with respect to VR adjustments).

2.3.3 Computation

A Markov chain Monte Carlo (MCMC) algorithm was used to obtain samples from the posterior distributions of the model parameters for the VR adjustment model in Section 2.3.1 and for the fully Bayesian maternal mortality estimation model in Section 2.3.2.

In the VR adjustment model and in the Bayesian maternal mortality estimation model, 75,000 iterations were used for each of the three MCMC chains. We thinned for every 10 iterations and discarded the first 20,000 iterations. Convergence was

Parameter	Prior	Posterior median estimate (95% CI)
w	$U(1/2,1)$	0.77 (0.53, 0.98)
ρ	$U(0,1)$	0.97 (0.90, 1.00)
σ_{AR}	$U(0,0.5)$	0.08 (0.05, 0.12)
σ_p	$U\left(0,\frac{1/2}{\sqrt{12}}\right)$	0.079 (0.005, 0.142)
σ_W	$U(0,0.05)$	0.046 (0.034, 0.050)
θ_s	$TN_{[1,\infty)}(\log(1.1)-0.5\cdot 0.05^2, 0.05^2)$	1.10 (1.01, 1.20)
θ_o	$TN_{[1,\infty)}(\log(1.1)-0.5\cdot 0.05^2, 0.05^2)$	1.06 (1.00, 1.15)
β_0	$N(\hat{\beta}_0, 100^2)$	2.68 (1.56, 3.74)
β_1	$N(0,100^2)$	-0.31 (-0.44, -0.17)
β_2	$N(0,100^2)$	0.94 (0.67, 1.24)
β_3	$N(0,100^2)$	-1.20 (-1.82, -0.52)
q_S	Beta(mean=0.10, sd=0.04)	0.10 (0.04, 0.19)
q_o	Beta(mean=0.15, sd=0.06)	0.13 (0.05, 0.25)
σ_{ac}	$U(0,100)$	0.41 (0.32, 0.51)
σ_{ar}	$U(0,100)$	0.48 (0.29, 0.84)
σ_y	$U(0,100)$	0.31 (0.27, 0.35)

Table 2.2 **Posterior estimates for the Bayesian mortality estimation model parameters.** Notes: $\hat{\beta}_0 = 2.83$, obtained from WHO multilevel regression model fit. $q_i = q_S$ for i in Sub-Saharan Africa, and $q_i = q_o$ otherwise.

checked through visual inspection of trace plots and convergence diagnostics of Gelman and Rubin [14].

Models were implemented in `R 2.15` [15] and `JAGS 3.3.0` [16]. The WHO model used `R`-package `lme4` [17] and the Bayesian model used packages `rjags` [18] and `coda` [19].

2.4 Results

2.4.1 Bayesian VR adjustment estimates

The results in this section are based on the Bayesian VR adjustment model from Section 2.3.1. Prior and posteriors for selected model parameters are shown in Figure 2.3 and Table 2.3 summarizes the posterior medians and 95% credible intervals (CIs) for the five model parameters in the AR(1) model. The posterior distribution of w, the global mean of the p_c's (the country-specific mean parameters for the pro-

portion of accurately reported maternal deaths), suggests that values below 0.6 are unlikely (the posterior probability that $w < 0.6$ is 1.5%). The posterior and prior for σ_p (the standard deviation of the p_c's) are very similar, suggesting that there is little information in the data to estimate this parameter. The posterior for time series parameter ρ indicates high autocorrelation in the time series. The posterior distribution of σ_W suggests the standard deviation is close to its upper bound of 5%.

Parameter	Prior	Posterior median estimate (95%CI)	
		VR adj. model	PM est. model
w	$U(1/2,1)$	0.81 (0.63, 0.99)	0.77 (0.53, 0.98)
ρ	$U(0,1)$	0.94 (0.76, 0.99)	0.97 (0.90, 1.00)
σ_{AR}	$U(0,0.5)$	0.08 (0.05, 0.15)	0.08 (0.05, 0.12)
σ_p	$U\left(0,\frac{1/2}{\sqrt{12}}\right)$	0.081 (0.004, 0.142)	0.079 (0.005, 0.142)
σ_W	$U(0,0.05)$	0.045 (0.032, 0.050)	0.046 (0.034, 0.050)
$W_{c,k}$		1.34 (1.03, 2.40)	1.43 (1.03, 2.60)

Table 2.3 **Prior distributions and posterior estimates for the Bayesian VR adjustment model.** Posterior estimates are given for the VR adjustment model from Section 2.3.1 and the PM estimation model from Section 2.3.2. $W_{c,k}$ refers to the VR adjustment for a 5-year observation in a country with no external information on the VR misclassification error. Adj.=adjustment. Est.=estimation.

The bottom-right graph of Figure 2.3 shows the prior (induced by the hierarchical time series model and the prior on the time series model parameters) and posterior distribution for VR adjustment $W_{c,k}$ for a country without external information, for an observation period of 5 years. The posterior VR adjustment is also added to Figure 2.1. While the Bayesian posterior distribution is more weighted towards lower levels of under-reporting than the observed distribution of VR adjustments suggests (see Figure 2.1), its posterior median is smaller than the prior median (1.34 as compared to 1.43), suggesting that the estimated lower levels of under-reporting are data-driven as opposed to driven by prior model settings. The mismatch between the posterior distribution for the VR adjustment and the observations is explained by the fact that the posterior distribution is not directly comparable to the observed distribution because the observed distribution includes observations for time periods of various durations and some countries contributed multiple observations. In

comparison to the WHO expert distribution, the Bayesian median of 1.34 is lower than the WHO point estimate of 1.50. The Bayesian distribution suggests that there is considerable uncertainty in VR adjustment parameters; the 95% credible interval (CI) for the VR adjustment value is given by (1.03, 2.40), as compared to (1.36, 1.65) for the WHO distribution.

Figure 2.2 shows the observed VR adjustments and 5-year estimates for countries with external information on the VR adjustment. The 5-year estimates refer to $W_{c,k}$ from Eq.(2.4), obtained from the country-specific proportions $P_{c,t}$ for the standard 5-year periods that are used in the WHO estimation approach. For the majority of countries with partial information, the VR adjustment remains quite uncertain for many country-periods. Figure 2.4 compares the observed adjustments for the same set of countries (with external VR adjustment information) to the adjustments that would have been obtained if the Bayesian and WHO approaches for countries without external information would have been used. While the observed adjustments are inside the WHO uncertainty bounds only for approximately one out of three observation periods (35% of the observations), the Bayesian uncertainty bounds contain the observed values for approximately four out five observation periods (79%).

Two sets of maternal mortality estimates are shown in Figure 2.5 for the countries with VR data where the multilevel model was used to construct the WHO PM estimates. The estimates were obtained from the original WHO modeling approach, and from the WHO approach with VR adjustments imputed from the Bayesian VR adjustment model. Differences between the WHO and (partially) Bayesian estimates are small, but as expected, the Bayesian estimates are slightly lower and their uncertainty bounds are slightly wider than those from the WHO model.

Comparison to alternative estimates Alternative global estimates of maternal mortality were published in 2011 [20] and in 2012 [13]. In these studies, VR misclassification errors were obtained through a cause-of-death reclassification algorithm [12]. The adjustment factors for maternal mortality that were displayed in Figure 6 in Naghavi et al. (2010) are illustrated in Figure 2.6. The corresponding

Bayesian estimates ($W_{c,k}$) for a 1-year period are added for comparison. The two distributions differ slightly: while VR adjustments of around 1.1 are most likely in the Naghavi et al. distribution, the Bayesian mode is slightly higher and larger VR adjustments are more likely. The VR adjustment values from Naghavi et al. are not publicly available so we were not able to verify how the adjustments compare for the country-years that were included in our study. Hence, we are only able to compare the overall distribution of all available VR adjustment values based on the Bayesian approach and the results from Naghavi et al.

2.4.2 Bayesian maternal mortality estimates

The posteriors for the VR adjustment parameters resulting from the Bayesian maternal mortality model are similar to those resulting from fitting the VR adjustment model to the VR adjustment data only (see Table 2.3), except that the posterior for w, the global mean of the p_c's (the country-specific mean parameters for the proportion of accurately reported maternal deaths), assigns greater probability mass to lower values of under-reporting, and the resulting distribution of $W_{c,k}$ for a 5-year period in a country without information suggests greater VR adjustments as compared to the estimates obtained from the VR adjustment model fitted to the VR adjustment data only. The finding that posteriors for the VR adjustment parameters resulting from the Bayesian maternal mortality model suggest more uncertainty towards greater VR adjustments may be caused by a selection bias of countries that provide information about VR adjustments; the VR adjustment may be lower in countries that have the resources to provide follow-up studies to investigate the accuracy of VR reporting as compared to countries without additional information.

Figure 2.7 illustrates the differences in estimated PM between the modified WHO and the fully Bayesian model for selected countries. The comparison shows that for about half of the countries, the Bayesian estimates are comparable to or slightly lower than the WHO estimates. Among the remaining countries, the Bayesian PM estimates are notably higher than the modified WHO estimates for Fiji, Philip-

pines and Brunei Darussalam. For example, Fiji is the country with the largest adjustment (for under-reporting of maternal deaths) in the most recent observation period; the Bayesian point estimate for the adjustment is 2.30 (95% CI given by 1.44 to 3.43), and the resulting PM estimate for the year 2000 is 20 per 1000 (95% CI given by 9 to 39 per 1000) as compared to 11 per 1000 (95% CI given by 6 to 21 per 1000) as given by the modified WHO model. Given that no VR adjustment data are available in Fiji, the Bayesian VR adjustment value is driven by the expected PM from the covariates in the multilevel model, the regional intercept and the estimated variability in country intercepts. External information is necessary to verify the accuracy of this VR adjustment.

Figure 2.8 shows the point estimates and 95% CIs for the VR adjustment parameters in the most recent observation period for all non-AIDS countries with VR data but without external information on VR adjustments, estimated in the fully Bayesian model. The Bayesian posterior estimates for VR adjustment parameters vary from 1.14 (for Saint Lucia) to 2.30 (for Fiji) and have much wider credible bounds as compared to the WHO expert distribution. The comparison in Figure 2.8 allows for identification of countries where recent VR adjustments are higher or lower than expected, as compared to the WHO adjustment of 1.5, that may warrant further investigation, as discussed for Fiji. For Saint Lucia, an increasing trend in VR data on PM is observed (see Figure 2.7), which contradicts the decrease in PM that would be expected based on changes in the predictors of PM. This results in a downwards adjustment of recent VR data in the Bayesian model. Again, country information is required to understand the specific situation in Saint Lucia and the accuracy of VR data.

2.5 Discussion

In this paper, we aimed to provide a plausible assessment of the extent of misclassification of maternal deaths in VR data and the uncertainty therein for countries where no external quantification of misreporting is available, and to capture time

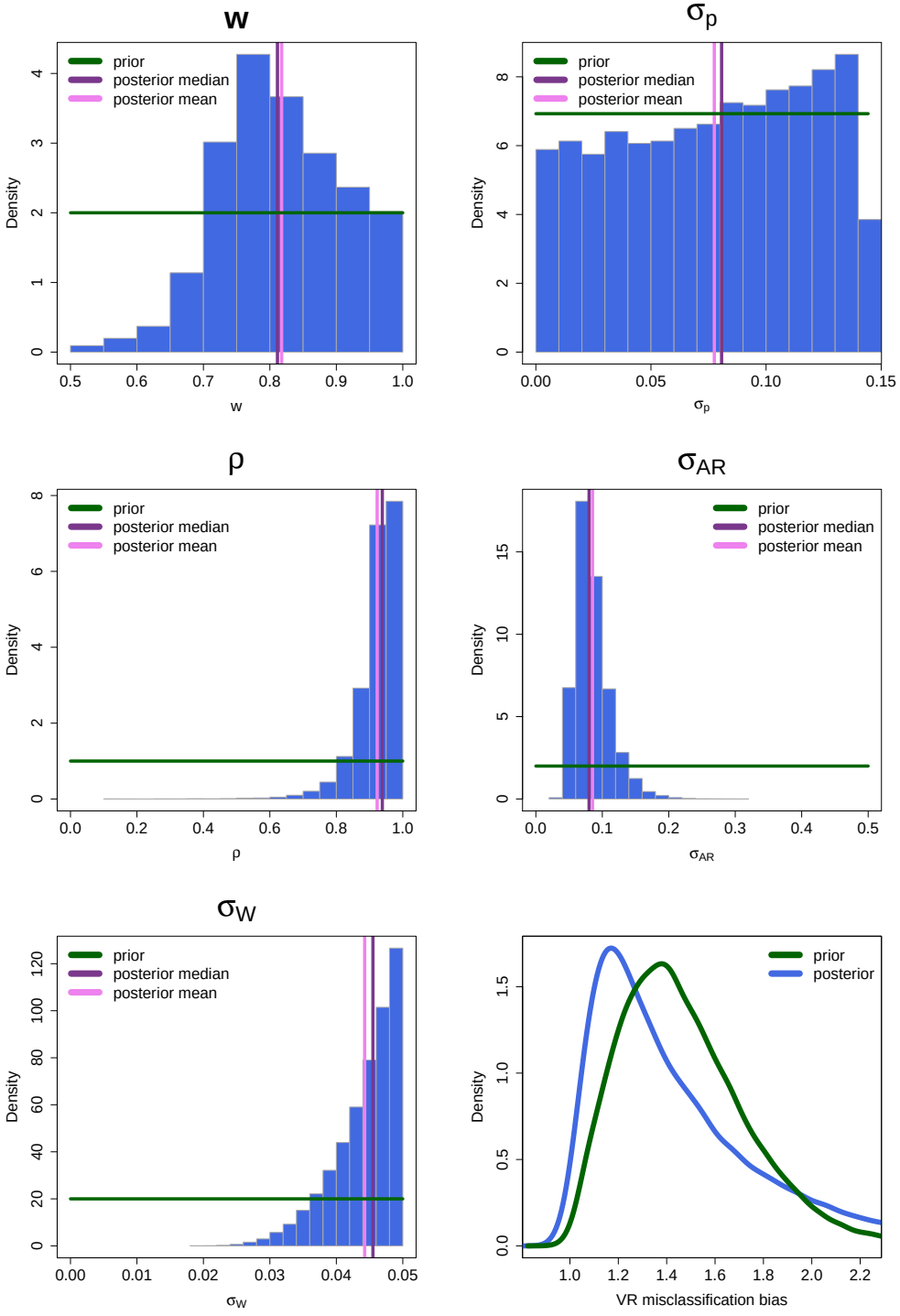

Fig. 2.3 **Prior and posterior distributions of VR adjustment model parameters.** Posterior samples are displayed in the histogram. Priors are denoted by the horizontal green lines. Posterior medians and means are represented in the vertical purple and pink lines respectively. $W_{c,k}$ refers to the VR adjustment for a 5-year observation in a country with no external information on the VR misclassification error.

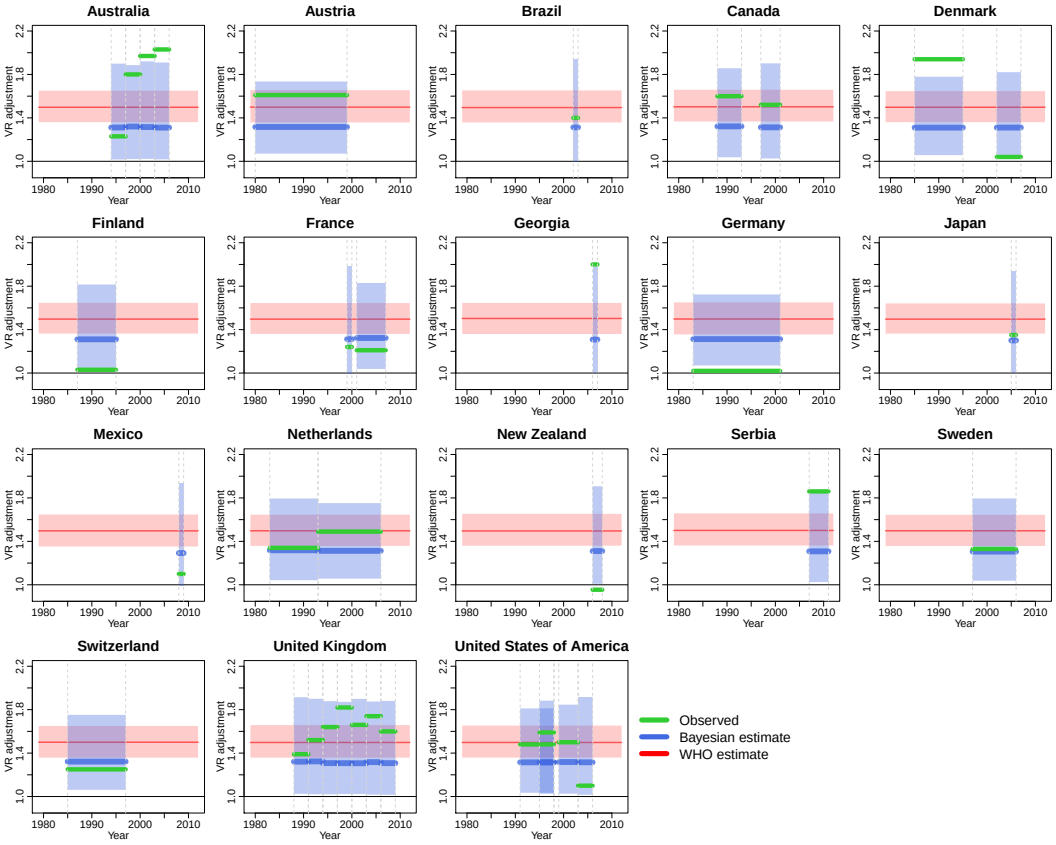

Fig. 2.4 **Point estimates and uncertainty bounds for VR adjustments for countries with external information that would have been obtained if the Bayesian and WHO approaches for countries without external information would have been used.** Light green lines indicate observed VR adjustment factors. Blue lines and shades indicate the corresponding "no-external-information" Bayesian posterior median estimates and 95% credible intervals respectively. The red shades and lines indicate the "no-external-information" WHO mean estimates and 95% uncertainty bounds. The line span corresponds to the observation period.

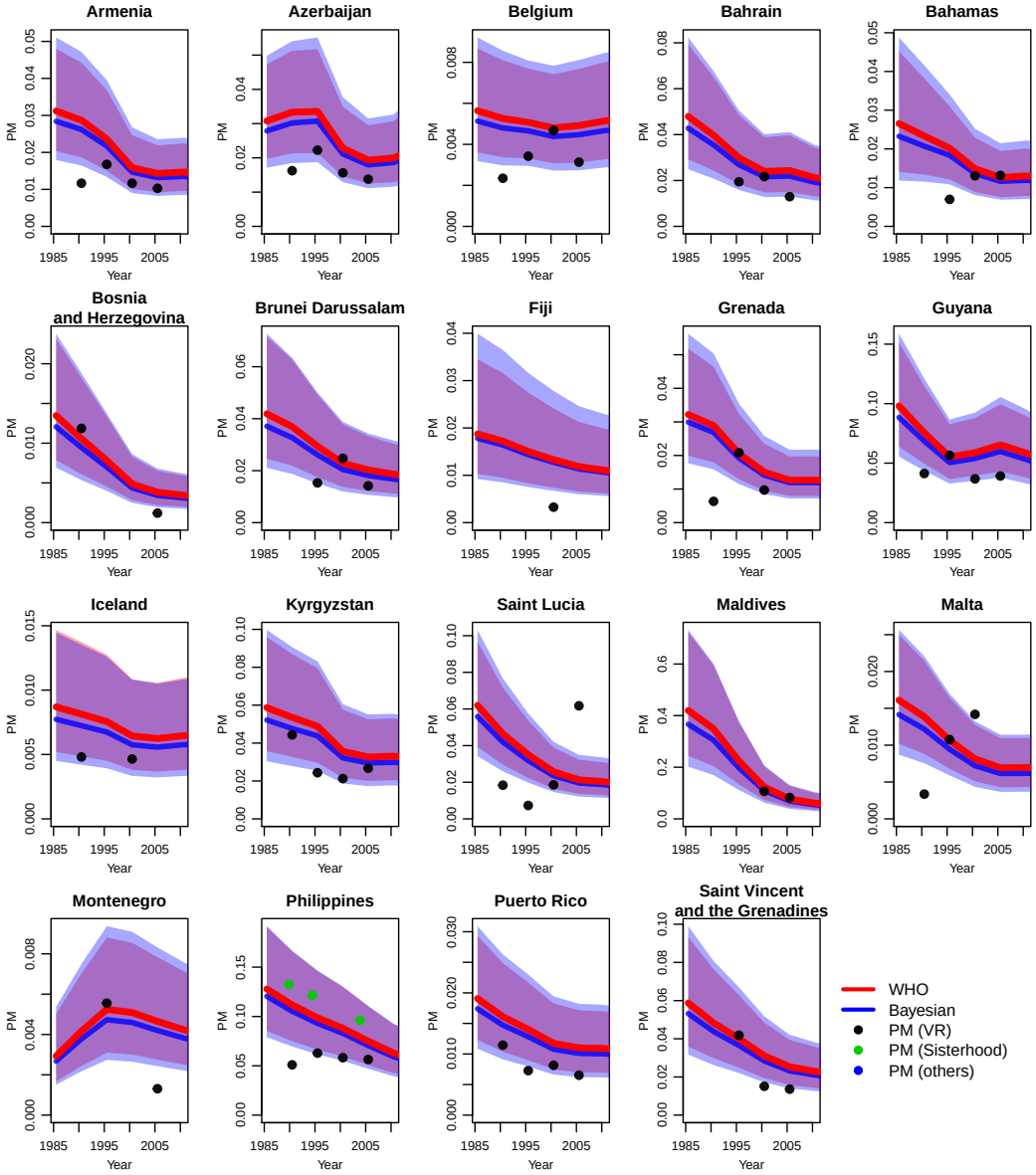

Fig. 2.5 **Maternal mortality (PM) estimates and 95% credible intervals for selected countries based on the WHO model (red) and the WHO model with Bayesian VR adjustment estimates (blue).** Observations are displayed by source type. The selected countries are the countries with VR data but without external information on the VR misclassification, for which the WHO used a multi-level model for constructing PM estimates. The estimates from the WHO model with Bayesian VR adjustment estimates are referred to as "Bayesian".

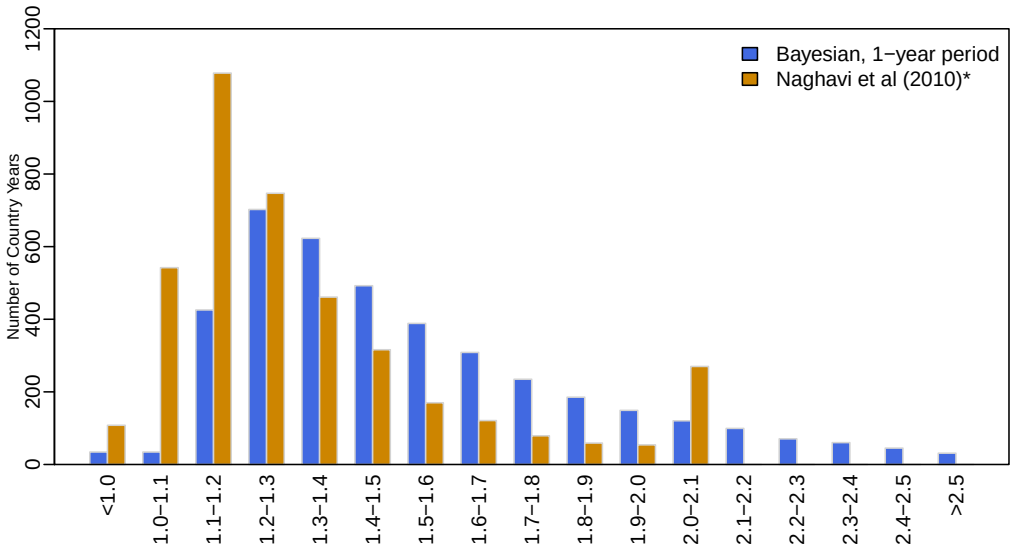

Fig. 2.6 **Comparison of VR misclassification values from Naghavi et al. (2010) and the Bayesian VR adjustment model.** The Bayesian estimates are based on 1-year observation periods. *Values greater than 2 were aggregated in the Naghavi et al. results.

trends within countries with partial external information. We used a Bayesian hierarchical time series model to assess the extent of VR misclassification errors, which resulted in a distribution that is more comparable to the observed biases and increases the uncertainty that is associated with maternal mortality rates. A comparison of the Bayesian estimates, the WHO estimates and alternative estimates published by Naghavi et al. (2010) suggested that the estimates of the VR adjustment from the Bayesian approach are in between the medians of the two sets of estimates.

The inclusion of the Bayesian VR adjustment model in the WHO model for the proportion of maternal deaths illustrated in which country-periods greater or smaller misclassification errors are expected based on additional information on PM and model assumptions. It also showed that posteriors for the VR adjustment parameters resulting from the Bayesian maternal mortality model suggested slightly larger VR adjustments. This is possibly explained by a selection bias of countries that provide information about VR adjustments; the VR adjustment may be lower in countries that have the resources to provide follow-up studies to investigate the

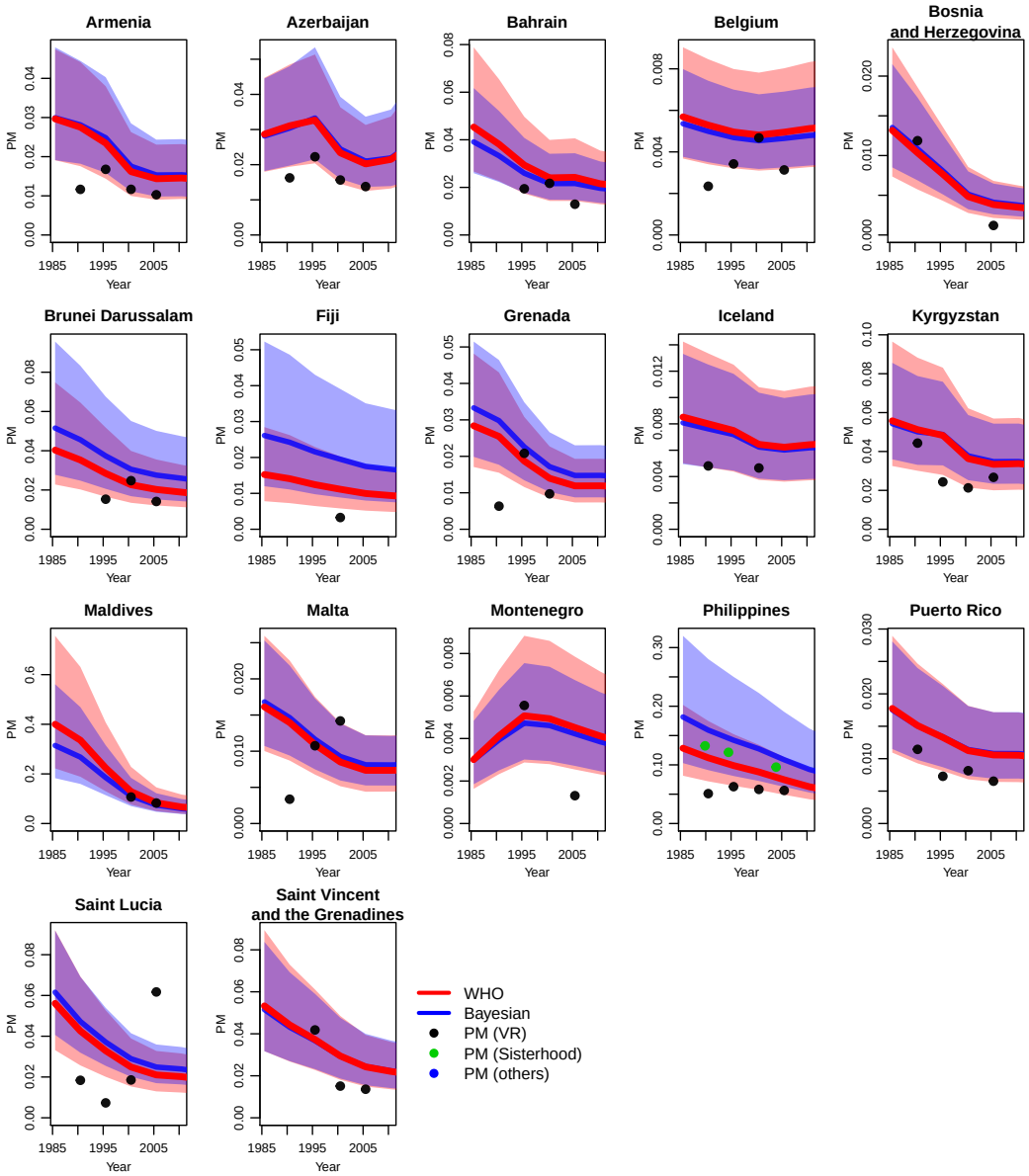

Fig. 2.7 **Maternal mortality (PM) estimates and 95% credible intervals for selected countries based on the modified WHO model (red) and the fully Bayesian model (blue).** Observations are displayed by source type. The selected countries are the non-AIDS countries with VR data but without external information on the VR misclassification, for which the WHO used a multi-level model for constructing PM estimates.

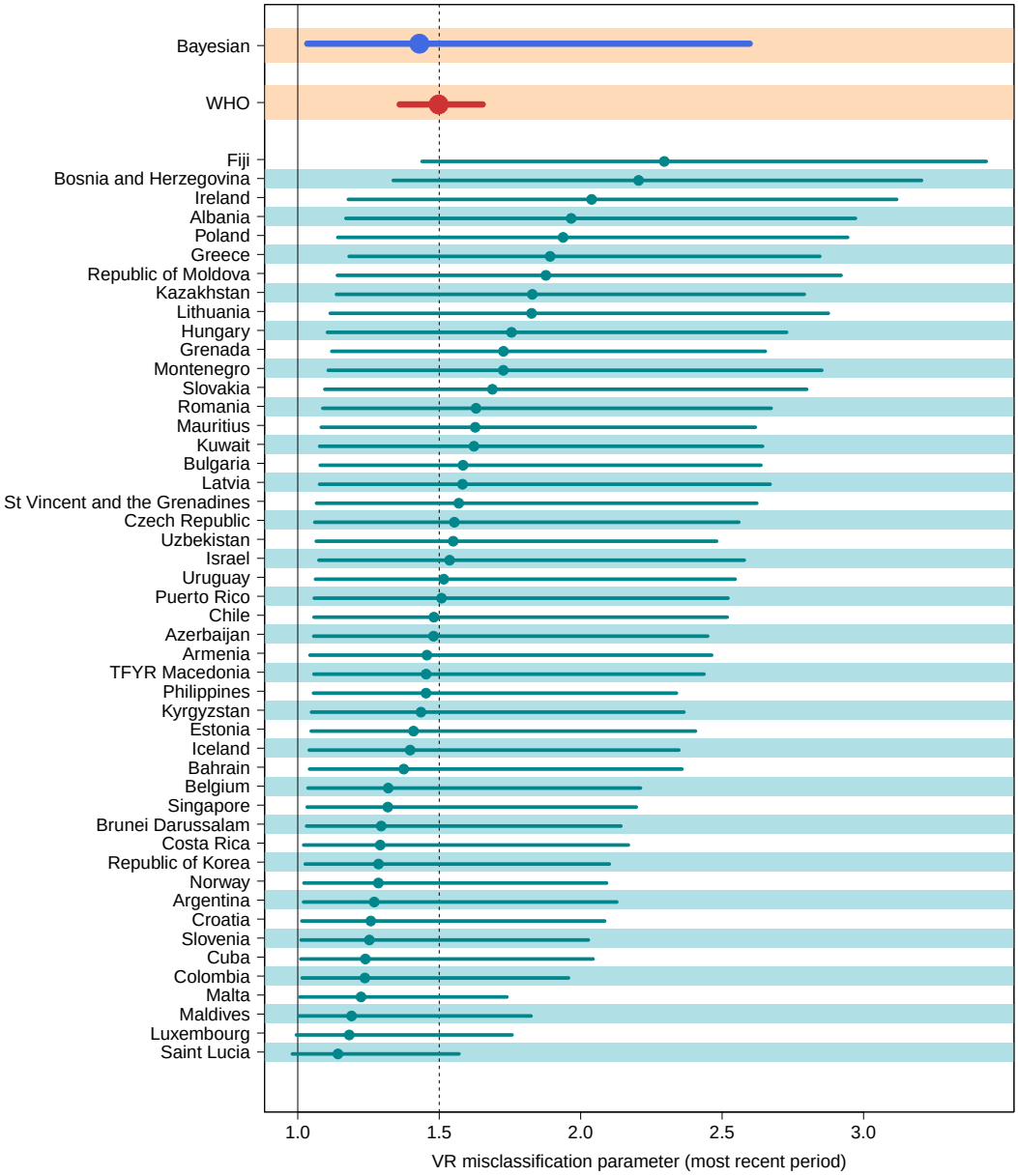

Fig. 2.8 **Bayesian posterior VR adjustment parameters in the most recent observation period for selected countries.** Point estimates (dots) and 95% credible intervals (lines). The selected countries are all non-AIDS countries with VR data but without out external information on the VR misclassification. The posterior Bayesian adjustment for a "new country" without information on p_c and the WHO adjustment are added for comparison.

accuracy of VR reporting as compared to countries without additional information. These findings warrant further investigation to avoid underestimation of maternal deaths.

With the analysis, we illustrated that Bayesian modeling approaches can be used to provide more objective and data-driven insights into maternal mortality estimates and data adjustment parameters. As illustrated in Figure 2.4 and explained in Section 2.4.1, we verified that the Bayesian VR adjustment model would provide more plausible adjustment estimates for countries with external information on VR quality than the WHO model, if the information available in those countries would not be used to construct the estimates. Also, prior and posterior distributions in the Bayesian model were compared to communicate which parameters were most influenced by prior assumptions. Unfortunately, given the limited number of data points, formal cross-validation exercises could not be not carried out. More data collection to assess VR data quality is needed to truly validate any VR adjustment modeling approach.

In this paper, we focused on the challenges in using VR data for estimating maternal mortality. Similar, or potentially greater challenges exist for using data from other sources. Instead of focusing more attention on statistical models for estimating maternal mortality, we call for more data collection and research to measure maternal mortality and assess data quality.

Chapter 3

A systematic assessment of national, regional and global levels and trends in the sex ratio at birth and scenario-based projections

This work has been submitted as:

Chao F, Gerland P, Cook A, Alkema L. A systematic assessment of national, regional and global levels and trends in the sex ratio at birth and scenario-based projections.

Contributors FC and LA designed research. FC and LA performed research. FC, PG, ARC, and LA wrote the paper.

Abstract

The sex ratio at birth (SRB) imbalance in recent decades is a direct consequence of sex-selective abortion, driven by the co-existence of son preference, readily available technology of prenatal sex determination, and fertility decline. Estimation of the degree of imbalance is complicated by the uncertainty associated with SRB observations, which in turn makes projection difficult. There are needs for repro-

ducible methods to construct SRB estimates and projections with uncertainty, and to assess past and potential future SRB inflation due to sex-selective abortion. We implemented Bayesian methods for probabilistic SRB estimation and projection for all countries based on an extensive database from vital registration systems, censuses, and surveys. We modeled the SRB regional biological norms, the fluctuation around regional norms, and the inflation. For countries without empirical evidence of past or current SRB inflation but with evidence of potential SRB inflation, projections with and without future inflation were constructed. The estimated regional biological norms range from 1.03 [1.02; 1.03] in Sub-Saharan Africa to 1.07 [1.06; 1.08] in Eastern Asia and Oceania. We found that the past and ongoing SRB inflation occurred mostly in Southern Asia and Eastern Asia, resulting in 9.3 (95% uncertainty interval [5.7; 13.7]) and 11.2 [7.2; 15.7] million missing female births during 1970–2015. Under the scenario that all countries at risk of SRB inflation will experience inflation, we projected that Southern Asia, Eastern Asia, and Sub-Saharan Africa will experience total deficit of 13.1 [8.4; 19.0], 13.0 [8.0; 20.0], and 8.1 [3.8; 15.7] million missing female births during 1970–2100.

keywords Bayesian hierarchical model; sex ratio at birth; sex-selective abortion; scenario-based projection.

3.1 Introduction

In this paper, we described a method for probabilistic estimation and projection of the sex ratio at birth (SRB; ratio of male to female livebirths) for all countries, with a focus on assessing the SRB imbalance due to sex-selective abortion.

Under normal circumstances, the SRB varies in a narrow range around 1.05, with only a few known variations among racial groups [21–32]. For most of human history, the SRB remained within that natural range. However, over recent decades, SRBs have risen in a number of Asian countries and in Eastern Europe [33–49]. The increasing imbalance in SRB is due to a combination of three main factors that lead to sex-selective abortion [41, 43]. Firstly, most societies with abnormal SRB

inflation have persisting strong son preference, which provides the motivation. Secondly, since the 1970s, prenatal sex diagnosis and access to sex-selective abortion have become increasingly available [50–54], providing the method. Thirdly, fertility have fallen to low levels around the world that resulted in a "squeezing effect": to attain both the desired small families and the desire of sex composition by resort to sex selection [41]. Consequently, sex-selective abortion provides a means to avoid large families while still having male offspring.

Estimation of the degree of SRB imbalance is complicated by the amount of uncertainty associated with SRB observations due to data quality issues and sampling errors, which in turn makes projection difficult. While the UN Population Division publishes estimates and projections for all countries in the World Population Prospects (WPP), its estimates and projections are deterministic, and depend on expert-based opinions which are not reproducible [55]. The current methodology in the UN WPP 2017 version for SRB projections are based on the basic assumption of a natural level of SRB at 1.05, and future SRB outcomes either remain at the same level as the most recent data or return towards the natural level within the next 10–40 years. An up-to-date systematic analysis for SRB–one of the most fundamental demographic indicators–for all countries over time using all available data with reproducible methods for estimation and projection is urgently needed.

To fill the research void, we developed model-based estimates and probabilistic projections for 212 countries (referring to populations that are considered as "countries" or "areas" in the United Nation classification) from 1950 to 2100. Our analyses are based on a comprehensive database on national-level SRB with data from vital registration (VR) systems, censuses, international and national surveys. We developed two Bayesian hierarchical models to estimate and project SRBs in two types of country-years: 1) those that are not affected by sex-selective abortion, and 2) those that may be affected by sex-selective abortion that leads to unnatural SRB inflation.

We identified 33 countries where SRB inflation may have happened in the past

or may happen in the future, which we refer to as countries at risk of SRB inflation. To identify a country that may potentially have SRB inflation, we used inclusive criteria based on a combination of qualitative and quantitative approaches to identify all possible countries: 1) strong son preference suggested by literature review, 2) high level of desired sex ratio at birth (based on figures in [34]), 3) high level of sex ratio of the last birth (based on figures in [34]), 4) excess female under-5 mortality rate (based on figures in [6, 56]). As long as a country satisfies at least one criterion, we assume that this country may have a potential SRB inflation after 1970, the earliest date when sex-selective abortions became available.

To model SRB in country-years not affected by sex-selective abortion, we developed a model for natural fluctuations in the SRB and fitted it to the global database after excluding data from country-years with potential SRB inflation. The actual level of SRB was modeled as the product of a biological norm and a country-year-specific multiplier that accounts for natural fluctuation around the norm. We allowed biological norms to differ across regions to incorporate SRB differences due to race [21–32]. Hence, for this purpose, regions refer to groupings of countries based on their majority race (Table 3.2). For example, we grouped countries in Europe, North America, Australia, and New Zealand to refer to the regional grouping of countries with a majority of Caucasians. Within each region, we assumed that the biological norm was constant over time.

We parameterized the potential SRB inflation in the 33 countries at risk of SRB inflation using a trapezoid to represent consecutive phases of increase, stagnation, and a decrease back to zero. Parameters were estimated with a Bayesian hierarchical model [57] to share information across countries about the start year of the inflation, the maximum inflation, and the length of the inflation period during the three phases. We incorporated the effect of the fertility squeeze into the model by using the total fertility rate (TFR, obtained from UN WPP 2017 [55]) to inform the start year of the SRB inflation period. For those countries at risk of SRB inflation without empirical evidence of an inflation during the observation period, referred

to as countries at risk of future SRB inflation, SRB projections were constructed based on two scenarios: 1) no SRB inflation will occur, i.e. the SRB will fluctuate around its respective regional biological norm in future years; and 2) the SRB will inflate due to sex-selective abortion for some future period (as determined by the hierarchical model for SRB inflation and the country-specific TFR projections).

To quantify the effect of SRB imbalance due to sex-selective abortion, we calculated the annual number of missing female births (AMFB) and the cumulative number of missing female births (CMFB) over time. The AMFB is defined as the difference between the number of female livebirths based on the SRB without the inflation factor and the number of female livebirths based on the SRB with the inflation factor. The CMFB for a certain period is the sum of the AMFB over the period.

3.2 Data: overview

We produced SRB estimates and projections for 212 countries with total population size greater than 90,000 as of 2015. Due to data availability and inclusion criteria, we constructed a database with data from 194 countries. The database included 9,929 data points on national-level SRB, corresponding to 15,354 country-years of information. On average, 72.4 country-years of data are available for each of the 212 countries for which we produced SRB estimates and projections in our analysis. An overview of the data sources included in the database is in Table 3.1. Table 3.2 lists the data availability for the 212 countries. A listing of all data series is given in Appendix 6.4.

Data source type	Number of observations
Census	61
DHS	2,005
Other DHS	886
Other	151
VR/SRS	6,826

Table 3.1 **Distribution of observations by source type.** Observations are grouped by source type. DHS: Demographic and Health Surveys, where Other DHS refer to non-standard Demographic and Health Surveys, i.e. Special, Interim and National DHS, Malaria Indicator Surveys, AIDS Indicator Surveys and World Fertility Surveys; VR: Vital Registration; SRS: sampling registration system.

Table 3.2 **Regional grouping and data availability by country.** "ENAN": the combination of Europe, North America, Australia, and New Zealand.

Region	**Major race/ethno-linguistic groups**	**[194] Country with data**	**[18] Country without data**
Southern Asia	Indian; Pakistan; Dravidians; Indo-Aryans; Munda peoples	[9] Afghanistan; Bangladesh; Bhutan; India; Iran (Islamic Republic of); Maldives; Nepal; Pakistan; Sri Lanka	[0]
ENAN	Russians; Germans; French; British; Italians; Spanish; Ukrainians; Poles	[46] Albania; Andorra; Australia; Austria; Belarus; Belgium; Bosnia and Herzegovina; Bulgaria; Canada; Channel Islands; Croatia; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Iceland; Ireland; Italy; Latvia; Lithuania; Luxembourg; Macedonia; Malta; Republic of Moldova; Monaco; Montenegro; Netherlands; New Zealand; Norway; Poland; Portugal; Romania; Russian Federation; San Marino; Slovakia; Slovenia; Spain; Sweden; Switzerland; United Kingdom; United States of America; Ukraine	[1] Serbia
Northern Africa	Maghrebis; Egyptians	[5] Algeria; Egypt; Libya; Morocco; Tunisia	[1] Western Sahara

Continued on next page

Table 3.2 – continued from previous page

Region	Major race/ethno-linguistic groups	[194] Country with data	[18] Country without data
Sub-Saharan Africa	Luba; Mongo; Kongo; Kanuri; Oromo; Amhara; Somali; Hutu; Chewa; shona; Zulu; Xitsonga; Yoruba; Igbo; Hausa; Mande peoples; Akan; Fulbe	[44] Angola; Benin; Burkina Faso; Burundi; Cameroon; Cape Verde; Central African Republic; Chad; Comoros; Republic of the Congo; Democratic Republic of the Congo; Cote d'Ivoire; Djibouti; Ethiopia; Gabon; Gambia; Ghana; Guinea; Kenya; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Mauritius; Mozambique; Namibia; Niger; Nigeria; Reunion; Rwanda; Sao Tome and Principe; Senegal; Seychelles; Sierra Leone; South Africa; Sudan; Swaziland; Tanzania; Togo; Uganda; Zambia; Zimbabwe	[7] Botswana; Equatorial Guinea; Eritrea; Guinea-Bissau; Mayotte; Somalia; South Sudan
Latin America and the Caribbean	Mexicans; Mestizos; Caucasians; Native Americans; Afro Central Americans; Marranos; Afro-Caribbean	[40] Antigua and Barbuda; Argentina; Aruba; Bahamas; Barbados; Belize; Bolivia (Plurinational State of); Brazil; Chile; Colombia; Costa Rica; Cuba; Curacao; Dominica; Dominican Republic; Ecuador; El Salvador; French Guiana; Grenada; Guadeloupe; Guatemala; Guyana; Haiti; Honduras; Jamaica; Martinique; Mexico; Nicaragua; Panama; Paraguay; Peru; Puerto Rico; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Suriname; Trinidad and Tobago; Uruguay; United States Virgin Islands; Venezuela (Bolivarian Republic of)	[0]
Western Asia	Arabs; Jews; Samaritans; Druze; Semites; Iranian peoples; Turkmen; Turks	[15] Arab Emirates; Bahrain; Cyprus; Iraq; Israel; Jordan; Kuwait; Lebanon; Oman; Qatar; Saudi Arabia; State of Palestine; Syria; Turkey; Yemen	[0]

Continued on next page

Table 3.2 – continued from previous page

Region	**Major race/ethno-linguistic groups**	**[194] Country with data**	**[18] Country without data**
Caucasus and Central Asia	Turkic peoples; Iranian peoples; Mongols; Russians; Peoples of the Caucasus	[7] Armenia; Azerbaijan; Georgia; Kazakhstan; Kyrgyz Republic; Tajikistan; Uzbekistan	[1] Turkmenistan
South-eastern Asia	Tai-Kadai; Austronesian peoples; Negrito peoples; Sino-Tibetan; Austro-Asiatic; Indo-Aryan and Dravidian	[10] Brunei; Cambodia; Indonesia; Laos; Malaysia; Philippines; Singapore; Thailand; Timor-Leste; Vietnam	[1] Myanmar
Eastern Asia	Chinese; Sino-Tibetan peoples; Japanese; Korean	[8] China; China, Macao SAR; China, Hong Kong SAR; Japan; Democratic People's Republic of Korea; Republic of Korea; Mongolia; China, Taiwan Province	[0]
Oceania	Polynesians; Melanesians; Mocronesians; Papuans; Australian Aborigines; Europeans	[10] Cook Islands; Fiji; French Polynesia; Guam; Nauru; New Caledonia; Niue; Palau; Samoa; Tonga	[7] Kiribati; Marshall Islands; Micronesia; Papua New Guinea; Solomon Islands; Tuvalu; Vanuatu

In general, data on births by sex are recorded in vital registration (VR) systems, or in censuses or surveys with retrospective questions on recent births or full birth histories asked to women of reproductive ages. VR systems typically provide data on an annual basis, while censuses usually provide information for the previous 12 or 24 months, and surveys for longer retrospective periods from 5 to 20 years before the survey date when using full birth histories.

In the SRB database of this study, we compiled VR data from the Demographic Year Book and the Human Mortality Database, sampling registration system (SRS) data for India, Pakistan, and Bangladesh from annual reports, international survey data from microdata or reports: Demographic and Health Surveys (DHS), World Fertility Surveys (WFS), Reproductive Health Survey (RHS), Pan Arab Project for Family Health (PAPFAM), Pan Arab Project for Child Development (PAPCHILD), and census and national-level survey data from reports. For survey data with available microdata files, we used a Jackknife method to calculate sampling errors for observations with varying reference periods. We conducted data quality checks for data prior to inclusion. Detailed information on all the data pre-processing steps are in Section 3.3.

Estimates and projections of the TFR and the number of births were obtained from the UN WPP 2017 version [55]; we used the annual estimates and median-variant projections from 1950 to 2100.

3.3 Data: pre-processing procedures

The SRB database as summarized in Table 3.1 is based on several steps of data quality checking and pre-processing. In summary, we first calculated the Jackknife repeated replication method to devrive the standard error for Demographic and Health Surveys (DHS) and other DHS (see Table 3.1 for definition of other DHS) data series and the stochastic error for vital registration/sampling registration system (VR/SRS) data, for each 1-year observation period based on microdata. We then merged the observation period based on the coefficient of variation (CV)

for log-transformed SRB. After the merging, we applied inclusion and exclusion criteria.

3.3.1 Sampling errors for survey data

The Jackknife repeated replication method is the standard approach to compute the variance of complex statistic such as mortality and fertility for DHS data [58]. This approach is mean to take into account the sampling design of the DHS data, which is usually multi-stage cluster and/or stratified sampling of households. Hence, we adopted the same approach to calculate the Jackknife estimate and sampling error for log-transformed SRB for DHS and other DHS data series, for each country-specific survey s and reference year (year of birth) t.

Let U denote the total number of clusters or primary sampling units (PSUs). The u-th partial prediction of SRB $r_{s,t}$ is given by:

$$r_{-u} = \frac{\sum_{n=1}^{N} \mathbb{I}_n(\text{sex}_n = \text{male}; \text{cluster}_n \neq u) \cdot w_n}{\sum_{n=1}^{N} \mathbb{I}_n(\text{sex}_n = \text{female}; \text{cluster}_n \neq u) \cdot w_n}, \text{ for } u = 1, \ldots, U,$$

where n indexes the livebirths in the survey-year, N is the total number of livebirths, and w_n is the sampling weight for the n-th livebirth. The u-th pseudo-value estimate of $\log(r_{s,t})$ is:

$$\begin{aligned} \log(r)^*_u &= U \cdot \log(r_{\text{obs}}) - (U-1) \cdot \log(r_{-u}), \text{ where} \\ r_{\text{obs}} &= \frac{\sum_{n=1}^{N} \mathbb{I}_n(\text{sex}_n = \text{male}) \cdot w_n}{\sum_{n=1}^{N} \mathbb{I}_n(\text{sex}_n = \text{female}) \cdot w_n}. \end{aligned}$$

The Jackknife estimate and standard error of $\log(r_{s,t})$ are:

$$\begin{aligned} \log(r_{s,t}) &= \frac{1}{U} \sum_{u=1}^{U} \log(r)^*_u, \\ \sigma_{s,t} &= \sqrt{\frac{\sum_{u=1}^{U} (\log(r)^*_u - \log(r_{s,t}))^2}{U(U-1)}}. \end{aligned}$$

The Jackknife sampling variance was replaced by its corresponding stochastic variance (described below for VR/SRS data) if its stochastic variance was bigger than

its jackknife counterpart. Most of such replacements were carried out to observations with the earliest reference date in a certain data series, with small numbers of births.

3.3.2 Stochastic errors for VR/SRS data

For observations from VR/SRS, a Monte Carlo simulation was used to approximate the stochastic variance. For a country-year, the g-th simulated number of male livebirths $B_m^{(g)}$ was obtained as follows:

$$B_m^{(g)} \sim Bin(B_{\text{total}}^{\text{obs}}, p_m^{\text{obs}}), \text{ for } g = 1, \ldots, G,$$

where G is the total number of simulations, $B_{\text{total}}^{\text{obs}}$ is the total number of livebirths as observed in VR data, and p_m^{obs} is the observed proportion of male livebirths. The corresponding g-th simulation for SRB was given by:

$$r^{(g)} = \frac{B_m^{(g)}}{B_{\text{total}}^{\text{obs}} - B_m^{(g)}}, \text{ for } g = 1, \ldots, G.$$

The stochastic error for SRB on log-scale is:

$$\sqrt{\frac{1}{G-1}\sum_{g=1}^{G}\left(\log(r^{(g)}) - \overline{\log(r)}\right)^2}, \text{ where } \overline{\log(r)} = \frac{1}{G}\sum_{g=1}^{G}\log(r^{(g)}).$$

3.3.3 Recalculating observation periods

For data series from (other) DHS and VR, instead of using the data at each reference year with 1-year-interval, each country-specific data series were optimized by merging the data points (with 1-year observation period) in order to reach a certain precision. The precision of the data series is optimized by controlling the coefficient of variance of each data point in that data series (CV; defined as the ratio of standard error to estimate). We use the cutoff value of 5% for CV to merge the observation period [59]. Hence, the length of the observation period for the annual log-scaled SRB observations $r_{s,t}$ for country-specific survey s and reference year t is deter-

mined by the upper limit of CV such that $\exp\{\sigma_{s,t}\} < 1.05$. Annual observation were merged in backwards direction, i.e. by combining the most recent observation years.

3.3.4 Inclusion and exclusion criteria

We considered for inclusion in the database all data from countries with total population greater than 90,000 in 2015. For DHS and Other DHS data series, we excluded observations with reference dates beyond 20 years of the survey date due to potentially larger recall errors and truncation for older women compared to the recent reference period.

Inclusion criteria for VR/SRS data for a given country are as follows:

1. The earliest data point for reference year t to be included has to satisfy the following 3 criteria:

   (a) Its livebirth completeness ratio $> 85\%$; AND

   (b) Its mean livebirth completeness ratio within the period $[t-2.5; t+2.5] > 85\%$; AND

   (c) Its data reliability is either "High", or "Fair",

   where

   - The completeness for a certain country-year is the ratio of the total number of livebirths from VR/SRS data to the total number of livebirths from UN World Population Prospect (WPP) version 2015 [60].
   - Data reliability is a measure of VR data provided by the UN Population Division, based on a qualitative assessment reported to the UN by the national authorities and/or an assessment by UN Population Division analysts.

2. For data past the earliest included reference year:

(a) For a country belonging to the group of high income countries according to the World Bank 2014 country income classifications [61] and/or the group of developed countries as per Millennium Development Indicators of regional grouping [62], all data with more recent reference years are included.

(b) For all the other countries, we included a data point with reference year t if:

i. Its livebirth completeness ratio $> 80\%$; AND

ii. Its mean livebirth completeness ratio within the period $[t-2.5; t+2.5] > 80\%$; AND

iii. Its data reliability is either High, or Fair;

Additional VR exclusion rules are as follows:

1. For countries with GNP per capital < 500 based on the World Bank 1973 country income classification [63, 64], we excluded all data with reference years before 1970, regardless of data reliability or completeness. Based on this rule, 22 countries have their VR data excluded before 1970:

   - Albania; Antigua & B.; Cape Verde; Macao; Dominica; Egypt; El Salvador; Grenada; Guyana; Jordan; Maldives; Mauritius; Saint Kitts & Nevis; Saint Lucia; Samoa; Sao Tome Pr; Seychelles; Sri Lanka; St. Vincent & Gren.; Thailand; Tonga; Tunisia.

2. We excluded VR data for colonial periods for African countries because these assessments do not include the African population during the period. The VR data points are excluded for the following country-specific periods:

   (a) Equatorial Guinea: before and inclusive of 1968;

   (b) Guinea-Bissau: before and inclusive of 1973;

   (c) Mozambique: before and inclusive of 1975;

(d) Sao Tome Pr.: before and inclusive of 1975

3. We excluded VR data before 1980 from the Republic of Korea [65, 66].

3.4 Methods: overview

3.4.1 Selection of countries at risk of SRB inflation

We conducted a systematic literature review on Feb 22nd, 2017 to identify countries with empirical evidence of SRB inflation, as well as countries with populations that are considered to have a son preference or to be a patrimonial society. By searching the keywords "sex selective abortion" on PubMed, we found 416 articles. By searching the keywords "son preference" or "patrimonial society" on Scopus, there were 526 articles in the search result. By going through the abstract and conclusion of the 942 articles, we selected 31 articles that identified countries with SRB inflation and/or having a son preference on the national level. The selected articles are listed in Table 3.3. Besides countries that were identified by the systematic literature review, we also considered a country to have a potential for SRB inflation if it was identified as having an outlying female under-5 mortality rate in the year 2015 [6, 56], or if recent records of the desired sex ratio at birth are higher than 120 and/or the sex ratio of last birth is higher than 130 [34]. In total, we identified 33 countries at risk of SRB inflation.

3.4.2 Modeling Country-Years Without Inflation of Sex Ratio at Birth

We modeled the SRB in country-years without inflation as a product of two components: 1) a biological norm, which is assumed to be constant over time within a region; and 2) a country-year-specific multiplier that captures the natural fluctuations of the country-specific SRB around its respective biological norm over time. We allowed for biological norms to differ across regions to incorporate SRB differences

due to race and assigned independent uniform priors to each of the regional biological norms. The country-year-specific multiplier is modeled with an auto-regressive time series process of order 1 within a country. For countries without any data (or with very limited information), the multiplier is equal to (or shrunk towards) 1, such that the estimated SRB without inflation due to prenatal sex discrimination is given by (or close to) its regional biological norm. For countries where the data suggest different levels or trends, the multipliers capture these natural deviations from the regional biological norms.

To estimate the SRB for country-years without inflation, and to estimate the parameters associated with the natural SRB (i.e., the biological norms), we fitted the model to a reduced database that excluded data from the 33 countries at risk of SRB inflation with reference year from 1970 onward. We kept the data with reference year before 1970 for the 33 countries since sex-selected abortion technology was not widely available or affordable before 1970.

3.4.3 Modeling Country-Years With Potential Inflation of Sex Ratio at Birth

We modeled the SRB in the 33 countries at risk of SRB inflation as the sum of two parts: A) the inflation-free SRB level, given by the model of country-years without SRB inflation as described above; and B) a non-negative SRB inflation factor. The country-year-specific SRB inflation factor is modeled from 1970 onward for those countries where a son preference may have led or may lead to prenatal sex discrimination once sex selective technology becomes accessible and family sizes have declined. The parameterization of the inflation factor is described in the introduction. The hierarchical distributions for the parameters of the trapezoid function are given by normal distributions with lower truncation at zero. We assign weakly informative priors to the mean and standard deviation of these truncated normal distributions, with the exception of the mean of the start year of the SRB inflation. The mean for the start year was determined by an analysis of the relation between

fertility levels and the start as observed in countries with high quality VR data (see Section 3.5.3). Given that the inflation in India started at an unusually high TFR, the start year for this country was not estimated as part of the hierarchical model but instead, a uniform distribution was assigned to allow any start year between 1970 and 1980.

We constructed scenario-based projections for 19 countries at risk of future SRB inflation, which are countries where either the start year of the inflation period is beyond the observation period, or where the inflation in the observation period is negligible. The best-case scenario projection does not include a future inflation for these countries. While in the worst-case scenario, country-specific TFR projections and the hierarchical model for the inflation are used to project the start and trajectory of the SRB inflation. In the worst-case scenario, we do not consider the uncertainty of any other conditions of the population.

3.4.4 Model validation

We used two out-of-sample validation exercises and one simulation to assess model performance.

In the first out-of-sample validation exercise for countries without SRB inflation, we left out all data that were collected after 2004, corresponding to around 20% of the global (no-potential-SRB-inflation) database. We fitted the model without the inflation factor to the remaining training database, and obtained estimates, projections, and uncertainty intervals that would have been constructed in the year 2004 based on available data at that time. In the second exercise, we focused on the countries at risk of SRB inflation and left out all data in these countries collected after 2008, corresponding to approximately 20% of the data for these countries. We fitted the model with the inflation factor to the training set to obtain estimates and projections for the SRB and inflation. We also assessed the performance of the inflation model by simulating the SRB for each country at risk of SRB inflation after 1970 based on the estimates of the global parameters of the inflation model only

(and not the country-specific data).

We calculated various validation measures to assess model performance, including prediction errors and coverage. The error for each left-out observation was defined as the difference between the left-out observation and the posterior median of the predictive distribution based on the training database. Coverage refers to the percentage of left-out data points falling above or below their corresponding 95% or 80% prediction intervals. The model validation results suggest that the models are reasonably well calibrated (see Section 3.6.4).

3.5 Methods: technical details

We modeled the true SRB $R_{c,t}$ for country c, year t without SRB inflation as follows:

$$R_{c,t} = N_{r[c]} \cdot P_{c,t}, \tag{3.1}$$

where $N_{r[c]}$ is the regional biological norm from country c in region $r[c]$ in the absence of prenatal sex discrimination and sex-selective abortion and $P_{c,t}$ is the divergence from that norm under natural circumstances. If the SRB is inflated in country c in year t, the true level of SRB $R_{c,t}$ is modeled as follows:

$$R_{c,t} = N_{r[c]} \cdot P_{c,t} + \alpha_{c,t}, \tag{3.2}$$

where the additional term $\alpha_{c,t}$ is the non-negative inflation factor to capture high SRB levels that deemed to be due to sex-selective abortion (as opposed to natural fluctuations).

The following subsections explain the steps to estimate $R_{c,t}$:

- Step 1 (Section 3.5.1): Select all countries in which SRB inflation may have happened in the past or may happen in the future, referred to as countries at risk of SRB inflation;

- Step 2 (Section 3.5.2): Model SRB $R_{c,t}$ without inflation based on a reduced

database (obtained by excluding all data after 1970 from the countries at risk of SRB inflation);

- Step 3 (Section 3.5.3): Model SRB $R_{c,t}$ with inflation factor $\alpha_{c,t}$ for countries at risk of SRB inflation.

3.5.1 Step 1 – Select countries at risk of SRB inflation

We conducted a systematic literature review on February 22, 2017 to find articles to identify countries at risk of SRB inflation. We searched on PubMed and Scopus with the following search terms:

1. Pubmed
    - search term: "sex selective abortion";
    - number of articles found: 416;
2. Scopus
    - search term: "son preference" OR "patrimonial society";
    - number of articles found: 526.

The selection criteria of countries at risk of SRB inflation are as follows:

1. Literature suggests inflated past or current SRB;
2. Literature reports on son preference or patrimonial society;
3. The desired sex ratio at birth (DSRB) is higher than 120 male births per 100 female births (as suggested in Bongaarts (2013) [34]);
4. The sex ratio of last birth (SRLB) is higher than 130 male births per 100 female births (Figure 3, Bongaarts (2013) [34]);
5. The sex ratio of the under-five mortality rate (U5MR) is outlying and associated with excess female deaths, which may be caused by postnatal gender

discrimination (2015 UN IGME report [6]; with "outlying" defined in Alkema et al. (2014) [56]).

We selected 33 countries as listed in Table 3.3, which satisfy at least one of the aforementioned criteria.

3.5.2 Step 2 – Model SRB without inflation and estimate regional biological norms

In the first step of modeling, parameters that are not related to prenatal gender discrimination and sex-selective abortion are estimated. That is, we want to estimate N_r and all the hyper-parameters related to $P_{c,t}$. In order to do that, we used a reduced SRB database by excluding observed SRB data points that may be affected by prenatal sex discrimination and sex-selective abortion. The excluded data points are from the 33 countries at risk of SRB inflation listed in Table 3.3 from reference year 1970 onward ([43] suggests 1980). We assume that the true SRB for selected countries at risk of SRB inflation before 1970 and all the other country-years are the product of two components:

$$R_{c,t} \quad = \quad N_{r[c]} \cdot P_{c,t}.$$

We estimate biological norms that vary between regional groups to capture racial variation in SRB [21–32]. We assume that the regional biological norm N_r is constant over time and assign independent uniform priors to each N_r:

$$N_r \quad \sim \quad U(1, 1.1), \text{ for } r = 1, \ldots, R.$$

The multiplier $P_{c,t}$ is estimated by a time series model. For countries without any data or with very limited information, the multiplier fluctuates around one, such that the estimated SRB without prenatal gender discrimination is given by N_r. For countries where the data suggest different levels or trends, $P_{c,t}$ captures these devi-

Country	(1) Inflated SRB	(4) Excess female U5MR	(2) High DSRB	(3) High SRLB	(5) Son preference	Reference
Afghanistan		✓				[56]
Albania	✓					[43]
Algeria		✓				[56]
Armenia	✓		✓	✓	✓	[34, 37, 41, 48]
Azerbaijan	✓		✓	✓	✓	[34, 37, 41, 48]
Bangladesh					✓	[67, 68]
Chad			✓			[34]
China	✓				✓	[42, 44, 69]
Egypt		✓			✓	[56, 70–74]
Georgia	✓				✓	[37, 41, 48]
Guinea			✓			[34]
Hong Kong SAR (China)	✓					[33]
India	✓	✓	✓	✓	✓	[34, 43, 44, 56, 75]
Iran		✓				[56]
Jordan		✓	✓	✓		[34, 56]
Korea, Republic of	✓				✓	[41, 49]
Mali			✓			[34]
Mauritania			✓			[34]
Montenegro	✓					[43]
Morocco					✓	[70]
Nepal		✓	✓	✓	✓	[34, 56, 76–79]
Niger			✓			[34]
Nigeria					✓	[80, 81]
Pakistan	✓	✓	✓	✓	✓	[34, 41, 56]
Senegal			✓		✓	[34, 82]
Singapore	✓					[83, 84]
Taiwan province (China)	✓					[47]
Tanzania					✓	[85]
Tonga		✓				[56]
Tunisia					✓	[70]
Turkey					✓	[86]
Uganda					✓	[87]
Vietnam	✓				✓	[40]

Table 3.3 **Countries with past/current/potential future SRB inflation.** Selection criteria 1–5 are described in section 3.5.1.

ations from $N_{r[c]}$:

$$\begin{aligned} \log(P_{c,t}) &= \rho \cdot \log(P_{c,t-1}) + \varepsilon_{c,t}, \\ \varepsilon_{c,t} &\sim N_{[\log(0.9),\log(1.1)]}(0, \sigma_\varepsilon^2). \end{aligned}$$

The fluctuations $\varepsilon_{c,t}$ are modeled with an auto-regressive time series model of order one (AR(1)) with a truncated normal distribution. Weakly informative priors were assigned to ρ and σ_ε:

$$\begin{aligned} \rho &\sim U(0,1), \\ \sigma_\varepsilon &\sim U(0,0.05). \end{aligned}$$

The data model for the i-th observed SRBs r_i is as follows:

$$\log(r_i) \sim N(\log(R_{c[i],t[i]}), \sigma_i^2 + \omega_{s[i]}^2), \tag{3.3}$$

where σ_i^2 is the sampling or stochastic variance for the i-th observation (set to a minimum of 1%) and $\omega_{s[i]}^2$ is the non-sampling variance, where $s[i]$ refers to the source type of the i-th observation (shown in Table 3.1). The prior $U(0,2)$ was assigned to each ω_s. For VR/SRS data, we assume that the non-sampling variance is zero.

3.5.3 Step 3 – Model SRB with inflation factor

We estimated $R_{c,t}$ for countries with possible SRB inflation using data from the 33 countries at risk of SRB inflation listed in Table 3.3. We modeled the SRB $R_{c,t}$ for country c, year t, as follows:

$$R_{c,t} = N_{r[c]} \cdot P_{c,t} + \alpha_{c,t}.$$

In the model fitting, we used the posterior medians for N_r, ρ, σ_ε (to get $P_{c,t}$), and ω_s (non-sampling error) from step 2 described above in Section 3.5.2.

$\alpha_{c,t}$ is the upward inflation factor for country c in year t to capture higher SRB levels that may be due to sex-selective abortion. It is modeled from 1970 onward for a selected group of countries where gender discrimination may be present and where a son preference may have led or may lead to prenatal gender discrimination once fertility declines and sex selective technology becomes accessible [43].

We parameterized the potential SRB inflation $\alpha_{c,t}$ using a trapezoid to represent consecutive phases of increase, stagnation, and a decrease back to zero (see Figure 3.1). The trapezoidal form is chosen such that it can represent various SRB imbalance transition processes, including the one that occurred in Republic of Korea. Other countries are assumed to follow a similar transition process if they are at risk of SRB inflation. Parameters were estimated with a Bayesian hierarchical model to share information across countries about the start year of the inflation, the maximum inflation, and the length of the inflation period during the three phases [57, 88].

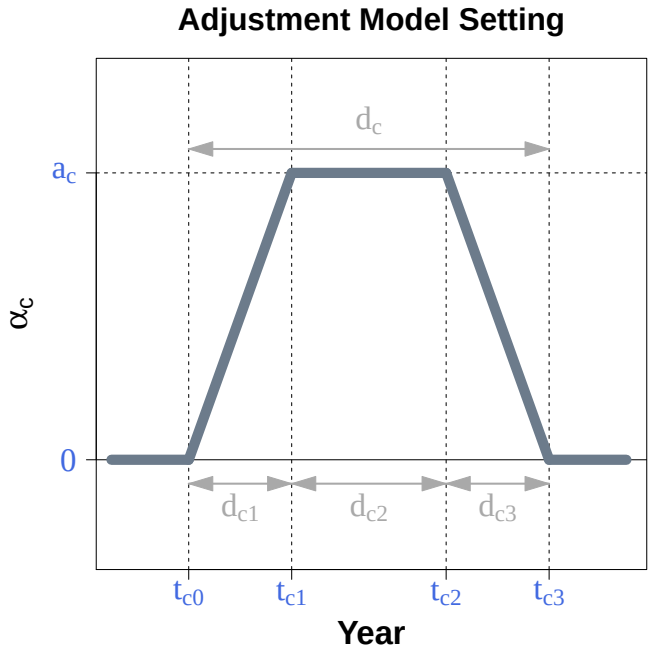

Fig. 3.1 **Illustration for model setting of the inflation factor.** $t_{c,0}$ and $t_{c,3}$ refer to the start and end year of SRB inflation period for country c. d_c is the total length of the SRB inflation period for country c. a_c is the maximum value of the inflation value in country c.

The inflation factor $\alpha_{c,t}$ is modeled as:

$$\alpha_{c,t} = \begin{cases} (a_c/d_{c,1}) \cdot (t - t_{c,0}), & t \in (t_{c,0}, t_{c,1}) \\ a_c, & t \in (t_{c,1}, t_{c,2}) \\ a_c - (a_c/d_{c,3}) \cdot (t - t_{c,2}), & t \in (t_{c,2}, t_{c,3}) \\ 0, & \text{o.w.} \end{cases}$$

where

$$\begin{aligned} t_{c,1} &= t_{c,0} + d_{c,1}, \\ t_{c,2} &= t_{c,0} + d_{c,1} + d_{c,2}, \\ t_{c,3} &= t_{c,0} + d_{c,1} + d_{c,2} + d_{c,3}. \end{aligned}$$

Truncated normal hierarchical distributions are used for a_c, the d_cs and the start year $t_{c,0}$:

$$\begin{aligned} a_c &\sim N(\mu_{ac}, \sigma^2_{ac})T(0,), \\ d_{c,k} &\sim N(\mu_{d(k)}, \sigma^2_{d(k)})T(0,), \text{ for } k = 1,2,3, \\ t_{c,0} &\sim N(t_{c,\eta}, \sigma^2_{\eta})T(t_{c,\eta 6}, 2100), \text{ for all countries except India,} \\ t_{c,0} &\sim U(1970, 1980), \text{ for India,} \end{aligned}$$

with an exception made for the start year in India (as explained further below).

Weakly informative priors were assigned to hierarchical mean and variance parameters of the hierarchical distributions:

$$\begin{aligned} \sigma_{\eta_c} &\sim U(0,10), \\ \mu_{ac} &\sim U(0,2), \\ \mu_{d(k)} &\sim U(0,40), \text{ for } k = 1,2,3, \\ \sigma_{ac} &\sim U(0,2), \\ \sigma_{d(k)} &\sim U(1,10), \text{ for } k = 1,2,3, \end{aligned}$$

except for the mean $t_{c,\eta}$ for the start year $t_{c,0}$, as explained in Section 3.5.3.

Distribution of the start year in India The start year parameter $t_{c,0}$ for India is assigned a uniform distribution as opposed to being included in the hierarchical model. As shown in Figure 3.2, the start year of its SRB inflation period is estimated to be in 1990 when using the hierarchical distribution. However, as noted in the literature (explained below), the SRB inflation in India started much earlier, i.e. during the 1970s. Hence, the hierarchical distribution does not provide an appropriate fit for India; we consider India to be an exception regarding the timing of its inflation period and did not include it in the hierarchical model.

In India, prenatal diagnosis (PD) became available soon after abortion was legalized in 1971. PD was introduced in India as a method for detecting fetal abnormalities but was soon used for prenatal sex selection [50, 54]. Since then, the combination of prenatal sex determination and selective abortion has been widely used for the systematic elimination of females fetuses [89]. First amniocentesis in the 1970s was openly advertised and extensively used in urban areas for sex-selective abortions [90]. The results of the 1981 census already showed skewing of the sex ratio among children, and there were concerns about the sex imbalance in the population [90]. The sharp increase in the sex ratio among children between 0 and 6 years (as an approximation of SRB) since the 1970s is now unequivocally linked to the widespread use of prenatal sex determination and selective abortions of girls [51, 53, 54, 91–93].

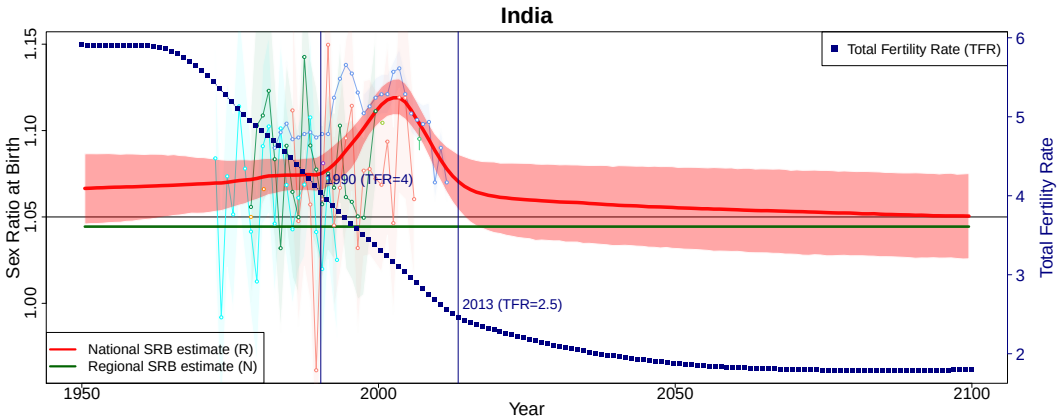

Fig. 3.2 **Model fit for India using a hierarchical distribution for start year $t_{c,0}$.** The model results for India here are based on using the same hierarchical model for the start year of SRB inflation as all the other countries listed in Table 3.3.

Inflation start year

We incorporated the effect of the fertility squeeze into the model by using the total fertility rate (TFR) from the World Population Prospects 2017 (WPP) [55] to inform the start year of the SRB inflation period. Specifically, in the hierarchical distribution for start year parameter $t_{c,0}$, the mean is equal to the year that the TFR in country c decreased (or will decrease) to a TFR value η (i.e. same across countries) in country-specific year $t_{c,\eta}$.

The TFR value η and the country-specific year $t_{c,\eta}$ were computed as follows:

1. Among the countries at risk of SRB inflation, select those countries with high quality data, here quantified by those countries with mean sampling or stochastic error for log-transformed SRB at most 0.02. This resulted in a selection of 9 countries as listed in Table 3.4.

2. For each of the 9 countries, if there were 5 consecutive VR data points greater than the posterior median estimate from the non-inflation model in Step 1, the start year for that country was given by the year preceding those 5 VR observations. We then extracted the country-specific TFR value η_c that corresponded to that start year, see Table 3.4.

3. The global TFR value η is defined as the median of the country-specific TFR values.

Country	$t_{c,j}$	η_c
Albania	1970	4.91
Armenia	1991	2.48
Azerbaijan	1992	2.93
Georgia	2002	1.59
Hong Kong, China SAR	1996	1.12
Iran	1970	6.44
Korea, Republic of	1980	2.54
Singapore	1970	3.19
Taiwan province (China)	1977	2.78
median TFR η		**2.8**

Table 3.4 **List of countries to compute η, the global TFR value.**

Given η, the $t_{c,\eta}$'s for all countries at risk of SRB inflation were computed by extracting the year with the TFR value closest to η. The lower truncation $t_{c,\eta 6}$ of the start year distribution is the year that the TFR in country c decreased to 6 or the year 1970, whichever occurred later.

3.5.4 Computing

We obtained posterior samples using a Markov chain Monte Carlo (MCMC) algorithm, implemented in the open source software `R 3·3·3` [94] and `JAGS 4·0·1` (Just another Gibbs Sampler) [16], using `R`-packages `rjags` [18], `R2jags` [95], and `MCMCpack` [96]. Convergence of the MCMC algorithm and the sufficiency of the number of samples obtained were checked through visual inspection of trace plots and convergence diagnostics of Gelman and Rubin [14], implemented in the `coda R`-package [19]. Table 3.5 summarizes the MCMC specifications for the model runs. The numbers of chains, burn-in, thinning as shown in Table 3.5 are chosen in order to optimize the converging process in an efficient fashion.

MCMC specifications	**Reduced model**		**inflation model**	
	full	validation	full	validation
# chains	4	8	8	8
# burn-in	902,000	152,000	142,000	112,000
# thinning	70	70	40	60
# posterior samples per parameter	8,400	8,400	8,000	8,160

Table 3.5 **MCMC specifications for model runs.**

3.5.5 Estimates of sex-specific livebirths, missing births, and aggregates

Estimates of country-specific annual livebirths $B_{c,t}$ were obtained from the World Population Prospects 2017 (WPP) [55]. WPP estimates are available from 1950 up to 2099. We used the 2099 birth estimates for the calendar year 2100 by assuming that the number of births in 2100 are equal to those in 2099.

The estimated and expected female livebirths for a country-year, denoted as $B^F_{c,t}$ and $B^{FE}_{c,t}$ respectively, are obtained as follows:

$$\begin{aligned} B^F_{c,t} &= \frac{B_{c,t}}{1+R_{c,t}}, \\ B^{FE}_{c,t} &= \frac{B_{c,t}}{1+R^E_{c,t}}, \end{aligned}$$

where $R^E_{c,t} = N_{r[c]} \cdot P_{c,t}$, which is the inflation-factor-free sex ratio at birth.

The annual number of missing female births (AMFBs) for country c in year t was defined as below:

$$B^{F*}_{c,t} = B^{FE}_{c,t} - B^F_{c,t}.$$

The cumulative number of missing female births (CMFBs) for period t_1 to t_2 in country c was defined as the sum of AMFBs from the year t_1 up to the year t_2:

$$Z^{F*}_{c,[t_1,t_2]} = \sum_{t=t_1}^{t_2} B^{F*}_{c,t}.$$

Aggregate estimates for the world and all Millennium Development Goal (MDG) regions were calculated based on the totals for the number of livebirths by sex.

3.5.6 Scenario-based projections

We constructed scenario-based projections for those countries at risk of SRB inflation where the SRB inflation is considered to be after the data period, or where the inflation may have started but is still negligible during the data period, with scenarios including and excluding future inflation. The set of countries with a potential future inflation was selected as follows, for each country at risk of SRB inflation c:

1. Approximate the probability that the start year was before the end of the observation period by the proportion $v_c = \frac{1}{G}\sum_{g=1}^{G} \mathbb{I}\left\{t^{(g)}_{c,0} < t_{c,max}\right\} \left\{t^{(g)}_{c,0} | g = 1,\ldots,G\right\}$, which is the proportion of posterior samples for the start year that fall before the most recent reference year $t_{c,max}$ in country c.

2. If $\nu_c > 95\%$, consider this country as having a past or ongoing inflation;

3. If $\nu_c < 5\%$, consider this country as not having a past or ongoing inflation;

4. If $5\% \leq \nu_c \leq 95\%$, the following steps were conducted:

   (a) Select trajectories g where the start year of inflation is before the most recent reference year, with $t_{c,0}^{(g)} < t_{c,max}$;

   (b) Calculate the posterior median of the inflation factor $\alpha_{c,t}^{(g)}$ based on the selected subset of trajectories, and let ψ_c denote the maximum posterior median in the period $t \leq t_{c,max}$;

   (c) Calculate $\zeta_c = (N_{r[c]} \cdot (P_{c,\forall t} - 1))^{(99th)}$, the 99-th percentile of the difference between the inflation-excluded SRB and the regional biological norm $N_{r[c]}$ for all years and posterior samples combined;

      i. If $\psi_c > \zeta_c$, consider this country as having a past or ongoing inflation;

      ii. If $\psi_c < \zeta_c$, consider this country as not having a past or ongoing inflation.

Table 3.6 summarizes the results for all the 33 countries at risk of SRB inflation. We identified 19 countries without past or ongoing SRB inflation: Afghanistan; Algeria; Bangladesh; Chad; Egypt; Guinea; Jordan; Mali; Mauritania; Morocco; Nepal; Niger; Nigeria; Pakistan; Senegal; Tanzania; Tonga; Turkey; Uganda.

Country	ν_c (%)	ψ_c (inflation)	ζ_c (fluctuation)	Past/ongoing fluctation?
Afghanistan	0.2	–	–	
Albania	100.0	–	–	yes
Algeria	65.0	0.006	0.026	
Armenia	100.0	–	–	yes
Azerbaijan	100.0	–	–	yes
Bangladesh	53.1	0.009	0.026	
Chad	0.0	–	–	
China	100.0	–	–	yes
Egypt	2.6	–	–	
Georgia	100.0	–	–	yes
Guinea	0.0	–	–	
Hong Kong SAR (China)	100.0	–	–	yes
India	100.0	–	–	yes
Iran	97.3	–	–	yes
Jordan	4.8	–	–	
Korea, Republic of	100.0	–	–	yes
Mali	0.0	–	–	
Mauritania	0.0	–	–	
Montenegro	100.0	–	–	yes
Morocco	31.9	0.006	0.026	
Nepal	59.0	0.025	0.029	
Niger	0.0	–	–	
Nigeria	0.0	–	–	
Pakistan	2.0	–	–	
Senegal	0.0	–	–	
Singapore	100.0	–	–	yes
Taiwan province (China)	99.9	–	–	yes
Tanzania	0.0	–	–	
Tonga	0.0	–	–	
Tunisia	95.5	–	–	yes
Turkey	80.4	0.005	0.030	
Uganda	0.0	–	–	
Vietnam	100.0	–	–	yes

Table 3.6 **Assessment of past or ongoing inflation for countries at risk of SRB inflation.** A country is considered as having a past or ongoing inflation if: 1) $\nu_c > 95\%$; or 2) when $5\% \leq \nu_c \leq 95\%$ and $\psi_c > \zeta_c$.

3.5.7 Model validation

Model performance was assessed via two approaches: 1) out-of-sample validation, and 2) one-country simulation.

Out-of-sample validation

To test the performance for the reduced model and inflation model respectively, we left out about 20% of the data points after a certain survey year (not reference year) [97]. After leaving out data, we fitted the model to the training data set, and obtained point estimates and uncertainty intervals that would have been constructed based on available data set in the survey year selected. We computed mean/median errors, and coverage based on left-out observations and based on estimates obtained from the full data set and estimated based on the training data set.

For the left-out observations, the errors are defined as: $e_{s,t} = r_{s,t} - \widetilde{r}_{s,t}$, where $\widetilde{r}_{s,t}$ refers to the posterior median of the predictive distribution based on the training data set for the left-out observation $r_{s,t}$. Coverage is given by $1/n \cdot \sum 1[r_{s,t} \geq l_{s,t}] \cdot 1[r_{s,t} \leq u_{s,t}]$, where n refers to the number of left-out observations, and $l_{s,t}$ and $u_{s,t}$ correspond to the lower and upper bounds of the 95% prediction interval for the left-out observation $r_{s,t}$. The validation measures were calculated for 1000 sets of left-out observations, where each set consisted of one randomly selected left-out observation from each country. The reported validation results were based on the mean of the outcomes from the 1000 sets of left-out observations.

For the point estimates based on full data set and training data set, errors are defined as $e_{c,t} = \widehat{R}_{c,t} - \widetilde{R}_{c,t}$, where $\widehat{R}_{c,t}$ is the posterior median for country c in year t based on the full data set, and $\widetilde{R}_{c,t}$ is the posterior median for the same country-year based on the training data set. Coverage was computed in a similar manner as for the left-out observations, based on the lower and upper bounds of the 95% uncertainty interval of $\widetilde{R}_{c,t}$ from the training data set.

One-country simulation

The inflation model performance was assessed by one-country simulation. For each of the 33 countries at risk of SRB inflation, we considered data after reference year 1970 as test data and simulated the SRB using the posterior samples of the global parameters from the inflation model (obtained using the full data set).

The g-th simulated SRB $R^{(g)}_{c,t}$ for country c in year t, and the g-th simulated SRB $R^{(g)}_{c[j],t[j]}$ for the j-th left-out data point after 1970 for country $c[j]$ in year $t[j]$ with data source type $s[j]$ were obtained as follows for $g = 1,\ldots,G$:

$$\begin{aligned} R^{(g)}_{c,t}) &= N^{(g)}_{r[c]} \cdot P^{(g)}_{c,t} + \alpha^{(g)}_{c,t}, \\ \log(r^{(g)}_{c[j],t[j]}) &\sim N\left(\log\left(R^{(g)}_{c[j],t[j]}\right), (\sigma_j)^2 + \left(\omega^{(g)}_{s[j]}\right)^2\right), \end{aligned}$$

where samples for $N^{(g)}_r$ and $\omega^{(g)}_s$ were obtained from the model fit in the Step 1 (see Section 3.5.1), and $P^{(g)}_{c[j],t[j]}$ and $\alpha^{(g)}_{c[j],t[j]}$ were simulated to refer to a "new" country, without taking into account any country-specific data, following the model specification for both parameters. I.e., the g-th sample of parameters related to the inflation term $\alpha_{c,t}$ were simulated from their respective hierarchical distributions for $g = 1,\ldots,G$:

$$\begin{aligned} a^{(g)}_c &\sim N(\mu^{(g)}_{ac}, (\sigma^{(g)}_{ac})^2)T(0,), \\ d^{(g)}_{c,m} &\sim N(\mu^{(g)}_{d(m)}, (\sigma^{(g)}_{d(m)})^2)T(0,), \\ t^{(g)}_{c,0} &\sim N(t_{c,\eta}, (\sigma^{(g)}_{\eta})^2)T(t_{c[j],\eta 6}, 2100), \text{ for all countries except India,} \end{aligned}$$

with posterior samples for hierarchical means and variance parameters obtained from the model fit to the full data set. After generating the simulated values, we calculated the same set of results as described in Section 3.5.7 on out-of-sample validation.

3.6 Results

3.6.1 Global and Regional Estimates

The global and regional SRB estimates and 95% uncertainty intervals in 1990 and 2015 are illustrated in Figure 3.3 and Table 3.7. Results are weighted according to the numbers of livebirths in the respective regions. Globally, the SRB in 2015 was 1.06 (95% uncertainty interval, [1.05; 1.07]). Levels and trends varied across regions. In 2015, the regional SRB ranged from 1.03 [1.03; 1.04] in Sub-Saharan Africa to 1.14 [1.07; 1.22] in Eastern Asia. Between 1990 and 2015, none of the regional SRBs had significant reductions, while Caucasus and Central Asia had an increase at 0.01 [0.00; 0.02].

The regional biological norms of SRB range from 1.03 [1.02; 1.03] in Sub-Saharan Africa to 1.07 [1.06; 1.08] in Eastern Asia and Oceania and differ significantly from 1.05 for six out of ten regions (Table 3.7, Figure 3.3). When comparing to the conventional value of 1.05 for the natural SRB adopted by the UN WPP [55], the regional biological norms are significantly above 1.05 for most regions including "ENAN" (the combination of countries in Europe, North America, Australia, and New Zealand), South-eastern Asia, Eastern Asia, and Oceania and significantly below 1.05 for Sub-Saharan Africa and Latin America and the Caribbean. In 2015, the aggregated SRB in three regions (Caucasus and Central Asia, South-eastern Asia, and Eastern Asia) were significantly above their corresponding regional biological norms estimates. In 1990, the aggregated regional-level SRB in Southern Asia, Sub-Saharan Africa, and Eastern Asia were estimated to be significantly above their regional biological norms estimates.

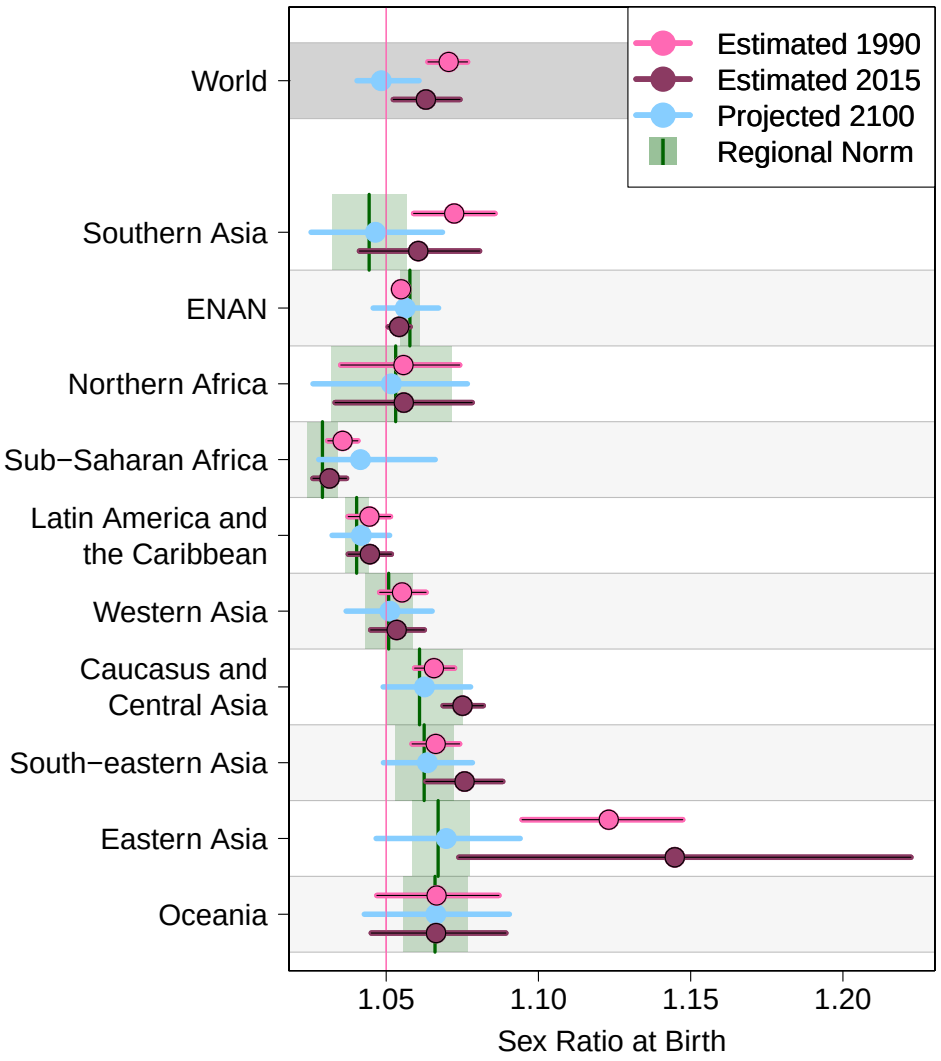

Fig. 3.3 **Global and regional SRB estimates in 1990 and 2015, projections for 2100, and regional biological norms of SRB.** Estimated SRBs in 1990 and 2015 are in light pink and dark pink respectively. Projected SRBs for 2100 are in light blue. Dots indicate estimates, and horizontal lines refer to 95% uncertainty intervals. Regional biological norms are in dark green, where the vertical line segments refer to median estimates and light green shaded areas are 95% uncertainty intervals. Region "ENAN" refers to the combination of countries in Europe, North America, Australia, and New Zealand. The projection results are based on the scenario that all countries at risk of SRB inflation will experience the inflation.

Table 3.7 **Global and regional SRB in 1990, 2015, and 2100.** The estimates are the numbers before the brackets. The numbers inside the brackets are the 95% uncertainty intervals of the estimates. The projection results are based on the scenario that all countries at risk of SRB inflation will experience the inflation. Region "ENAN" refers to the combination of countries in Europe, North America, Australia, and New Zealand.

		SRB			Change of SRB	
	Regional norm	1990	2015	2100	1990–2015	2015–2100
World	–	1.07	1.06	1.05	-0.01	-0.01
		[1.06; 1.08]	[1.05; 1.07]	[1.04; 1.06]	[-0.02; 0.00]	[-0.03; 0.00]
Southern Asia	1.04	1.07	1.06	1.05	-0.01	-0.01
	[1.03; 1.06]	[1.06; 1.09]	[1.04; 1.08]	[1.03; 1.07]	[-0.03; 0.00]	[-0.04; 0.01]
ENAN	1.06	1.05	1.05	1.06	0.00	0.00
	[1.05; 1.06]	[1.05; 1.06]	[1.05; 1.06]	[1.05; 1.07]	[0.00; 0.00]	[-0.01; 0.01]
Northern Africa	1.05	1.06	1.06	1.05	0.00	0.00
	[1.03; 1.07]	[1.04; 1.07]	[1.03; 1.08]	[1.03; 1.08]	[-0.01; 0.01]	[-0.02; 0.02]
Sub-Saharan Africa	1.03	1.04	1.03	1.04	0.00	0.01
	[1.02; 1.03]	[1.03; 1.04]	[1.03; 1.04]	[1.03; 1.07]	[-0.01; 0.00]	[0.00; 0.03]
Latin America and the Caribbean	1.04	1.04	1.04	1.04	0.00	0.00
	[1.04; 1.04]	[1.04; 1.05]	[1.04; 1.05]	[1.03; 1.05]	[-0.01; 0.01]	[-0.01; 0.01]
Western Asia	1.05	1.06	1.05	1.05	0.00	0.00
	[1.04; 1.06]	[1.05; 1.06]	[1.04; 1.06]	[1.04; 1.07]	[-0.01; 0.01]	[-0.02; 0.01]
Caucasus and Central Asia	1.06	1.07	1.08	1.06	0.01	-0.01
	[1.05; 1.08]	[1.06; 1.07]	[1.07; 1.08]	[1.05; 1.08]	[0.00; 0.02]	[-0.02; 0.00]
South-eastern Asia	1.06	1.07	1.08	1.06	0.01	-0.01
	[1.05; 1.07]	[1.06; 1.07]	[1.06; 1.09]	[1.05; 1.08]	[0.00; 0.02]	[-0.03; 0.00]
Eastern Asia	1.07	1.12	1.14	1.07	0.02	-0.07
	[1.06; 1.08]	[1.09; 1.15]	[1.07; 1.22]	[1.05; 1.09]	[-0.05; 0.11]	[-0.15; 0.00]
Oceania	1.07	1.07	1.07	1.07	0.00	0.00
	[1.06; 1.08]	[1.05; 1.09]	[1.05; 1.09]	[1.04; 1.09]	[-0.01; 0.01]	[-0.02; 0.02]

3.6.2 Country-level case studies of SRB estimates and projections

The SRB estimates and projections are illustrated for ten example countries from three groups: 1) countries without risk of SRB inflation in Figure 3.4; 2) countries with past and ongoing SRB inflation in Figure 3.5 and Figure 3.6; and 3) countries at risk of future SRB inflation in Figure 3.7.

Sweden, Guatemala, and Zimbabwe are examples of countries without risk of SRB inflation (Figure 3.4). Sweden typifies countries with high quality annual VR data, here available from 1753 to 2013. SRB model estimates follow the VR data trend and the uncertainty assessment takes into account the stochastic uncertainty associated with the VR data. The estimated SRB for Sweden ranges from 1.04 [1.04; 1.05] in 1774 to 1.06 [1.06; 1.07] in 1953. The SRB has fluctuated around its corresponding regional norm for the region of ENAN at 1.06 since around 1900. The SRB projection for Sweden is approximately constant and given by its regional norm, with the projection for 2100 given by 1.06 [1.03; 1.08]. Guatemala, a lower-middle income country from Latin America and the Caribbean, has data from VR as well as surveys. The data period is from 1948 to 2011. The estimated SRB for Guatemala was the highest in 1959 at 1.05 [1.04; 1.06] and was the lowest in 2010 at 1.03 [1.02; 1.04]. The SRB estimates are mostly informed by the VR data since the VR data have less uncertainty associated with them as compared to survey data. The projection for Guatemala slowly converges from 1.03 [1.02; 1.04] in 2011 towards its regional norm 1.04, and is expected to eventually reach 1.04 [1.01; 1.06] in 2100. Lastly, Zimbabwe, a low-income country in Sub-Saharan Africa, only has survey data that are subject to large sampling errors. Its SRB was estimated slightly above its regional biological norm 1.03 during the early data period from 1972 to 1995, and was estimated to be approximately equal to its regional biological norm after 1995. The SRB for Zimbabwe in 2100 is projected to be 1.03 [1.00; 1.05].

Azerbaijan, India, China, and Republic of Korea are example countries with past and ongoing SRB inflation (Figure 3.5 and Figure 3.6). The TFR estimates

and projections for these four countries are overlaid on to the SRB estimates in the figure, to illustrate the relationship between the start year of the SRB inflation period and the fertility decline, as incorporated into the model to estimate the start year of the inflation period. For example, the start year of the SRB inflation period for Azerbaijan is estimated to be 1990, which corresponds to the year in which the TFR decreased to 3.1. The start year in China is estimated to be 1981 when its TFR decreased to 2.6. India is a country with an outlying high TFR value of 5.2 at the start of its inflation period in 1975. As shown in Table 3.8, the maximum SRB estimates for all these 4 countries during the inflation period have already occurred during their data periods. In Azerbaijan, the SRB has reached its maximum at 1.17 [1.16; 1.19] in 2007. The SRB in China and India peaked at 1.20 [1.16; 1.25] in 2006 and at 1.11 [1.10; 1.13] in 2003 respectively. The maximal SRB in Republic of Korea occurred in 1991 at 1.14 [1.13; 1.15]. Based on the model projections, the SRB will converge or has converged back to the range of natural fluctuations in the 2030s for Azerbaijan, in 2020s for China, in 2016 for India, and in 2008 for the Republic of Korea. The recent SRB convergence for India is largely informed by the sample registration system data between 2007 and 2011.

For the countries at risk of future SRB inflation, estimates and projections that are based on the inclusion and the exclusion of future inflation are illustrated for Egypt, Mali, and Nepal (Figure 3.7). As the data in these countries do not suggest SRB inflation during the observation periods, the projections without future inflation all converge from the estimates at the end of data period to the regional biological norms. When assuming that inflation does occur, the start year of the SRB inflation in Egypt is projected to be in the 2030s, in Mali in the 2060s, and in Nepal in the 2010s (see Table 3.8), corresponding to the year when TFR projections in these countries decrease to around 2.8.

The SRB estimates and uncertainty intervals for all 14 countries with past or ongoing SRB inflation are shown in Table 3.8 and Figure 3.8. Eleven countries are from Asian regions (Caucasus and Central Asia, Eastern Asia, South-eastern Asia,

and Southern Asia). The start years of SRB inflation range from 1972 in Singapore to 2007 in Georgia. The SRB inflation started before 2000 for all countries expect Hong Kong (China SAR) and Georgia. Since the start of the inflation, the SRB reached its maximum before 2015 for all countries except for Vietnam and Iran where the SRB maxima are projected to occur in 2016 and 2017 respectively. The SRB inflation reached its maximum in the first decade of this century in 9 countries. The earliest maxima occurred in Singapore and Republic of Korea in 1982 and 1991 respectively. The in-country maximum SRBs since the start of inflation range from 1.06 [1.03; 1.08] for Iran in 2017 to 1.27 [1.24; 1.30] for Georgia in 2008. In 2015, the SRB in all these countries except Vietnam and Iran, were in the midst of converging back to their regional biological norms. The SRBs in 2015 among the 14 countries range from 1.06 [1.03; 1.08] in Iran to 1.16 [1.08; 1.25] in China.

The SRB estimates and uncertainty intervals for all 14 countries with past or ongoing SRB inflation are shown in Figure 3.8. Eleven countries are from Asian regions (Caucasus and Central Asia, Eastern Asia, South-eastern Asia, and Southern Asia). The start years of SRB inflation range from 1972 in Singapore to 2007 in Georgia. The SRB inflation started before 2000 for all countries expect Hong Kong (China SAR) and Georgia. Since the start of the inflation, the SRB reached its maximum before 2015 for all countries except for Vietnam and Iran where the SRB maxima are projected to occur in 2016 and 2017 respectively. The SRB inflation reached maximum in the first decade of this century in 9 countries. The earliest maxima occurred in Singapore and Republic of Korea in 1982 and 1991 respectively. The in-country maximum SRBs since the start of inflation range from 1.06 [1.03; 1.08] for Iran in 2017 to 1.27 [1.24; 1.30] for Georgia in 2008. In 2015, the SRB in all these countries except Vietnam and Iran, were in the midst of converging back to their regional biological norms. The SRBs in 2015 among the 14 countries range from 1.06 [1.03; 1.08] in Iran to 1.16 [1.08; 1.25] in China.

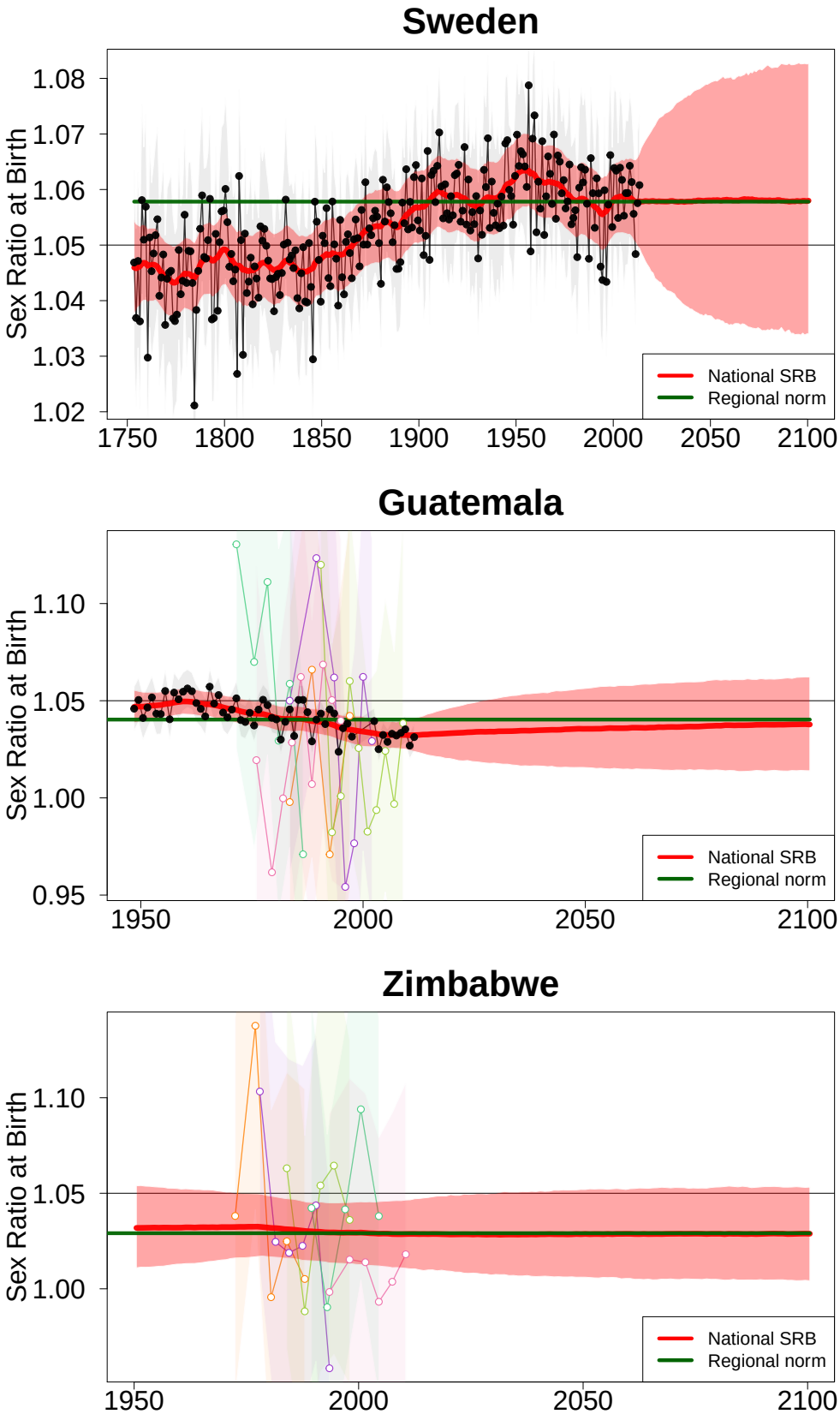

Fig. 3.4 **SRB estimates and projections over time for example countries without inflation risk.** The green horizontal lines are the estimates for the regional biological norm of SRB. The red lines and shaded areas are the country-specific SRB estimates and their 95% uncertainty intervals. The shaded areas surrounding observations represent the sampling or stochastic errors associated with the observations.

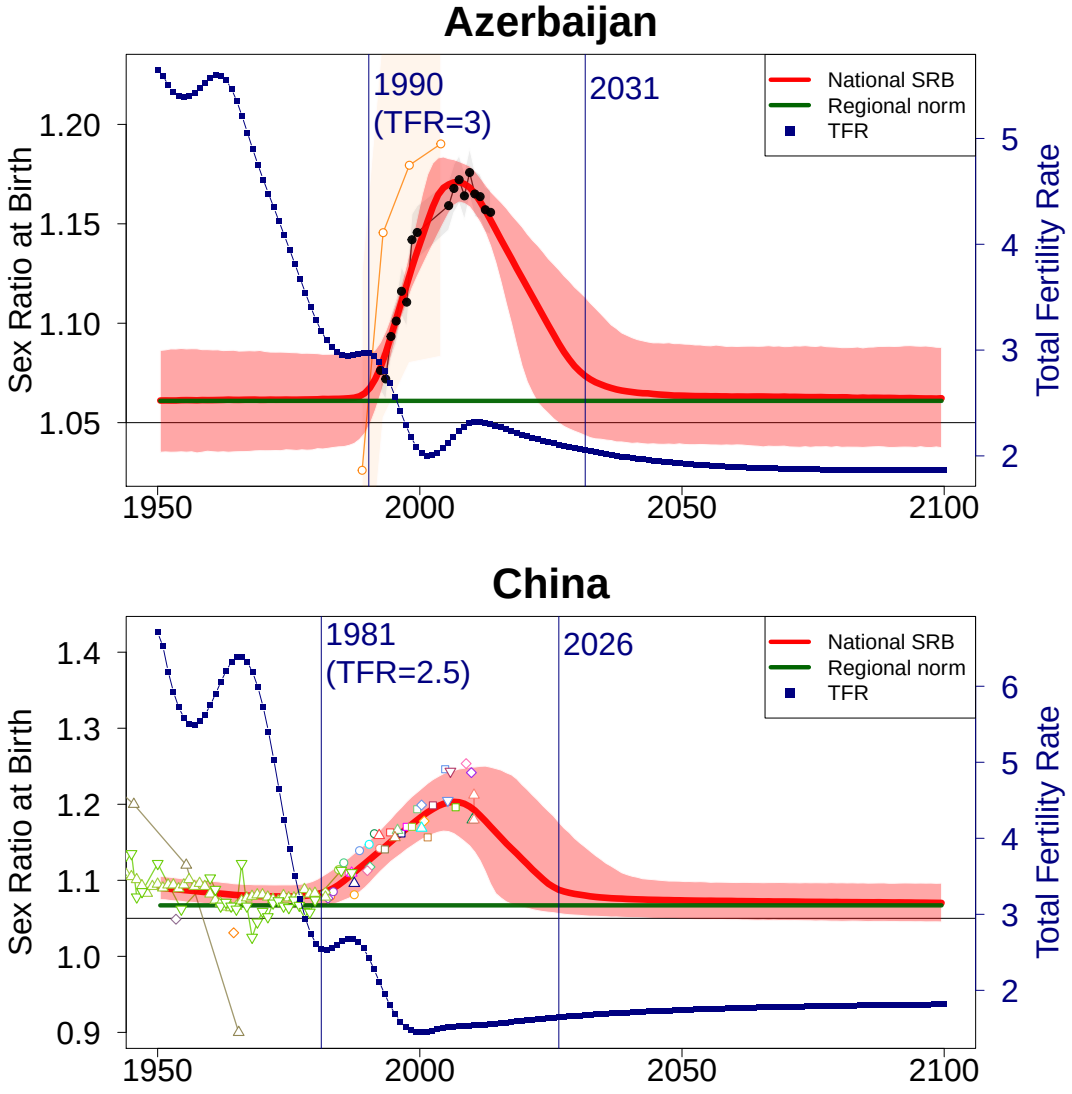

Fig. 3.5 **SRB estimates and projections over time for example countries with past/ongoing inflation (Azerbaijan and China).** The green horizontal lines are the estimates for the regional biological norm of SRB. The red lines and shaded areas are the country-specific SRB estimates and their 95% uncertainty intervals. The blue square dots are UN WPP 2017 total fertility rate estimates and median projections. The two blue vertical lines indicate the median estimates for start and end years of SRB inflation period. The TFR values in the start years of SRB inflation periods are shown. Observations from different data series are differentiated by colors. The shaded areas surrounding observations represent the sampling or stochastic errors associated with the observations.

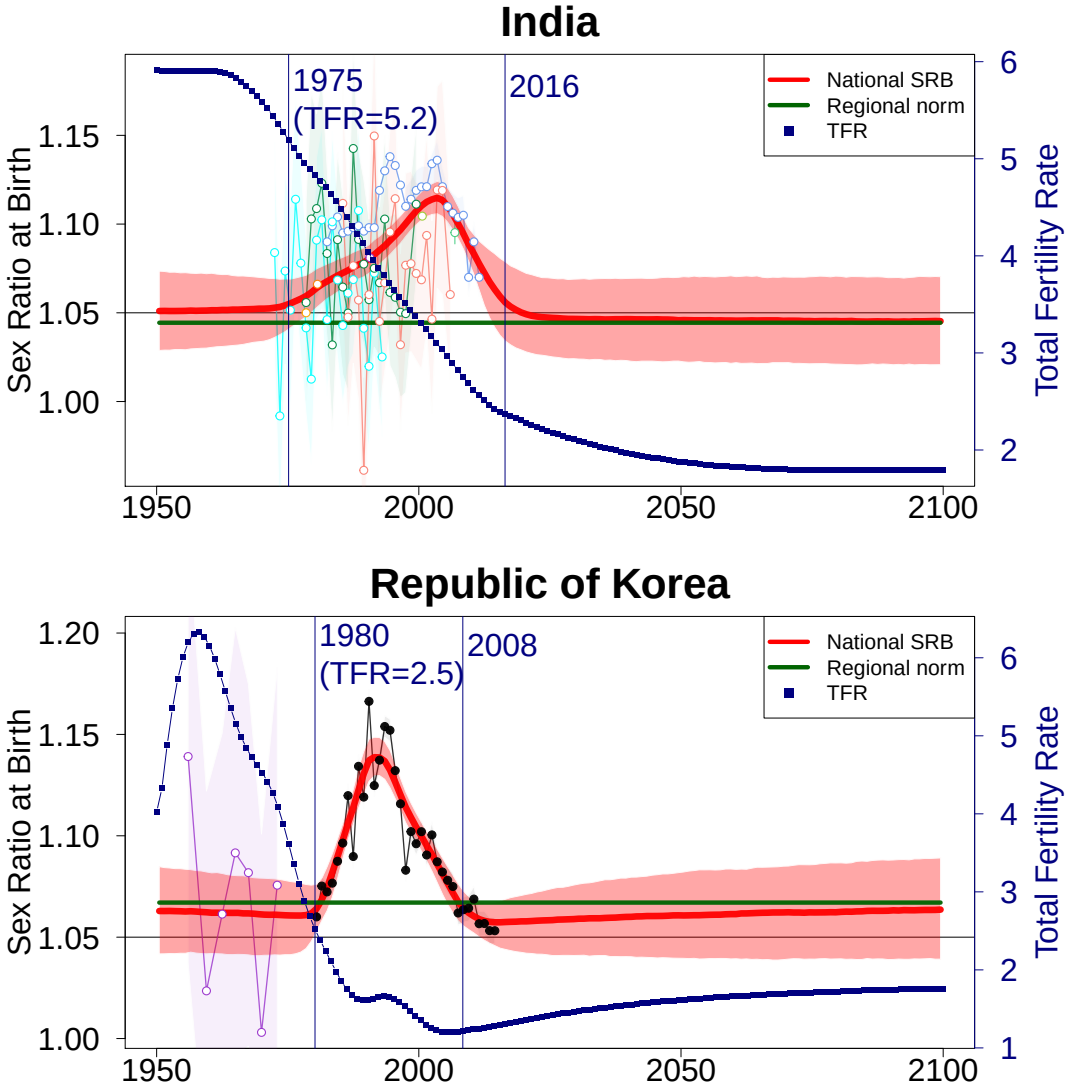

Fig. 3.6 **SRB estimates and projections over time for example countries with past/ongoing inflation (India and Republic of Korea).** The green horizontal lines are the estimates for the regional biological norm of SRB. The red lines and shaded areas are the country-specific SRB estimates and their 95% uncertainty intervals. The blue square dots are UN WPP 2017 total fertility rate estimates and median projections. The two blue vertical lines indicate the median estimates for start and end years of SRB inflation period. The TFR values in the start years of SRB inflation periods are shown. Observations from different data series are differentiated by colors. The shaded areas surrounding observations represent the sampling or stochastic errors associated with the observations.

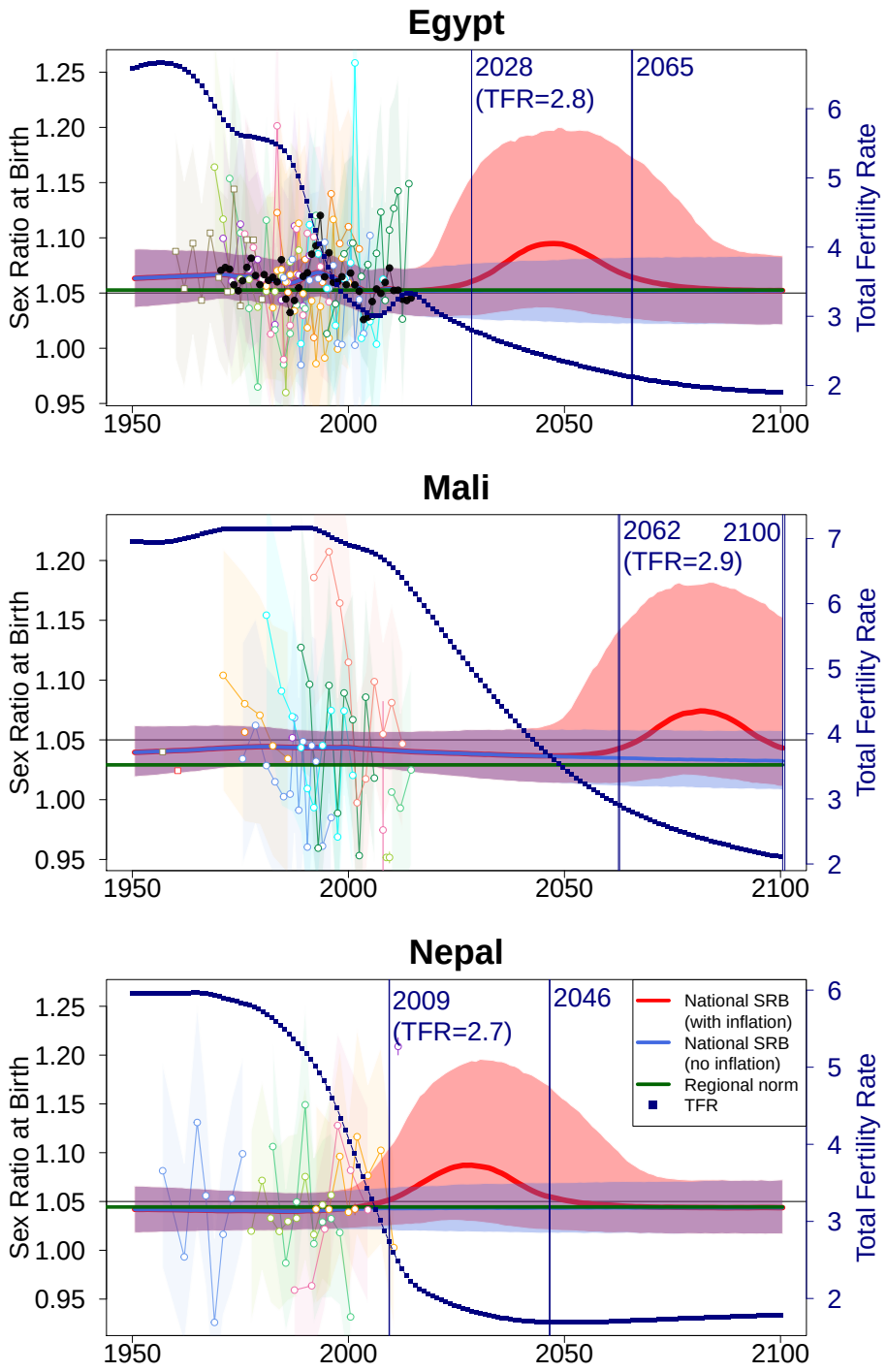

Fig. 3.7 **SRB estimates and projections over time for example countries at risk of future inflation.** The green horizontal lines are the estimates for the regional biological norm of SRB. The red lines and shaded areas are the country-specific SRB estimates and their 95% uncertainty intervals for scenario 1: with SRB inflation in projection period. The blue lines and shaded areas are the country-specific SRB estimates and their 95% uncertainty intervals for scenario 2: no SRB inflation in projection period. The blue square dots are UN WPP 2017 total fertility rate estimates and median projections. The two blue vertical lines indicate the median estimates for start and end years of SRB inflation period. The TFR values in the start years of SRB inflation periods are shown. Observations from different data series are differentiated by colors. The shaded areas surrounding observations represent the sampling or stochastic errors associated with the observations.

Table 3.8 **Results for countries at risk of SRB inflation.** *: countries at risk of future SRB inflation. Countries are in the alphabetic order. The estimates are the numbers before the brackets. The numbers inside the brackets are the 95% uncertainty intervals of the estimates. CMFB refers to cumulative number of missing female births. "Max SRB" refers to the maximum SRB after inflation starts. "Max year" refers to the year in which the maximum SRB is after inflation starts. The projection results are based on the scenario that all countries at risk of SRB inflation will experience the inflation.

Country	SRB			Year		CMFB (in millions)			
	start year	max	2015	start inflation	max	1970–2015	2016–2060	2061–2100	1970–2100
Afghanistan*	1.06	1.09	1.05	2033	2051	0.0	0.3	0.1	0.4
	[1.03; 1.16]	[1.03; 1.20]	[1.03; 1.08]	[2015; 2052]		[0.0; 0.0]	[0.0; 0.8]	[0.0; 0.5]	[0.0; 1.0]
Albania	1.08	1.13	1.08	1995	2006	0.0	0.0	0.0	0.0
	[1.07; 1.10]	[1.12; 1.14]	[1.06; 1.10]	[1988; 2000]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
Algeria*	1.05	1.07	1.05	2012	2033	0.0	0.1	0.0	0.1
	[1.03; 1.07]	[1.02; 1.18]	[1.02; 1.07]	[1987; 2025]		[0.0; 0.1]	[0.0; 0.6]	[0.0; 0.1]	[0.0; 0.6]
Armenia	1.06	1.18	1.12	1992	2000	0.0	0.0	0.0	0.0
	[1.05; 1.08]	[1.16; 1.20]	[1.09; 1.14]	[1991; 1993]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
Azerbaijan	1.07	1.17	1.14	1990	2007	0.1	0.0	0.0	0.1
	[1.05; 1.09]	[1.16; 1.19]	[1.12; 1.17]	[1985; 1993]		[0.0; 0.1]	[0.0; 0.0]	[0.0; 0.0]	[0.1; 0.1]
Bangladesh*	1.04	1.08	1.04	2013	2031	0.0	0.8	0.0	0.9
	[1.02; 1.06]	[1.03; 1.19]	[1.02; 1.12]	[2002; 2026]		[0.0; 0.2]	[0.0; 2.3]	[0.0; 0.2]	[0.1; 2.4]
Chad*	1.04	1.07	1.04	2065	2084	0.0	0.0	0.3	0.3
	[1.01; 1.15]	[1.02; 1.18]	[1.02; 1.06]	[2046; 2084]		[0.0; 0.0]	[0.0; 0.1]	[0.0; 0.8]	[0.0; 0.8]
China	1.08	1.20	1.16	1981	2006	11.0	1.7	0.0	12.7
	[1.06; 1.11]	[1.16; 1.25]	[1.08; 1.25]	[1974; 1989]		[7.0; 15.4]	[0.0; 6.9]	[0.0; 0.0]	[7.6; 20.1]
Egypt*	1.06	1.09	1.05	2029	2047	0.0	0.7	0.2	0.9
	[1.03; 1.16]	[1.04; 1.20]	[1.03; 1.07]	[2014; 2047]		[0.0; 0.0]	[0.1; 2.0]	[0.0; 1.2]	[0.1; 2.5]

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Country	SRB			Year		CMFB (in millions)			
	start year	max	2015	start inflation	max	1970–2015	2016–2060	2061–2100	1970–2100
Georgia	1.10	1.27	1.09	2007	2008	0.0	0.0	0.0	0.0
	[1.08; 1.13]	[1.24; 1.30]	[1.07; 1.11]	[2007; 2008]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
Guinea*	1.04	1.08	1.04	2056	2074	0.0	0.0	0.2	0.2
	[1.02; 1.14]	[1.02; 1.18]	[1.02; 1.06]	[2038; 2075]		[0.0; 0.0]	[0.0; 0.2]	[0.0; 0.6]	[0.0; 0.6]
China, Hong Kong SAR	1.08	1.15	1.08	2003	2011	0.0	0.0	0.0	0.0
	[1.07; 1.10]	[1.14; 1.17]	[1.06; 1.09]	[2001; 2005]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
India	1.06	1.11	1.06	1975	2003	9.2	0.2	0.0	9.3
	[1.04; 1.07]	[1.10; 1.13]	[1.03; 1.08]	[1970; 1980]		[5.5; 13.5]	[0.0; 1.4]	[0.0; 0.0]	[5.6; 14.1]
Iran	1.02	1.06	1.06	1992	2017	0.1	0.1	0.0	0.2
	[1.01; 1.04]	[1.03; 1.08]	[1.03; 1.08]	[1986; 2014]		[0.0; 0.3]	[0.0; 0.5]	[0.0; 0.0]	[0.1; 0.6]
Jordan*	1.06	1.09	1.05	2027	2046	0.0	0.1	0.0	0.1
	[1.03; 1.15]	[1.04; 1.20]	[1.04; 1.06]	[2011; 2046]		[0.0; 0.0]	[0.0; 0.2]	[0.0; 0.1]	[0.0; 0.2]
Republic of Korea	1.06	1.14	1.06	1980	1991	0.2	0.0	0.0	0.2
	[1.05; 1.08]	[1.13; 1.15]	[1.04; 1.07]	[1976; 1983]		[0.1; 0.3]	[0.0; 0.0]	[0.0; 0.0]	[0.1; 0.3]
Mali*	1.04	1.07	1.04	2063	2081	0.0	0.0	0.4	0.4
	[1.01; 1.14]	[1.02; 1.18]	[1.02; 1.06]	[2044; 2082]		[0.0; 0.0]	[0.0; 0.2]	[0.0; 1.0]	[0.0; 1.1]
Mauritania*	1.04	1.07	1.04	2064	2081	0.0	0.0	0.1	0.1
	[1.02; 1.15]	[1.02; 1.18]	[1.02; 1.06]	[2045; 2083]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.2]	[0.0; 0.2]
Montenegro	1.05	1.10	1.08	1979	2002	0.0	0.0	0.0	0.0
	[1.04; 1.07]	[1.08; 1.12]	[1.05; 1.11]	[1971; 1988]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
Morocco*	1.05	1.09	1.07	2007	2027	0.0	0.2	0.0	0.2
	[1.02; 1.08]	[1.03; 1.20]	[1.03; 1.16]	[1994; 2022]		[0.0; 0.1]	[0.0; 0.5]	[0.0; 0.0]	[0.0; 0.6]

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Table 3.8 – continued from previous page

Country	SRB			Year		CMFB (in millions)			
	start year	max	2015	start inflation	max	1970–2015	2016–2060	2061–2100	1970–2100
Nepal*	1.05	1.09	1.06	2009	2028	0.0	0.2	0.0	0.2
	[1.03; 1.11]	[1.03; 1.19]	[1.03; 1.15]	[1994; 2028]		[0.0; 0.1]	[0.0; 0.4]	[0.0; 0.0]	[0.0; 0.5]
Niger*	1.04	1.08	1.04	2084	2100	0.0	0.0	0.4	0.4
	[1.01; 1.14]	[1.02; 1.18]	[1.03; 1.06]	[2066; 2098]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 1.9]	[0.0; 1.9]
Nigeria*	1.04	1.07	1.04	2067	2084	0.0	0.0	3.6	3.6
	[1.01; 1.14]	[1.02; 1.18]	[1.02; 1.05]	[2048; 2086]		[0.0; 0.0]	[0.0; 1.3]	[0.3; 9.7]	[0.3; 9.8]
Pakistan*	1.08	1.11	1.08	2029	2046	0.0	1.4	0.4	1.8
	[1.05; 1.18]	[1.05; 1.21]	[1.06; 1.10]	[2013; 2048]		[0.0; 0.0]	[0.1; 4.0]	[0.0; 2.4]	[0.2; 4.8]
Senegal*	1.04	1.07	1.04	2064	2082	0.0	0.0	0.3	0.3
	[1.01; 1.14]	[1.02; 1.18]	[1.02; 1.05]	[2045; 2083]		[0.0; 0.0]	[0.0; 0.1]	[0.0; 0.8]	[0.0; 0.8]
Singapore	1.07	1.08	1.07	1972	1982	0.0	0.0	0.0	0.0
	[1.05; 1.08]	[1.07; 1.09]	[1.05; 1.08]	[1970; 1988]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
China, Taiwan Province	1.07	1.10	1.08	1980	2004	0.0	0.0	0.0	0.0
	[1.06; 1.08]	[1.08; 1.11]	[1.06; 1.11]	[1971; 1988]		[0.0; 0.1]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.1]
Tanzania*	1.03	1.07	1.02	2071	2090	0.0	0.0	1.3	1.3
	[1.00; 1.14]	[1.01; 1.17]	[1.00; 1.04]	[2052; 2090]		[0.0; 0.0]	[0.0; 0.2]	[0.1; 3.6]	[0.1; 3.6]
Tonga*	1.08	1.11	1.08	2044	2062	0.0	0.0	0.0	0.0
	[1.05; 1.18]	[1.06; 1.22]	[1.06; 1.10]	[2025; 2063]		[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]	[0.0; 0.0]
Tunisia	1.06	1.08	1.08	1986	2008	0.0	0.0	0.0	0.0
	[1.04; 1.08]	[1.06; 1.10]	[1.05; 1.11]	[1977; 2013]		[0.0; 0.0]	[0.0; 0.1]	[0.0; 0.0]	[0.0; 0.1]
Turkey*	1.06	1.06	1.06	2003	2027	0.0	0.1	0.0	0.1
	[1.05; 1.07]	[1.04; 1.17]	[1.04; 1.08]	[1975; 2021]		[0.0; 0.2]	[0.0; 0.8]	[0.0; 0.0]	[0.0; 0.9]

Continued on next page

Table 3.8 – continued from previous page

Country	SRB			Year		CMFB (in millions)			
	start year	max	2015	start inflation	max	1970–2015	2016–2060	2061–2100	1970–2100
Uganda*	1.03	1.06	1.01	2062	2081	0.0	0.0	1.0	1.0
	[1.00; 1.13]	[1.01; 1.17]	[1.00; 1.03]	[2043; 2081]		[0.0; 0.0]	[0.0; 0.6]	[0.1; 2.7]	[0.1; 2.8]
Vietnam	1.07	1.15	1.15	1999	2016	0.3	0.3	0.0	0.6
	[1.05; 1.10]	[1.07; 1.22]	[1.08; 1.22]	[1986; 2004]		[0.1; 0.5]	[0.0; 1.1]	[0.0; 0.0]	[0.2; 1.4]

3.6.3 Estimates and projections of past and future missing female births

From 1970 to 2015, the world had 21.2 [15.4; 26.9] million cumulative missing female births (CMFB) (Table 3.9). As shown in Figure 3.9, the majority of CMFB between 1970 and 2015 were concentrated in Southern Asia with 9.3 [5.7; 13.7] million CMFB and in Eastern Asia with 11.2 [7.2; 15.7] million CMFB. The CMFB between 1970 and 2015 in Southern Asia and Eastern Asia made up 44.3% [31.0; 58.4] and 53.3% [39.2; 66.7] respectively of the global CMFB. The estimates of CMFB during 1970–2015 in the two regions are largely driven by the numbers in India with 9.2 [5.5; 13.5] million and in China with 11.0 [7.0; 15.4] million CMFB (Table 3.8). As shown in Figure 3.11, the annual number of missing female births (AMFB) started to increase since 1970 in Southern Asia and since 1980 in Eastern Asia, peaking between 2000 and 2020.

Based on the scenario that none of the countries at risk of future SRB inflation will experience SRB inflation, the AMFB is projected to be close to zero from 2040s onwards, with the global CMFB from 1970 to 2040 given by 23.6 [16.5; 32.0] million (see Figure 3.12).

Under the scenario that the countries at risk of future SRB inflation will experience inflation, we projected that during 2016–2060, Southern Asia and Eastern Asia are expected to continue to experience a further deficit of 3.2 [2.4; 4.5] and 1.8 [0.6; 4.7] million CMFB, corresponding to 45.4% [19.5; 73.6] and 22.7% [0.0; 59.2] of the global CMFB of that period (Table 3.9). Particularly, the majority of CMFB between 2016 and 2060 in Southern Asia are expected to occur in Pakistan with 1.4 [0.1; 4.0] million CMFB since the year 2029 [2013; 2048] when SRB inflation is projected to start in Pakistan, while most of the CMFB in Eastern Asia are projected to be from China with 1.7 [0.0; 6.9] million (Table 3.8).

After 2060, again under the scenario that inflation will happen in countries at risk of future SRB inflation, the deficit in Southern Asia and Eastern Asia will be close to zero while Sub-Saharan Africa may experience 8.0 [3.8; 14.0] million

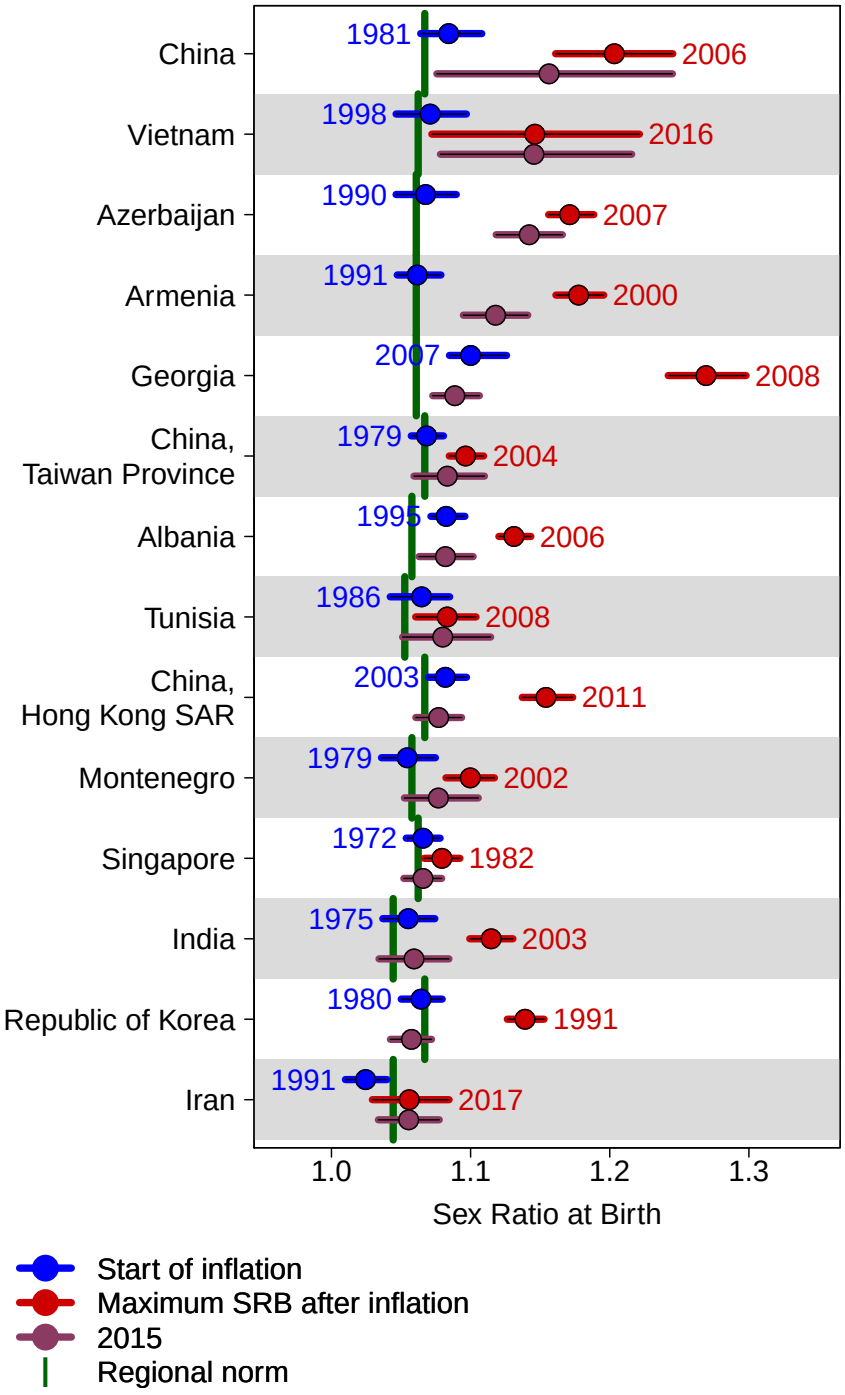

Fig. 3.8 **Countries with past and present SRB inflation.** Countries are ordered by decreasing SRB estimates for the year 2015. Dots are median estimates, and horizontal lines are 95% uncertainty intervals. Blue dots and line segments are the estimates and 95% uncertainty intervals for the SRB in the year when the inflation period started. The red dots and line segments are the estimates and 95% uncertainty intervals for the SRB in the year when it reached the maximum level after inflation started. For each country, its corresponding regional biological norm is plotted in green (estimate).

CMFB during 2061–2100 (Table 3.9). The SRB for the nine countries at risk of SRB inflation in Sub-Saharan Africa are projected to start to inflate due to potential sex-selective abortion from around the 2060s onward in response to the projected fall in the TFR (Table 3.8). The regional aggregated start year of SRB inflation in Sub-Saharan Africa is 2069 [2059; 2078], i.e. much later than when inflation starts in other regions (Table 3.9). As a result, almost all of the CMFB in Sub-Saharan Africa from 1970 to 2100 are projected to occur after 2060. The AMFB is projected to peak between 2080 and 2100 in Sub-Saharan Africa (see Figure 3.11), reaching 0.2 [0.0; 0.5] million in 2100. This implies that the CMFB in Sub-Saharan Africa could keep growing into the 22nd century. In the projections illustrated in Figure 3.10, Sub-Saharan Africa would become a third locus of missing girls by 2100. On the other hand, the CMFB in Southern Asia and Eastern Asia during 2061–2100 are merely 0.5 [0.3; 0.8] and 0.0 [0.0; 0.0] million, or 3.0% [0.0; 25.3] and 0.0% [0.0; 0.0] of the global CMFB respectively.

During the entire period of exposure to the risk of sex-selective abortion from 1970 to 2100, the global CMFB is projected to be 37.2 [27.0; 50.7] million, of which Southern Asia, Eastern Asia, and Sub-Saharan Africa would contribute 13.1 [8.4; 19.0] million, 13.0 [8.0; 20.0] million, and 8.1 [3.8; 15.7] million respectively, corresponding to 35.2% [24.2; 47.5], 35.1% [23.5; 48.3], and 22.1% [11.4; 35.7] of the global total.

Table 3.9 **Global and regional cumulative number of missing female births (CMFB) for periods 1970–2015, 2016–2100, and 1970–2100.** The estimates are the numbers before the brackets. The numbers inside the brackets are the 95% uncertainty intervals of the estimates. The projection results are based on the scenario that all countries that may have SRB inflation will experience the inflation. The regional start year of SRB inflation is the average of the start years within the same region weighted by the number of births in the corresponding country-year. Proportions may not sum up to 100% due to rounding. Region "ENAN" refers to the combination of countries in Europe, North America, Australia, and New Zealand.

	Start year	CMFB (in millions)				Proportion of the global CMFB (%)			
		1970–2015	2016–2060	2061–2100	1970–2100	1970–2015	2016–2060	2061–2100	1970–2100
World	–	21.2 [15.4; 26.9]	7.3 [5.1; 11.1]	8.8 [6.5; 12.7]	37.2 [27.0; 50.7]	100	100	100	100
Southern Asia	1990 [1986; 1994]	9.3 [5.7; 13.7]	3.2 [2.4; 4.5]	0.5 [0.3; 0.8]	13.1 [8.4; 19.0]	44.3 [31.0; 58.4]	45.4 [19.5; 73.6]	3.0 [0.0; 25.3]	35.2 [24.2; 47.5]
ENAN	1993 [1987; 1996]	0.9 [0.0; 0.0]	0 [0; 0]	0 [0; 0]	0.9 [0.0; 0.0]	0.0 [0.0; 0.1]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]
Northern Africa	2019 [2009; 2032]	0.1 [0.0; 0.2]	1.1 [0.3; 2.4]	0.2 [0.1; 0.5]	1.4 [0.4; 3.0]	0.2 [0.0; 0.8]	15.6 [4.0; 35.8]	0.5 [0.0; 14.2]	3.7 [1.1; 7.8]
Sub-Saharan Africa	2069 [2059; 2078]	0 [0; 0]	0.1 [0; 1.6]	8.0 [3.8; 14.0]	8.1 [3.8; 15.7]	0.0 [0.0; 0.0]	1.9 [0.0; 20.7]	94.2 [70.1; 100.0]	22.1 [11.4; 35.7]
Latin America and the Caribbean	–	0 [0; 0]	0 [0; 0]	0 [0; 0]	0 [0; 0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]
Western Asia	2007 [1982; 2023]	0.0 [0; 0.2]	0.2 [0.0; 0.7]	0.0 [0.0; 0.0]	0.2 [0.1; 1.0]	0.1 [0.0; 0.8]	2.3 [0.2; 13.0]	0.0 [0.0; 1.3]	0.6 [0.1; 2.5]
Caucasus and Central Asia	1993 [1991; 1996]	0.1 [0.0; 0.1]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.1 [0.1; 0.2]	0.4 [0.3; 0.6]	0.3 [0.1; 0.9]	0.0 [0.0; 0.0]	0.3 [0.2; 0.5]
South-eastern Asia	1998 [1986; 2003]	0.3 [0.1; 0.5]	0.3 [0.0; 1.0]	0.0 [0.0; 0.0]	0.6 [0.2; 1.5]	1.4 [0.7; 2.5]	4.4 [0.1; 16.2]	0.0 [0.0; 0.0]	1.7 [0.6; 3.8]
Eastern Asia	1981 [1974; 1988]	11.2 [7.2; 15.7]	1.8 [0.6; 47]	0.0 [0.0; 0.0]	13.0 [8.0; 20.0]	53.3 [39.2; 66.7]	22.7 [0.0; 59.2]	0.0 [0.0; 0.0]	35.1 [23.5; 48.3]
Oceania	2044 [2025; 2063]	0 [0; 0]	0 [0; 0]	0 [0; 0]	0 [0; 0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]

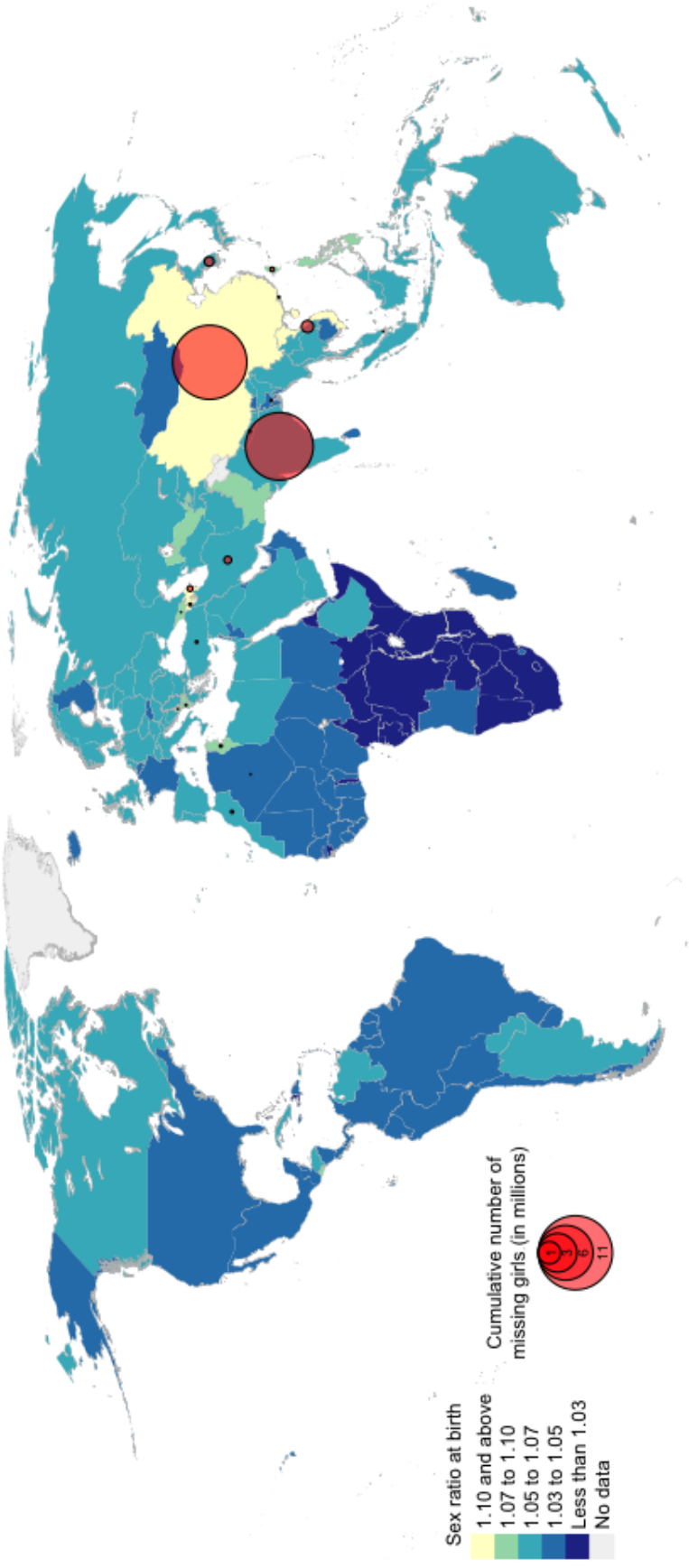

Fig. 3.9 **SRB and the cumulative number of missing female births (CMFB) for all countries in 2015.** The CMFB are from 1970 to 2015. Countries are colored by the levels of the estimates of SRB. The radii of the circles are proportional to the CMFB for countries.

Fig. 3.10 **Projected SRB and the cumulative number of missing female births (CMFB) for all countries in 2100.** The CMFB are from 1970 to 2100. Countries are colored by the levels of the estimates of SRB. The radii of the circles are proportional to the CMFB for countries. The projection results are based on the scenario that all countries at risk of SRB inflation will experience the inflation.

3.6.4 Validation and simulation results

To test the performance of the "normal" model as described in Section 3.5.2 for country-years without SRB inflation, we left out observations obtained from the year 2004 onward. There are 1,620 left-out observations, consisting 19.7% of the total observations. To test the performance of the inflation model as described in Section 3.5.3 for country-years with potential SRB inflation, we left out observations obtained from the year 2008 onward. There are 372 left-out observations, consisting 19.8% of the total observations.

Table 3.10 summarizes the results related to the left-out observations for the validation exercise. Median errors were very close to zero for left-out observations. For the normal model, coverage of 95% and 80% prediction intervals was reasonable at 95.3% and 83.7%, respectively. For the inflation model, the coverage of 95% prediction intervals was at 91.3% and 80.2%, respectively.

Table 3.11 shows the results for the comparison between estimates obtained based on the full data set, and estimates based on the training set. Median errors and the median absolute errors were close to zero. The proportions of updated estimates that fell below the uncertainty intervals constructed based on the training set are all within the expected range, indicating a reasonable good calibration of the model.

	Normal Model	**Inflation model**	
	validation	**validation**	**simulation**
# country in the training data set	173	33	–
# country in the test data set	143	30	1
Median error	-0.00	-0.00	-0.00
Median absolute error	0.01	0.02	0.03
Below 95% PI (%)	1.9	3.8	3.3
Above 95% PI (%)	2.8	4.9	3.4
Expected (%)	**2.5**	**2.5**	**2.5**
Below 80% PI (%)	6.2	9.1	9.3
Above 80% PI (%)	8.1	10.7	9.0
Expected (%)	**10**	**10**	**10**

Table 3.10 **Validation and simulation results for left-out observations.** Errors are defined as the difference between a left-out observation and the posterior median of its predictive distribution. PI=prediction interval.

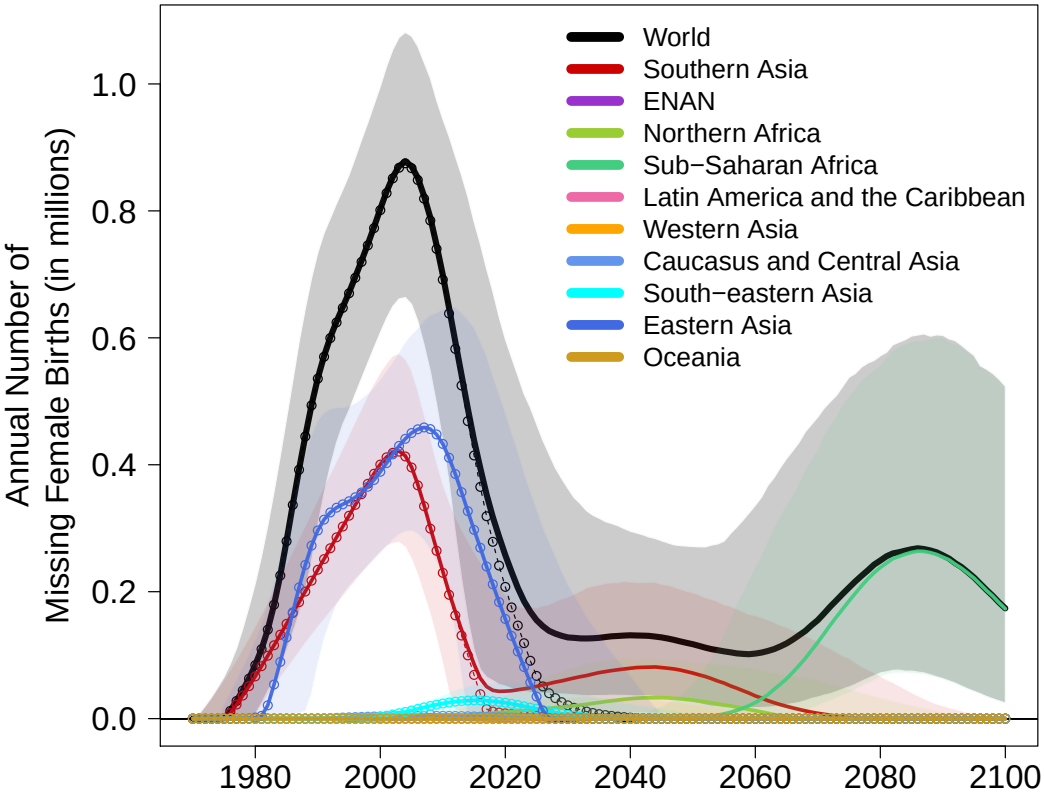

Fig. 3.11 **Global and regional annual number of missing female births (AMFB) from 1970 to 2100.** The solid lines are estimates and shaded areas represent 95% uncertainty intervals. Region "ENAN" refers to the combination of countries in Europe, North America, Australia, and New Zealand. The projections based on the scenario that all the countries at risk of future SRB inflation will experience the inflation are shown in solid curve (estimates) and shaded areas (95% uncertainty intervals). The projections based on the scenario that none of the countries at risk of future SRB inflation will experience the inflation are shown in dashed curves with hollow dots (estimates).

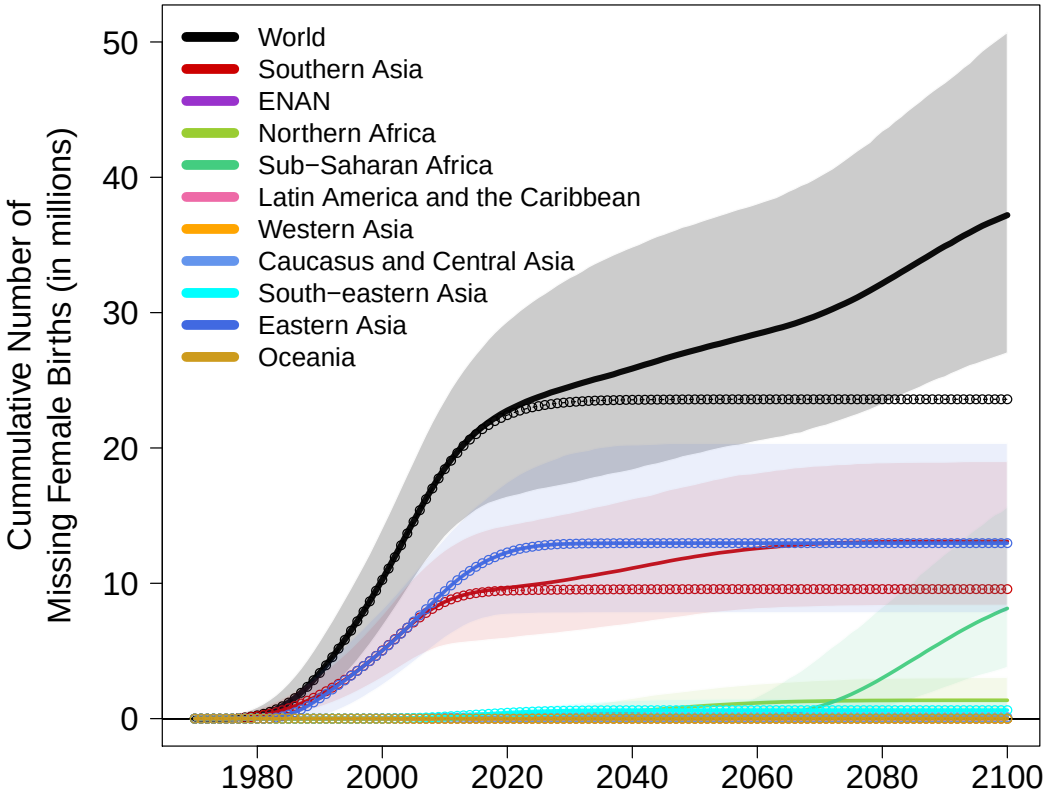

Fig. 3.12 **Global and regional cumulative number of missing female births (CMFB) from 1970 to 2100.** The solid lines are estimates and shaded areas represent 95% uncertainty intervals. Region "ENAN" refers to the combination of countries in Europe, North America, Australia, and New Zealand. The projections based on the scenario that all the countries at risk of future SRB inflation will experience the inflation are shown in solid curve (estimates) and shaded areas (95% uncertainty intervals). The projections based on the scenario that none of the countries at risk of future SRB inflation will experience the inflation are shown in dashed curves with hollow dots (estimates).

model name	**Normal Model**		**Inflation Model**	
Year	**1995**	**2000**	**1995**	**2000**
Median error	0.00	0.00	0.00	0.00
Median absolute error	0.00	0.00	0.00	0.00
Below 95% UI (%)	0.0	0.0	0.0	0.0
Above 95% UI (%)	0.0	0.0	0.0	0.0
Expected proportions (%)	**≤2.5**	**≤2.5**	**≤2.5**	**≤2.5**
Below 80% UI (%)	0.0	0.5	0.0	6.1
Above 80% UI (%)	0.5	0.5	3.0	3.0
Expected proportions (%)	**≤10**	**≤10**	**≤10**	**≤10**

Table 3.11 **Summary of differences in SRB estimates in observation years 1995 and 2000 based on training set and full data set.** Errors are defined as the differences between estimates based on the full dataset and the training set. The proportions refer to the proportions (%) of countries in which the median SRB estimates based on the full data set fall below or above their respective 95% and 80% uncertainty intervals based on the training set. UI=uncertainty interval.

3.7 Discussion

Our study is the first systematic analysis of the SRB for all countries that produces annual estimates and scenario-based projections from 1950 to 2100. We have compiled an extensive SRB database to include all available data from national vital registration systems, international surveys on full birth history, censuses, and national-level surveys and reports. These were synthesized using a Bayesian hierarchical model for estimation and projection, which allows sharing of information between data-rich country-years and neighboring country-years with limited information or without data. The model produces probabilistic projections based on certain scenarios and model assumptions. We found that past and ongoing SRB inflation occurred mostly in Southern Asia and Eastern Asia, resulting in 9.3 [5.7; 13.7] million and 11.2 [7.2; 15.7] million missing female births during 1970–2015. The deficit of missing female birth in the two regions are projected to continue to grow during 2016–2060 with an additional number of missing female births of 3.2 [2.4; 4.5] million in Southern Asia and 1.8 [0.6; 4.7] million in Eastern Asia. If Sub-Saharan Africa follows the same relationship between declining family sizes and inflated

SRBs, SRB inflation in that region would most likely start near the end of this century leading to 8.0 [3.8; 14.0] million extra missing female births during 2061–2100, and will continue to be off balance after 2100.

The natural level of SRB is related to individual-level factors including maternal or paternal age at conception, birth order, sex of the preceding child, maternal weight, family size, environment condition for mother during pregnancy i.e. the Trivers-Willard hypothesis, as well as race [21–32, 98–106]. While most of the information is not available for the aggregate level data we collated, we aimed to estimate the differences in SRB due to race, which we approximated by grouping countries from similar regions or with similar race due to European colonization. Given that the regional grouping is only an approximation of the race, the geographic location of a country may not always matches to the majority race of its neighbouring countries. For instance, the majority of Singapore population are Chinese although the country is located in South-eastern Asia. Given that the regional biological norms for South-eastern Asia and Eastern Asia are around the same level (1.06 [1.05; 1.07] and 1.07 [1.06; 1.08] respectively), the country-level result for Singapore is hardly affected in this case. Further refinements of the grouping are possible, e.g. to divide Sub-Saharan Africa into smaller regions since there is additional heterogeneity in the biological SRB levels within the region [22, 23, 28], or to divide Latin America and Caribbean into two sub-regions because of the majority of African ancestry in the Caribbean countries. However, in the absence of unanimously agreed regional groupings, we opted for larger aggregations in this study.

We highlighted that it is necessary to acknowledge the biological difference in SRB across regions. The estimated regional biological norms differ significantly from 1.05 for the majority of the regions we studied. The resulting norms provide a better reflection of observed heterogeneities than the widely adopted value 1.05 which is typically used in population estimates and projections [55, 107–111]. Based on the estimate of 37.1 million total births in Sub-Saharan Africa in 2015

[55], an estimated SRB of 1.03 would result in 178 thousand more female births than 1.05 would. In addition, when using 1.05 instead of the regional biological norm as a reference in Sub-Saharan Africa, deviations that signify the early stage of SRB inflation may be misjudged as natural fluctuations, and the severity of prenatal sex discrimination may be underestimated.

Our study analyzed the national-level SRB, which may mask the disparities of SRB within countries. Future work should assess subnational divisions in countries with outlying SRB to better understand where female births are most discriminated against in the prenatal period. In addition, without a full understanding of the subnational SRB, we are not able to conclude that the prenatal sex discrimination did not exist in countries that are normal at the national-level. Hence, subnational-level SRB studies based on reproducible methods for countries with or without imbalanced national-level SRB are urgently needed.

We aimed to be inclusive in identifying countries with potential past or future SRB inflation, using a combination of qualitative and quantitative measures to select countries at risk. For some of these countries, mainly in Sub-Saharan Africa, the inferential routine indicated that SRB inflation has not yet begun, and it is not clear to what extent the experience of Eastern Asia and Southern Asia will generalize to these countries. Hence, for these countries, we projected the SRB using the Bayesian hierarchical model structure based on worst- and best-case scenarios, represented by all countries experiencing SRB inflation versus no countries having future inflation. The best-case scenario projected additional missing female births in Eastern and Southern Asia until the 2040s, after which the SRBs in those regions will be back to their regional biological norms. Under the worst-case scenario, that all the countries at risk of future SRB inflation will follow the same relationship between declining family sizes and missing girls, and SRB inflation would continue throughout the 21st century. Countries in Southern Asia and Eastern Asia are projected to continuously contribute to the majority of missing female births until the 2060s under the worst-case scenario. From the 2060s onward, Sub-Saharan Africa

would also become a region with SRB imbalance. While the worst-case scenario projection is hypothetical and subject to the various assumptions made about future fertility declines and attitudes and behaviors regarding son preference, the findings in our study underscore the importance of monitoring the sex ratio at birth, and targeted action if estimates and projections suggest elevated levels.

Chapter 4

A systematic assessment of national, regional, and global sex ratios of infant, child, and under-5 mortality

This work has been published as:
Alkema L, **Chao F**, You D, Pedersen J, Sawyer CC. National, regional, and global sex ratios of infant, child, and under-5 mortality and identification of countries with outlying ratios: a systematic assessment. The Lancet Global Health. 2014 Sep 30;2(9):e521-30.

Contributors LA led the development of the Bayesian statistical model and oversaw the research. FC and CCS provided input on model specification. FC assisted in assessing and compiling the database, model implementation, and obtaining model-based estimates. CCS and DY provided substantive input on model findings. DY oversaw database construction. JP developed the methodology and software to extract data on sex ratios. LA, FC, DY, JP, and CCS wrote and revised the paper. All authors have seen and approved the final version of the paper.

Abstract

Under natural circumstances, the sex ratio of male to female mortality up to the

age of 5 years is greater than one but sex discrimination can change sex ratios. The estimation of mortality by sex and identification of countries with outlying levels is challenging because of issues with data availability and quality, and because sex ratios might vary naturally based on differences in mortality levels and associated cause of death distributions.

For this systematic analysis, we estimated country-specific mortality sex ratios for infants, children aged 1–4 years, and children under the age of 5 years (under 5s) for all countries from 1990 (or the earliest year of data collection) to 2012 using a Bayesian hierarchical time series model, accounting for various data quality issues and assessing the uncertainty in sex ratios. We simultaneously estimated the global relation between sex ratios and mortality levels and constructed estimates of expected and excess female mortality rates to identify countries with outlying sex ratios.

Global sex ratios in 2012 were 1.13 [90% uncertainty interval 1.12; 1.15] for infants, 0.95 [0.93; 0.97] for children aged 1–5 years, and 1.08 [1.07; 1.09] for under 5s, an increase since 1990 of 0.01 [-0.01 to 0.02] for infants, 0.04 [0.02 to 0.06] for children aged 1–4 years, and 0.02 [0.01 to 0.04] for under 5s. Levels and trends varied across regions and countries. Sex ratios were lowest in southern Asia for 1990 and 2012 for all age groups. Highest sex ratios were seen in developed regions and the Caucasus and central Asia region. Decreasing mortality was associated with increasing sex ratios, except at very low infant mortality, where sex ratios decreased with total mortality. For 2012, we identified 15 countries with outlying under-5 sex ratios, of which ten countries had female mortality higher than expected (Afghanistan, Bahrain, Bangladesh, China, Egypt, India, Iran, Jordan, Nepal, and Pakistan). Although excess female mortality has decreased since 1990 for the vast majority of countries with outlying sex ratios, the ratios of estimated to expected female mortality did not change substantially for most countries, and worsened for India.

Important differences exist between boys and girls with respect to survival up to

the age of 5 years. Survival chances tend to improve more rapidly for girls compared with boys as total mortality decreases, with a reversal of this trend at very low infant mortality. For many countries, sex ratios follow this pattern but important exceptions exist. An explanation needs to be sought for selected countries with outlying sex ratios and action should be undertaken if sex discrimination is present.

4.1 Introduction

Girls tend to have advantages over boys with respect to survival up to age 5 years, resulting in a mortality sex ratio, defined as the ratio of male to female mortality, greater than one [112]. This survival advantage for girls tends to increase as total (both sexes combined) mortality levels decrease because of changes in the associated cause of death distributions, which are generally more favourable for girls' survival at lower mortality levels [113–115]. However, additional factors that cause unusually high or low sex ratios might be at play, such as disadvantaging treatment of girls compared with boys, as reported in various, mostly Asian countries [116–131]. Pinpointing countries with unusually low or high sex ratios, where differential treatment is possibly at play, is of key importance for monitoring sex discrimination.

The monitoring of sex differences in mortality in children younger than 5 years (hereon in referred to as under-5 mortality) is challenging because of issues with data availability and quality, and because country-specific sex differentials tend to change over time as total mortality levels decrease. Although estimates of mortality sex ratios for all countries have been reported in previous analyses [132–134], these studies did not account for data quality issues such as standard errors in the estimated sex ratios (which can be substantial), they did not produce or publish uncertainty intervals, they did not assess country-specific data-driven time trends for all countries, and the extent to which the estimates were validated is not clear. Moreover, these studies did not provide sufficient insight into countries with outlying sex ratios, where sex discrimination might be present. The pinpointing of countries with outlying sex ratios is complicated because of difficulties in defin-

ing a standard expected sex ratio in the absence of sex discrimination—sex ratios tend to vary with total mortality and the associated cause of death distribution. To overcome this difficulty, some studies assessed female disadvantage on the basis of the relation between sex ratios and either male or total mortality using data from selected countries with high-quality vital registration data [135–137], but we know of no study that used all globally available data to estimate the relation between sex ratios and total mortality in a systematic fashion to pinpoint countries with outlying sex ratios.

For this systematic assessment, we estimated levels of and trends in sex ratios for rates of infant mortality (IMR; 0–1 year), child mortality (CMR; 1–4 years), and under-5 mortality (U5MR; 0–4 years) for 195 countries from 1990 (or earlier, depending on data availability) to 2012. Additionally, we assessed the global relation between sex ratios and total mortality rates and used this relationship to estimate expected and excess female mortality rates, to pinpoint countries with outlying sex ratios.

4.2 Data

The data used in this study were observed sex ratios for IMR, CMR, and U5MR from vital registration systems, sample registration and surveillance systems, surveys, and censuses. Data from vital registration systems were obtained from the World Health Organization (WHO). We used vital registration and sample registration and surveillance data to obtain sex ratios for IMR and CMR through standard life-table methods. For data from full birth histories collected in Demographic and Health Surveys, World Fertility Surveys, and selected surveys from the Pan-Arab Programme on Family Health, sex ratios for IMR were calculated for periods of varying optimized lengths, according to the method by Pedersen and Liu [59] to capture shorter-term changes for country-years with sufficient information. For sex ratios of CMR, we used 5-year estimates because the sampling errors associated with the estimates tend to be too large to obtain informative estimates for periods

shorter than 5 years. For all sources, we used sex ratios for the U5MR only if sex ratios for IMR and CMR were not available.

For surveys and censuses in which only summary birth histories were obtained, we calculated sex-specific estimates of U5MR using the Brass method [138], either from microdata or from published tabulations of number of children ever born and children living (we chose the U5MR because it is more robust to the choice of model life table than the IMR, which can vary substantially according to the model selected). When microdata or tabulations were not available, we obtained data from survey or census reports or data files in the holdings of the United Nations Population Division or UNICEF; through the process by UNICEF's Country Report on Indicators for the Goals and an annual country consultation process conducted by UNICEF and WHO; or from the internet or other sources.

Inclusion criteria for data series from censuses and surveys and vital registration and sample registration and surveillance observation years followed the inclusion criteria used for total U5MR estimation used by the UN IGME [138]. Additionally, extreme observations, with sex ratios greater than 5 or smaller than 0.2, were removed (less than 1% of the largest and smallest observations were removed because of this criterion; the excluded observations were mainly from vital registration systems in small countries). An overview of the data source is given in Table 4.1. Appendix 6.4 provides an overview of all data sources used, broken down by country.

4.3 Methods: overview

We developed a statistical model to estimate trends in sex ratios for IMR, CMR, and U5MR over time for each country (see Section 4.4.1). Briefly, for infants, we used a flexible regression model (penalized B-splines regression) to represent the global relation between sex ratios and total mortality rates. We modelled country-specific sex ratios using the product of the expected sex ratio (based on the regression model and the infant mortality rate in the country-year) and a country-specific multiplier,

Data source	Age group		
	[0, 1)	[1, 5)	[0, 5)
Census Direct	6	4	0
Census Indirect	0	0	90
DHS Direct	1284	1023	0
DHS Indirect	0	0	10
MICS Direct	78	55	0
MICS Indirect	0	0	335
Other DHS Direct	293	265	0
Other DHS Indirect	1	1	25
Others Direct	140	143	0
Others Indirect	4	4	165
SRS	74	66	12
VR	3057	2949	0

Table 4.1 **Distribution of observations by source type and age group.** Observations are grouped by source type and age groups. "Direct" refers to observations obtained from full birth histories while "Indirect" refers to observations obtained from summary birth histories. DHS: Demographic and Health Surveys; MICS: Multiple Indicator Cluster Surveys; SRS: Sample Registration System; VR: Vital Registration.

which represents the relative advantage or disadvantage of girls to boys compared with other countries at similar total mortality rates. We modelled these multipliers with a flexible time series model in which they were assumed to fluctuate around country-specific average levels. We estimated these country-specific average levels using a Bayesian hierarchical model, allowing for outlying countries where greater male or female advantages might be seen. By simultaneously estimating the global regression model fit and the country-specific sex ratios, country-specific information informs the global relation and, vice versa, the global relation informs the country-specific estimates.

We constructed country-specific estimates for the sex ratio for CMR and estimated the global relation between total child mortality and its sex ratio in a similar fashion. For each country-year, we derived the sex ratios for the U5MR and the global relation between total U5MR and its sex ratio from the estimated sex ratios for IMR and CMR (see Section 4.4.2).

Sex ratio estimates were based on all available data in a country (see Section 4.4.3). The data quality model incorporated stochastic and sampling variance

(caused by a small number of observed livebirths and deaths or by small samples from the overall population) and non-sampling error variance (which might differ across different source types). By including both variance terms, observations that were deemed to be less informative of true sex ratios were down-weighted compared with more informative observations. We used t distributions for more robust inference for U5MR sex ratios (where more outlying observations were present). For 11 countries without any data, estimates were inferred from the relation between sex ratios and total mortality: expected sex ratios followed from the global model and estimates for total mortality, and country-specific multipliers were simulated from the time series model to include the substantial uncertainty associated with the estimates in such countries.

We combined estimates of IMR and CMR sex ratios with estimates of total IMR and CMR from the UN Interagency Group on Child Mortality Estimation (UN IGME) to obtain sex-specific IMR, CMR, and U5MR, accounting for the uncertainty in total IMR and CMR [138] (see Section 4.4.5). We obtained estimates for the number of deaths through a standard life table approach adopted by the UN IGME [139], using information about population numbers from the 2012 Revision of World Population Prospects [140] and life table entries set by WHO. Aggregate estimates for the world and all Millennium Development Goal regions were based on the totals for the number of deaths and population numbers by region.

The global relation between expected sex ratios and mortality in both sexes implicitly defines a relation between male mortality and the expected sex ratio (see Section 4.4.6). We used this relation to calculate the expected sex ratio based on the estimated male mortality rate for each country- year. To identify countries with outlying sex ratios, we defined and calculated the expected female mortality rate that is associated with the expected sex ratio and estimated male mortality for a given country-year, and defined and calculated excess female mortality as the difference between the expected female mortality rate and the estimated rate for the country-year (where negative outcomes refer to lower-than-expected female mortal-

ity). Hence, the excess female mortality defined in this study is using the expected female mortality as reference rather than comparing to male mortality. A positive excess female mortality does not imply that the estimated female mortality is higher than the estimated male mortality.

We used a Markov chain Monte Carlo (MCMC) algorithm to generate samples of the posterior distributions of the parameters [141] (see Section 4.4.7). This approach produced a set of trajectories of sex ratios for all age groups for each country, and associated measures of sex-specific mortality, excess female mortality, and deaths.

We computed 90% uncertainty intervals (UIs) for all indicators of interest using the 5th and 95th percentiles of the posterior distributions (90% UIs are the standard choice in IGME reporting as opposed to the more standard 95% intervals in view of the inherent uncertainty in child-mortality-related outcomes; the uncertainty in estimates follows from the limitations of the available data at the country level). We defined country-years to have outlying sex ratios if the absolute value of the point estimate for excess female mortality was greater than one per 1000 livebirths for excess IMR and U5MR and one per 1000 survivors up to age 1 year for excess CMR, and if the posterior probability that the excess female mortality is either negative or positive is more than 90%, corresponding to a chance of one in ten of incorrectly flagging an outlying country.

We assessed model performance using an out-of-sample validation exercise (see Section 4.4.8).

4.4 Methods: technical details

The contents of this section were taken from the Online Appendix of the original paper.

4.4.1 Infant and child sex ratio models

The sex ratios for IMR, CMR, and U5MR are denoted by $S_{a,c,t}$ for country c, year t and age group $a = 1,4,5$, referring to infant, child and under-5 sex ratios respectively (age groups $[0,1)$, $[1,5)$, and $[0,5)$). Total IMR, CMR, and U5MR are denoted by $Q_{a,c,t}$ for the corresponding age group and country-year, referring to the UN IGME (United Nations Inter-agency Group for Child Mortality Estimation) estimates unless otherwise noted. The j-th observed ratio of male to female mortality is denoted by $s_{a,j}$ in country $c[a,j]$, year $t[a,j]$ for $a = 1,4,5$.

$S_{a,c,t}$ for $a = 1,4$ is modeled as follows:

$$\begin{aligned} S_{a,c,t} &= W_{a,c,t} \cdot P_{a,c,t}, \\ W_{a,c,t} &= f^{(a)}(Q_{a,c,t}), \end{aligned}$$

where $f^{(a)}(\cdot)$ represents the relation between the level of mortality for both sexes combined and the expected sex ratio on a global level, and $P_{a,c,t}$ represents the relative advantage or disadvantage of girls to boys compared to other countries at similar mortality rates, as indicated by the data in the country.

The country multipliers $P_{a,c,t}$ were estimated with a time series model:

$$\begin{aligned} \log(P_{a,c,t}) &= \beta_{a,c} + \varepsilon_{a,c,t}, \\ \varepsilon_{a,c,t} &\sim N(\rho \cdot \varepsilon_{a,c,t-1}, \sigma_\varepsilon^2), \end{aligned}$$

where the multipliers fluctuate around country-specific level $\beta_{a,c}$. The fluctuations $\varepsilon_{a,c,t}$ were modeled with an autoregressive time series model of order one (AR(1)).

Country-specific levels $\beta_{a,c}$ for $a = 1,4$, representing the average level difference in $\log(P_{a,c,t})$ across countries, were estimated using a hierarchical model [57, 88]:

$$\beta_{a,c} \sim t_3(\mu = 0, \sigma^2 = \sigma_{a,\beta}^2, \nu = 3)T(,\log(1.6)),$$

where a t-distribution with three degrees of freedom was chosen to allow for coun-

tries with outlying levels. The truncation was imposed to exclude the possibility of extreme (and implausible) median country-specific levels (here the median levels are restricted to be smaller than 1.6).

Specification of the global relations between infant and child mortality and their expected sex ratios We used flexible penalized B-spline regression models [142, 143] to estimate the global relation between total mortality and expected sex ratios, denoted by function $f^{(a)}(\cdot)$, for age groups $a = 1, 4$. The function $f^{(a)}(q)$ for some value q for total mortality was specified as follows:

$$\log(f^{(a)}(q)) \quad = \quad \sum_{k=1}^{K_a} B_k^{(a)}(q)\alpha_k^{(a)}, \tag{4.1}$$

where $B_k^{(a)}(q)$ refers to the k-th B-spline evaluated at q and $\alpha_k^{(a)}$ to the k-th spline coefficients. The expected sex ratio for country c, year t with mortality $Q_{a,c,t}$ is given by $W_{a,c,t} = f^{(a)}(Q_{a,c,t})$ for $a = 1, 4$ (where $Q_{a,c,t}$'s are rounded to three decimal places to reduce the number of splines evaluations).

The B-splines used in the regression models are illustrated in Figure 4.1. We used symmetric third-order polynomials, equally spaced on the log-transformed total mortality scale (knots are set to be 0.3 apart). The resulting splines add up to unity at any level of total mortality. To avoid extreme extrapolations, splines are combined for total mortality less than 0.005 for both age groups, and for total mortality greater than the 95-th percentile of $Q_{a,c,t}$ for the age-group specific country-years included in the data set.

When fitting the splines model to observations, second-order differences in adjacent splines coefficients were penalized to guarantee smoothness of the global relation between total mortality and expected sex ratios. The remainder of this subsection discusses the implementation details.

The splines regression model is specified as follows:

$$\log(f^{(a)}(\tilde{\boldsymbol{q}}^{(a)}) \quad = \quad \tilde{\boldsymbol{B}}^{(a)}\boldsymbol{\alpha}^{(a)}, \tag{4.2}$$

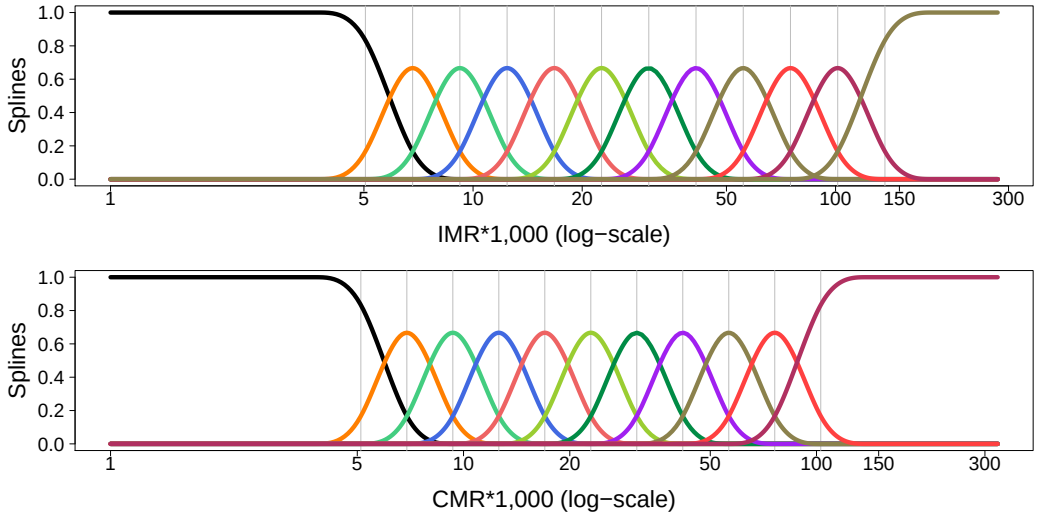

Fig. 4.1 **Illustration of the B-splines used for estimating the global relation between sex ratios and total mortality for age groups [0, 1) and [1, 5).** Each B-spline is plotted in a different color.

where $\tilde{\boldsymbol{q}}^{(a)}$ represents the vector of unique values $Q_{a,c,t}$ (rounded to three digits), $\tilde{\boldsymbol{B}}^{(a)} = \boldsymbol{B}^{(a)}(\tilde{\boldsymbol{q}}^{(a)})$ the matrix of splines evaluated at each entry of $\tilde{\boldsymbol{q}}^{(a)}$, and $\boldsymbol{\alpha}^{(a)}$ the vector of splines coefficients of length K_a. The splines equation can be written as follows [143–145]:

$$\begin{aligned} \tilde{\boldsymbol{B}}^{(a)}\boldsymbol{\alpha}^{(a)} &= \tilde{\boldsymbol{B}}^{(a)}\boldsymbol{G}^{(a)}\boldsymbol{b}^{(a)} + \boldsymbol{Z}^{(a)}\boldsymbol{e}^{(a)}, \\ \boldsymbol{G}^{(a)} &= (\mathbf{1}_{K_a}\ \boldsymbol{g}_{K_a}),\ \text{where } \boldsymbol{g}_{K_a} = (1-K_a/2,\ldots,K_a-K_a/2)', \\ \boldsymbol{Z}^{(a)} &= \tilde{\boldsymbol{B}}^{(a)}\boldsymbol{D}'_{K_a}(\boldsymbol{D}_{K_a}\boldsymbol{D}'_{K_a})^{-1}, \end{aligned} \tag{4.3}$$

where the elements of difference matrix $\boldsymbol{D}_K$ are given by $D_{K,i,i} = D_{K,i,i+2} = 1$, $D_{K,i,i+1} = -2$ and $D_{K,i,j} = 0$ otherwise. The first part in Eq.(5.1), $\tilde{\boldsymbol{B}}^{(a)}\boldsymbol{G}^{(a)}\boldsymbol{b}^{(a)}$, describes the linear change in the expected sex ratio, and the second part $\boldsymbol{Z}^{(a)}\boldsymbol{e}^{(a)}$ describes the fluctuations around the linear trend. The unknown parameters are given by:

$$\begin{aligned} \boldsymbol{b}^{(a)} &= (b_1^{(a)}, b_2^{(a)})', \\ \boldsymbol{e}^{(a)} &= \boldsymbol{D}_{K_a}\boldsymbol{\alpha}^{(a)}, \end{aligned}$$

where $\boldsymbol{e}^{(a)} = (e_1^{(a)}, \ldots, e_{J_a}^{(a)})'$, with $J_a = K_a - 2$ and $e_q^{(a)} = \Delta^2 \alpha_{q+2}^{(a)}$ for $q = 1, \ldots, J_a$. Second-order differences are penalized by imposing

$$e_q^{(a)} \sim N(0, \sigma_u^2), \text{ for } q = 1, \ldots, J_a,$$

where variance σ_u^2 determines the extent of smoothing. Spread out prior distributions were used for the splines model parameters.

4.4.2 Derivation of sex ratio estimates for U5MR

For each country c in year t, we derived $S_{5,c,t}$, the sex ratios for the U5MR, and the global relation between total U5MR and its sex ratio from the estimated sex ratios for IMR $S_{1,c,t}$ and sex ratio for CMR $S_{4,c,t}$ through standard cohort equations. In particular, male and female mortality rates for infants and children were derived as follows (leaving out country and year subscripts, and using superscripts M and F to denote male and female-specific indicators):

$$Q_a^M = Q_a/(w_a + (1 - w_a)/S_a), \tag{4.4}$$

$$Q_a^F = Q_a^M/S_a, \tag{4.5}$$

for $a = 1, 4$, where w_1 refers to the ratio of male livebirths over total livebirths and w_4 to the ratio of male survivors to age one over the total number of survivors up to age one:

$$w_1 = B_1^M/B_1 = \frac{SRB}{1 + SRB}, \tag{4.6}$$

$$w_4 = B_4^M/B_4 = \frac{B_1^M \cdot (1 - Q_1^M)}{B_1 \cdot (1 - Q_1)} = w_1 \cdot \frac{(1 - Q_1^M)}{(1 - Q_1)}, \tag{4.7}$$

where B_1 refers to the total number of livebirths, B_4 to the number of survivors up to age one (approximated by the number of livebirths times total infant mortality rate (IMR)), and SRB refers to the sex ratio at birth, which is set at 1.05 for all country-years. Given sex-specific mortality for infants and children, sex-specific U5MR is

obtained with the following equality:

$$Q_5 \quad = \quad 1-(1-Q_4)(1-Q_1),$$

for males and females, which are then used to obtain U5MR sex ratios $S_{5,c,t} = Q^M_{5,c,t}/Q^F_{5,c,t}$.

The expected sex ratio $W_{5,c,t}$ for the country-year of interest was derived in a similar fashion, using $W_{1,c,t}$ and $W_{4,c,t}$ instead of $S_{1,c,t}$ and $S_{4,c,t}$. Finally, country multiplier $P_{5,c,t} = S_{5,c,t}/W_{5,c,t}$.

Contrary to age groups [0, 1) and [1, 5), there is no function that describes the global relation between total U5MR and the expected sex ratio for the U5MR because this expected sex ratio depends on total IMR and total CMR (and their associated expected sex ratios). To visualize the global relation between total U5MR and the expected sex ratio, a Loess curve was fitted to all estimates of combinations $(Q_{5,c,t}, W_{5,c,t})$. The resulting relation is denoted by $\tilde{f}^{(5)}(\cdot)$.

4.4.3 Data model

For most observations, observed sex ratios for IMR and CMR were used. To avoid using data twice, observed sex ratios for U5MR were not included if information on IMR and CMR was included.

There are two exceptions: (1) for observations from summary birth histories, only sex ratios for U5MR were used (unless these were missing while the sex ratios for IMR and CMR were available); (2) for a small number of observations for which information on sex ratios for IMR was missing, information on the sex ratio for U5MR was used instead.

For observations on age groups $a = 1$ and 4, the data model was given by

$$\log(s_{a,j}) \quad \sim \quad N(\log(S_{a,c[a,j],t[a,j]}), \sigma^2_{a,j} + \omega^2_{a,x[a,j]}), \text{ for } a = 1,4,$$

where $s_{a,j}$ is the j-th observed ratio of male to female mortality for age group a

in country $c[a,j]$, year $t[a,j]$ for $a = 1,4$, and $x[a,j]$ is the source type of that observation (see Table 4.1 for the distribution of source types). The variance of the log-transformed observation is the sum of sampling variance $\sigma^2_{a,j}$ and non-sampling variance $\omega^2_{a,x[a,j]}$ (explained further below).

With similar notation, the data model for observations from age group [0, 5) ($a = 5$) was given by:

$$\log(s_{5,j}) \sim t(\mu = \log(S_{5,c[5,j],t[5,j]}), \sigma^2 = \sigma^2_{5,j} + \omega^2_{5,x[5,j]}, \nu = \nu_5),$$

which is a t-distribution with ν_5 degrees of freedom. A t-distribution, as opposed to a normal distribution, was used because additional analysis suggested that more outliers were present in the observations for this age group. A spread out prior distribution was assigned to the degrees of freedom ν_5.

Sampling variance was given for a large subset of DHS and MICS observations. For observations from vital registration systems, a Monte Carlo simulation was used to approximate the stochastic variances based on a synthetic cohort approach (explained below). For all the other observations with missing standard errors, the standard error on the log-scale was set at 15%, approximately equal to the median standard error in the data set of non-VR observations. Non-sampling variance parameter $\omega^2_{a,x}$ was estimated by source type and set to zero for observations from VR/SRS.

For observations from VR/SRS, a Monte Carlo simulation was used to approximate the stochastic variance based on a synthetic cohort approach, assuming that for females as well as males:

$$D_1 \sim \text{Poisson}(A_1 Q_1),$$

and similarly

$$D_4 \sim \text{Poisson}(A_1(1-Q_1)Q_4),$$

where D_a refers to the number of deaths in age group $a = 1,4$, Q_a to the total

mortality rate, A_1 refers to the midyear population aged [0, 1).

4.4.4 Model summary

Notation Notations are summarized in Table 4.2.

Symbol	Description
a	Indicator for age group, where index $a = 1,4,5$ refers to age groups $[0,1)$, $[1,5)$ and $[0,5)$ respectively.
t	Indicator for year.
c	Indicator for country.
j	Indicator for observation.
x	Indicator for source type.
$S_{a,c,t}$	Sex ratio for age group $a = 1,4,5$, country c, year t.
$Q_{a,c,t}$	Total mortality for age group $a = 1,4,5$, country c, year t (given by UN IGME estimate).
$W_{a,c,t}$	Expected sex ratio for age group $a = 1,4,5$, country c, year t.
$f^{(a)}(q)$	Expected sex ratio for age group $a = 1,4$ for a given total mortality level q.
$\boldsymbol{B}^{(a)}(q)$ and $\boldsymbol{\alpha}^{(a)}$	$\log(f^{(a)}(q)) = \boldsymbol{B}^{(a)}(q)\boldsymbol{\alpha}^{(a)}$, where $\boldsymbol{B}^{(a)}(q)$ refers to the splines matrix of age group $a = 1,4$ obtained for value q, and $\boldsymbol{\alpha}^{(a)}$ refers to the vector of spline coefficients for age group $a = 1,4$.
$P_{a,c,t}$	Country-year-multiplier for age group $a = 1,4,5$, country c, year t which represents the relative advantage or disadvantage of girls to boys compared to other countries at similar levels of total mortality.
$\beta_{a,c}$	Long-term median country multiplier for age group $a = 1,4$.
$\sigma^2_{a,\beta}$	Variance of long-term median country multiplier for age group $a = 1,4$.
ρ	Autoregressive parameter for AR(1) time series model for $\log(P_{1,c,t})$ and $\log(P_{4,c,t})$.
σ^2_{ε}	Variance of distortion terms in AR(1) time series model for $\log(P_{1,c,t})$ and $\log(P_{4,c,t})$.
$s_{a,j}$	The j-th observed ratio of male to female mortality in country $c[a,j]$, year $t[a,j]$ for $a = 1,4,5$.
$\sigma^2_{a,j}$	The j-th sampling variance for $\log(s_{a,j})$ for $a = 1,4,5$.
$\omega^2_{a,x[a,j]}$	The j-th non-sampling variance for $\log(s_{a,j})$ of source type $x[a,j]$ for $a = 1,4,5$.
ν_5	Degrees of freedom for t-distribution for observations in age group [0, 5).

Table 4.2 **Notation summary.**

Sex-ratio model

$$
\begin{aligned}
S_{a,c,t} &= W_{a,c,t} \cdot P_{a,c,t}, \\
W_{a,c,t} &= f^{(a)}(Q_{a,c,t}), \\
\log(P_{a,c,t}) &= \beta_{a,c} + \varepsilon_{a,c,t}, \\
\varepsilon_{a,c,t} &\sim N(\rho \cdot \varepsilon_{a,c,t-1}, \sigma_\varepsilon^2), \\
\beta_{a,c} &\sim t_3(\mu = 0, \sigma^2 = \sigma_{a,\beta}^2, \nu = 3)T(,\log(1.6)), \\
W_{a,c,t} &= f^{(a)}(Q_{a,c,t}), \text{ for } a = 1,4, \\
\log(f^{(a)}(\tilde{\boldsymbol{q}}^{(a)}) &= \tilde{\boldsymbol{B}}^{(a)} \boldsymbol{G}^{(a)} \boldsymbol{b}^{(a)} + \boldsymbol{Z}^{(a)} \boldsymbol{e}^{(a)}, \\
\boldsymbol{b}^{(a)} &= (b_1^{(a)}, b_2^{(a)})', \\
\boldsymbol{e}^{(a)} &= \boldsymbol{D}_{K_a} \boldsymbol{\alpha}^{(a)}, \\
e_q^{(a)} &\sim N(0, \sigma_u^2), \text{ for } q = 1, \ldots, J_a.
\end{aligned}
$$

Data model

$$
\begin{aligned}
\log(s_{a,j}) &\sim N(\log(S_{a,c[a,j],t[a,j]}), \sigma_{a,j}^2 + \omega_{a,x[a,j]}^2), \text{ for } a = 1,4, \\
\log(s_{5,j}) &\sim t(\mu = \log(S_{5,c[5,j],t[5,j]}), \sigma^2 = \sigma_{5,j}^2 + \omega_{5,x[5,j]}^2, \nu = \nu_5).
\end{aligned}
$$

Prior distributions

$$
\begin{aligned}
\rho &\sim U(0,1), \\
\sigma_\varepsilon &\sim U(0, 0.05), \\
\omega_{a,x} &\sim U(0,2), \text{ for all } x \text{ and } a = 1,4,5, \\
\nu_5 &\sim U(3,50), \\
\sigma_{1,\beta}^{-2} &\sim \text{Gamma}(1/2, 1/2 \cdot 0.03^2), \\
\sigma_{4,\beta}^{-2} &\sim \text{Gamma}(1/2, 1/2 \cdot 0.04^2), \\
b_1^{(a)} &\sim U(0, 0.3), \text{ for } a = 1,4, \\
b_2^{(a)} &\sim U(-0.1, 0.1), \text{ for } a = 1,4, \\
\sigma_u &\sim U(0, 0.2).
\end{aligned}
$$

Spread out prior distributions are used for all non-country-specific parameters.

4.4.5 Sex-specific mortality

Sex-specific mortality estimates were obtained from estimated sex ratios and total mortality, as described in Eq.(4.4) to (4.7). To account for the uncertainty in the sex ratios as well as the uncertainty in total mortality, we combined posterior samples of sex-specific mortality based on the posterior samples of sex ratios (from our sex ratio model) with posterior samples of total mortality (instead of point estimates), obtained from UN IGME [138].

Estimated number of deaths for each country-year were calculated by sex using a period life table approach, and used to obtain regional estimates of sex-specific mortality rates.

4.4.6 Excess female mortality

The global relation between expected sex ratios and mortality in both sexes for age groups $a = 1,4$ implicitly defines a relation between male mortality and the expected sex ratio. We used this relation to calculate the expected sex ratio based on the estimated male mortality rate for each country-year. In particular, for each value of male mortality Q_a^M, there exists an associated value of expected female mortality, here referred to as expected female mortality Q_a^{F*}, such that the ratio of male mortality over expected female mortality is equal to the expected ratio at the implied level of total mortality Q_a^*:

$$\frac{Q_a^M}{Q_a^{F*}} = f^{(a)}(Q_a^*), \tag{4.8}$$

where implied total mortality $Q_a^* = w_a \cdot Q_a^M + (1 - w_a) \cdot Q_a^{F*}$.

To identify countries with outlying sex ratios, we defined and calculated the expected female mortality rate that is associated with the expected sex ratio and estimated male mortality for country c in year t for age groups $a = 1,4$, $Q_{a,c,t}^{F*}$ by

minimizing the differences between the right and left-hand terms of Eq.(4.8). The expected female U5MR $Q^{F*}_{5,c,t}$ followed from $Q^{F*}_{1,c,t}$ and $Q^{F*}_{4,c,t}$.

Excess female mortality for all age groups was defined as:

$$E_{a,c,t} = Q^{F}_{a,c,t} - Q^{F*}_{a,c,t}.$$

Excess female deaths were defined as the number of deaths associated with the excess female mortality rate:

$$D^{F}_{a,c,t} - D^{F*}_{a,c,t},$$

where $D^{F*}_{a,c,t}$ and $D^{F}_{a,c,t}$ refer to the number of deaths associated with $Q^{F*}_{a,c,t}$ and $Q^{F}_{a,c,t}$ respectively.

4.4.7 Computing

We conducted statistical analyses using R (version 3.0) [146]. We obtained samples from the posterior distributions of all model parameters using a MCMC algorithm, implemented in JAGS 3.2.0 Open Source software [16], using `R`-packages `R2jags` [95] and `rjags` [18]. Posterior samples were obtained from 24 chains; the total number of iterations in each chain was 150,000, the first 5,000 iterations were discarded as burn-in, and after additional thinning 8,640 samples from each chain were kept. Convergence of the MCMC algorithm and the sufficiency of the number of samples obtained were checked through visual inspection of trace plots and convergence diagnostics of Gelman and Rubin [14], implemented in the `coda` `R`-package [19]. Software programs and data are available from the authors.

4.4.8 Model validation

We assessed model performance using an out-of-sample validation exercise. Given the retrospective nature of child mortality data and the occurrence of data in series, the training set was not constructed by leaving out observations at random, but based on including all available data in some year in the past [97]; here 2006 was

chosen. To construct the training dataset, all data that were collected in or after 2006 were removed. Fitting the model to the training dataset resulted in point estimates and uncertainty intervals that would have been constructed in 2006 based on the proposed method. To validate model performance, we calculated various validation measures (mean/median errors, coverage) based on the left-out observations and based on the estimates obtained from the full dataset and the estimates obtained from the training dataset.

For the left-out observations, errors are defined as $e_{a,j} = s_{a,j} - \tilde{s}_{a,j}$, where $\tilde{s}_{a,j}$ denotes the posterior median of the predictive distribution for a left-out observation $s_{a,j}$ based on the training dataset. Coverage is given by $1/n \cdot \sum 1[s_{a,j} \geq l_{a,c[a,j],t[a,j]}] \cdot 1[s_{a,j} \leq u_{a,c[a,j],t[a,j]}]$, where n denotes the total number of left-out observations considered and $l_{a,c[a,j],t[a,j]}$ and $u_{a,c[a,j],t[a,j]}$ the lower and upper bounds of the 90% predictions intervals for the j-th observation in age group a. The validation measures were calculated for 1,000 sets of left-out observations, where each set consisted of a random sample of one left-out observation per country. Reported results include the median of the validation measures based on the outcomes in the 1,000 sets.

"Updated" estimates, denoted by $\widehat{S}_{a,c,t}$ for country c in year t, refer to the sex ratio estimates obtained from the full dataset. The error in the estimate based on the training dataset is defined as $e_{c,a,t} = \widehat{S}_{a,c,t} - \widetilde{S}_{a,c,t}$, where $\widetilde{S}_{a,c,t}$ refers to the posterior median estimate based on the training dataset. Coverage was calculated in a similar manner as for the left-out observations, based on the lower and upper bound of the 90% uncertainty intervals for $S_{a,c,t}$ obtained from the training dataset.

4.5 Results

4.5.1 Aggregated sex-specific IMR, CMR, and U5MR

The dataset consisted of 10084 observations. More information on country-specific sources is given in Appendix 6.4. Figure 4.2, Table 4.3, Table 4.4, Table 4.5, Ta-

ble 4.6, Table 4.7, and Table 4.8 show estimates of sex ratios for the IMR, CMR, and U5MR for 1990 and 2012 for the world and Millennium Development Goal regions. Levels and trends varied across regions. Sex ratios of mortality were lowest in southern Asia for 1990 and 2012 for all age groups; it is the only region where the CMR and U5MR sex ratios were lower than one for both 1990 and 2012. In 2012, the highest mortality sex ratios were estimated for Caucasus and central Asia for infants (Table 4.3) and children younger than 5 years (Table 4.7), whereas developed regions had the highest CMR sex ratio (Table 4.5). In most regions and age groups, sex ratios increased between 1990 and 2012. We saw the largest increase in U5MR sex ratio in northern Africa (Table 4.7). Sex ratios decreased in developed regions in all age groups, in southern Asia for IMR, and in sub-Saharan Africa for CMR (Table 4.3, Table 4.5, and Table 4.7).

4.5.2 Global relation between sex ratios and total mortality

Much of the differences and changes in sex ratios can be explained by differences and changes in total mortality and associated expected sex ratios. Figure 4.3 shows the estimated expected sex ratios for a given level of total mortality based on the global relation between mortality levels and sex ratios for the IMR, CMR, and U5MR. For the IMR, the expected sex ratio is about 1.15 [90% UI 1.14; 1.17] for high levels of mortality (about 150 deaths per 1000 livebirths). This ratio increased to 1.26 [1.25; 1.27] as mortality decreased to about 20 deaths per 1000 livebirths and decreased to 1.20 [1.18; 1.22] as total IMR decreased to five deaths per 1000 livebirths. For CMR, expected sex ratios were close to one (1.01 [0.99; 1.02]) for total mortality above 30 deaths per 1000 survivors past the age of 1 year. The ratio increased to 1.21 [1.19; 1.22] as mortality decreased to five per 1000 survivors. The expected sex ratio for the U5MR is driven by the expected sex ratios for the IMR and CMR. The relation between total U5MR and its sex ratio based on all country-years suggests an increase in the U5MR sex ratio from about 1.09 to 1.25 as the U5MR decreased from around 400 deaths to 20 deaths per 1000 livebirths. This

increase was followed by a decrease in the expected sex ratio from about 1.25 to 1.18 as U5MR decreased from 20 deaths to five deaths per 1000 livebirths.

4.5.3 Outlying sex ratios on global, regional and national levels

Globally, ratios of estimated-to-expected female mortality rates were significantly greater than one in 1990 and 2012 for all age groups, being lowest for IMR in 1990 and highest for CMR in 1990 (Table 4.4, Table 4.6, Table 4.8, and Figure 4.4). Globally, the ratio decreased statistically significantly between 1990 and 2012 only for CMR (Table 4.6). Levels and changes differed across regions. Ratios were lowest in the Caucasus and central Asia and highest for southern Asia for all age groups in 2012 (Table 4.3, Table 4.6, and Table 4.8). The largest increase in ratios of estimated-to-expected female mortality from 1990 to 2012 was in infants in southern Asia (Table 4.3); the largest decrease was in children in northern Africa (Table 4.6).

Outlying sex ratios occur in regions with country-specific sex ratios of mortality that are higher or lower than expected based on the global relation between total mortality and sex ratios. For example, estimates for south Asia are driven by the estimates for India. Country-specific estimates of sex ratios, ratios of estimated to expected female mortality, excess mortality, and excess deaths for all age groups for all countries in 1990 and 2012 are given in Appendix 6.4. Figure 4.5 shows an overview of excess mortality for countries with outlying sex ratios, where female mortality is higher than expected for 1990, 2012, or both for infants, children, and under 5s separately. Table 4.9 gives an overview of all countries with higher-than-expected female mortality. For the IMR, 15 countries from different regions, but mostly from Asia and Africa, were identified to have excess infant female mortality in 1990. In all countries, excess mortality decreased between 1990 and 2012 but was still present in 2012 in five of these 15 countries (Bahrain, Egypt, India, Iran, and Jordan), as well as in Azerbaijan (Table 4.11). The highest excess female IMR in 2012 was in India (Table 4.11). Decreases in excess female mortality were

mostly related to decreases in overall mortality; the ratios of estimated-to-expected female mortality did not change substantially in most countries. Exceptions are India, where this ratio increased, and Serbia, where a substantial and statistically significant decrease was observed. Compared with IMR, we identified fewer countries as having outlying CMR sex ratios and excess female CMR—ten countries in 1990 (including seven countries for which the IMR was not identified as an outlier), of which three were still identified as outliers by 2012. India had the highest excess female mortality for children aged 1–4 years for 2012 (Table 4.14) and the ratio of estimated to expected female CMR increased between 1990 and 2012 (Table 4.15). Decreases in the ratio of estimated to expected female CMR were minor for most countries but notable for Bangladesh and Egypt (Table 4.15).

As a result of excess IMR, CMR, or both, 18 countries had excess female U5MR in 1990 and ten countries had excess U5MR in 2012 (Figure 4.5). Table 4.17 shows excess female U5MR and associated number of excess deaths for all countries with outlying U5MR sex ratios in 2012. India had the largest excess female U5MR, followed by Afghanistan and Pakistan (Table 4.17). The largest number of excess female deaths by far was in India (Table 4.17).

We also identified countries with outlying sex ratios and lower-than-expected female mortality (Figure 4.6 and Table 4.18). 17 countries had outlying U5MR sex ratios in 1990 and five had outlying U5MR sex ratios in 2012 (Guinea- Bissau, Kazakhstan, Mongolia, Uganda, and Uzbekistan). Table 4.16 also includes the excess U5MR and associated number of excess deaths for these five countries in 2012.

4.5.4 Validation results

Model validation exercises suggest that our model was well calibrated.

We left out all observations that were collected in or after the year 2006: 1853 observations were left out, corresponding to 18.4% of all observations. Table 4.19 summarizes the results related to the left-out observations for the validation exer-

cise. Median errors were very close to zero for left-out observations in age groups [0, 1) and [1, 5). Coverage of 90% prediction intervals was slightly higher than expected at 92% for age group [0, 1) and 94% for age group [1, 5).

Table 4.20 shows the results for the comparison between estimates obtained based on the full data set, and estimates based on the training set. Median errors and the median absolute errors were close to zero and the proportion of updated estimates that fell outside the uncertainty intervals constructed based on the training set was small.

We also verified that the global relations between total mortality and expected sex ratios and resulting country estimates were not substantially affected by outlying countries by leaving out countries with multipliers that were 10% smaller or greater than one.

	Sex ratio IMR		
	1990	2012	Change (1990–2012)
World*†	1.13 [1.11; 1.14]	1.13 [1.12; 1.15]	0.01 [-0.01; 0.02]
Developed regions	1.29 [1.28; 1.29]	1.22 [1.20; 1.24]	-0.07 [-0.08; -0.05]§
Northern Africa*†	1.12 [1.09; 1.14]	1.18 [1.15; 1.22]	0.07 [0.03; 0.10]§
Sub-Saharan Africa	1.17 [1.16; 1.19]	1.20 [1.17; 1.22]	0.03 [0.00; 0.05]§
Eastern Asia*	1.11 [1.04; 1.19]	1.15 [1.07; 1.24]	0.04 [-0.03; 0.12]
Southern Asia*†	1.07 [1.05; 1.09]	1.04 [1.01; 1.06]	-0.04 [-0.07; 0.00]§
South-eastern Asia*	1.25 [1.22; 1.28]	1.28 [1.23; 1.33]	0.03 [-0.01; 0.08]
Western Asia	1.18 [1.15; 1.21]	1.22 [1.18; 1.26]	0.04 [-0.01; 0.08]
Caucasus and Central Asia*†	1.27 [1.23; 1.33]	1.30 [1.24; 1.36]	0.02 [-0.03; 0.07]
Latin America and the Caribbean	1.23 [1.19; 1.26]	1.26 [1.23; 1.28]	0.03 [0.00; 0.06]
Oceania	1.20 [1.10; 1.30]	1.22 [1.11; 1.32]	0.02 [-0.06; 0.09]

Table 4.3 **Sex ratios for IMR, by region.** Data are ratios (90% uncertainty interval). *: Sex ratio outlying for 1990. †: Sex ratio outlying for 2012. §: Change significantly different from zero.

	Ratio of estimated-to-expected female IMR		
	1990	2012	Change (1990–2012)
World	1.05 [1.03; 1.06]‡	1.06 [1.04; 1.07]‡	0.01 [-0.01; 0.03]
Developed regions	0.97 [0.96; 0.98]‡	0.99 [0.98; 1.01]	0.03 [0.01; 0.04]§
Northern Africa	1.07 [1.05; 1.10]‡	1.06 [1.03; 1.09]‡	-0.01 [-0.05; 0.02]
Sub-Saharan Africa	1.00 [0.98; 1.01]	1.00 [0.98; 1.02]	0.00 [-0.02; 0.02]
Eastern Asia	1.10 [1.02; 1.18]‡	1.08 [1.01; 1.16]‡	-0.02 [-0.09; 0.06]
Southern Asia	1.10 [1.07; 1.12]‡	1.17 [1.14; 1.21]‡	0.08 [0.04; 0.12]§
South-eastern Asia	0.96 [0.93; 0.98]‡	0.97 [0.94; 1.01]	0.01 [-0.02; 0.05]
Western Asia	1.02 [1.00; 1.05]	1.02 [0.98; 1.06]	0.00 [-0.04; 0.03]
Caucasus and Central Asia	0.93 [0.90; 0.97]‡	0.94 [0.89; 0.99]‡	0.01 [-0.03; 0.05]
Latin America and the Caribbean	0.99 [0.96; 1.02]	0.99 [0.97; 1.02]	0.01 [-0.02; 0.03]
Oceania	1.00 [0.92; 1.09]	1.00 [0.91; 1.09]	0.00 [-0.07; 0.07]

Table 4.4 **Ratios of estimated-to-expected female IMR, by region.** Data are ratios (90% uncertainty interval). ‡: Ratio of estimated-to-expected female mortality significantly different from one. §: Change significantly different from zero.

	Sex ratio CMR		
	1990	2012	Change (1990–2012)
World*	0.91 [0.90; 0.93]	0.95 [0.93; 0.97]	0.04 [0.02; 0.06]§
Developed regions	1.25 [1.24; 1.26]	1.23 [1.21; 1.25]	-0.02 [-0.04; 0.00]
Northern Africa*	0.91 [0.89; 0.94]	1.13 [1.10; 1.16]	0.22 [0.18; 0.26]§
Sub-Saharan Africa*	1.04 [1.02; 1.06]	1.02 [1.00; 1.05]	-0.02 [-0.04; 0.01]
Eastern Asia	1.02 [0.86; 1.13]	1.14 [0.97; 1.27]	0.12 [0.05; 0.20]§
Southern Asia*†	0.75 [0.73; 0.77]	0.79 [0.76; 0.82]	0.04 [0.01; 0.07]§
South-eastern Asia	1.04 [1.01; 1.07]	1.18 [1.13; 1.24]	0.15 [0.10; 0.19]§
Western Asia	0.99 [0.95; 1.04]	1.10 [1.04; 1.17]	0.11 [0.05; 0.17]§
Caucasus and Central Asia	1.11 [1.05; 1.19]	1.21 [1.13; 1.31]	0.10 [0.03; 0.16]§
Latin America and the Caribbean	1.07 [1.03; 1.10]	1.16 [1.13; 1.19]	0.09 [0.06; 0.13]§
Oceania	1.02 [0.91; 1.14]	1.07 [0.95; 1.20]	0.05 [-0.02; 0.12]

Table 4.5 **Sex ratios for CMR, by region.** Data are ratios (90% uncertainty interval). *: Sex ratio outlying for 1990. †: Sex ratio outlying for 2012. §: Change significantly different from zero.

	Ratio of estimated-to-expected female CMR		
	1990	2012	Change (1990–2012)
World	1.11 [1.09; 1.13]‡	1.07 [1.05; 1.09]‡	-0.04 [-0.06; -0.01]§
Developed regions	0.97 [0.95; 0.98]‡	0.99 [0.97; 1.01]	0.02 [0.00; 0.04]§
Northern Africa	1.14 [1.10; 1.19]‡	1.07 [1.04; 1.10]‡	-0.07 [-0.12; -0.03]§
Sub-Saharan Africa	0.98 [0.96; 0.99]‡	0.98 [0.96; 1.01]	0.01 [-0.01; 0.03]
Eastern Asia	1.07 [0.96; 1.28]	1.06 [0.95; 1.24]	-0.01 [-0.10; 0.06]
Southern Asia	1.34 [1.30; 1.37]‡	1.38 [1.33; 1.43]‡	0.04 [-0.02; 0.10]
South-eastern Asia	0.99 [0.95; 1.02]	0.98 [0.93; 1.02]	-0.01 [-0.05; 0.03]
Western Asia	1.05 [1.00; 1.10]‡	1.03 [0.97; 1.09]	-0.02 [-0.08; 0.04]
Caucasus and Central Asia	0.95 [0.88; 1.01]	0.94 [0.85; 1.01]	-0.01 [-0.08; 0.05]
Latin America and the Caribbean	1.01 [0.97; 1.05]	1.01 [0.98; 1.03]	0.00 [-0.04; 0.03]
Oceania	1.00 [0.90; 1.13]	1.00 [0.88; 1.14]	0.00 [-0.09; 0.09]

Table 4.6 **Ratios of estimated-to-expected female CMR, by region.** Data are ratios (90% uncertainty interval). ‡: Ratio of estimated-to-expected female mortality significantly different from one. §: Change significantly different from zero.

	Sex ratio U5MR		
	1990	2012	Change (1990–2012)
World*†	1.05 [1.04; 1.06]	1.08 [1.07; 1.09]	0.02 [0.01; 0.04]§
Developed regions	1.28 [1.28; 1.29]	1.22 [1.21; 1.24]	-0.06 [-0.07; -0.04]§
Northern Africa*†	1.07 [1.05; 1.09]	1.18 [1.15; 1.20]	0.11 [0.08; 0.14]§
Sub-Saharan Africa*	1.11 [1.10; 1.12]	1.13 [1.11; 1.14]	0.02 [0.00; 0.04]§
Eastern Asia*	1.09 [1.03; 1.15]	1.15 [1.08; 1.22]	0.06 [0.00; 0.13]
Southern Asia*†	0.97 [0.95; 0.98]	0.98 [0.96; 1.00]	0.01 [-0.01; 0.04]
South-eastern Asia*	1.18 [1.16; 1.21]	1.26 [1.22; 1.30]	0.08 [0.04; 0.11]
Western Asia*	1.13 [1.10; 1.15]	1.19 [1.16; 1.23]	0.06 [0.03; 0.10]§
Caucasus and Central Asia*†	1.24 [1.21; 1.28]	1.28 [1.23; 1.34]	0.04 [0.00; 0.08]§
Latin America and the Caribbean	1.19 [1.16; 1.22]	1.24 [1.22; 1.26]	0.05 [0.02; 0.08]§
Oceania	1.14 [1.07; 1.23]	1.18 [1.09; 1.27]	0.03 [-0.03; 0.09]

Table 4.7 **Sex ratios for U5MR, by region.** Data are ratios (90% uncertainty interval). *: Sex ratio outlying for 1990. †: Sex ratio outlying for 2012. §: Change significantly different from zero.

	Ratio of estimated-to-expected female U5MR		
	1990	2012	Change (1990–2012)
World*†	1.06 [1.05; 1.08]‡	1.06 [1.05; 1.07]‡	-0.01 [-0.02; 0.01]
Developed regions	0.97 [0.96; 0.98]‡	0.99 [0.98; 1.01]	0.03 [0.01; 0.04]§
Northern Africa*†	1.09 [1.07; 1.11]‡	1.06 [1.04; 1.09]‡	-0.03 [-0.06; 0.00]
Sub-Saharan Africa*	0.99 [0.98; 1.00]‡	0.99 [0.98; 1.01]	0.00 [-0.01; 0.02]
Eastern Asia*	1.09 [1.03; 1.16]‡	1.08 [1.02; 1.15]‡	-0.01 [-0.08; 0.05]
Southern Asia*†	1.16 [1.14; 1.18]‡	1.21 [1.19; 1.24]‡	0.05 [0.02; 0.09]§
South-eastern Asia*	0.97 [0.95; 0.99]‡	0.97 [0.94; 1.00]	0.00 [-0.02; 0.03]
Western Asia*	1.03 [1.01; 1.06]‡	1.02 [0.99; 1.05]	-0.01 [-0.04; 0.02]
Caucasus and Central Asia*†	0.94 [0.91; 0.97]‡	0.94 [0.90; 0.98]‡	0.00 [-0.03; 0.04]
Latin America and the Caribbean	0.99 [0.97; 1.02]	1.00 [0.98; 1.02]	0.00 [-0.02; 0.03]
Oceania	1.00 [0.93; 1.07]	1.00 [0.92; 1.08]	0.00 [-0.06; 0.06]

Table 4.8 **Ratios of estimated-to-expected female U5MR, by region.** Data are ratios (90% uncertainty interval). ‡: Ratio of estimated-to-expected female mortality significantly different from one. §: Change significantly different from zero.

Country	IMR	CMR	U5MR
Afghanistan			*†
Azerbaijan	†		
Bahamas	*		*
Baharain	*†		*†
Bangladesh		*	*†
China	*		*†
Egypt	*†	*	*†
India	*†	*†	*†
Iran	*†	*	*†
Jordan	*†		*†
Lebanon	*		*
Macedonia	*		*
Malawi	*		
Montenegro	*		*
Morocco		*	
Mozambique	*		
Nepal		*†	*†
Niger		*	*
Pakistan		*†	*†
Serbia	*		*
Sri Lanka			*
Palestine	*		*
Tanzania	*		
Tunisia		*	
Yemen		*	

Table 4.9 **Countries with higher-than-expected female mortality for 1990 or 2012, by age group.** *: Sex ratio outlying for 1990. †: Sex ratio outlying for 2012. Countries are ordered alphabetically.

Country	Sex ratio IMR		
	1990	2012	Change 1990–2012
Azerbaijan*	1.18 [1.11; 1.25]	1.15 [1.07; 1.23]	-0.03 [-0.11; 0.05]
Bahamas†	1.16 [1.10; 1.23]	1.17 [1.08; 1.26]	0.00 [-0.08; 0.09]
Bahrain†*	1.05 [0.99; 1.10]	1.05 [0.97; 1.13]	0.00 [-0.07; 0.08]
China†	1.11 [1.03; 1.19]	1.15 [1.06; 1.23]	0.04 [-0.04; 0.12]
Egypt†*	1.06 [1.02; 1.10]	1.10 [1.08; 1.13]	0.04 [0.00; 0.09]
India†*	1.05 [1.02; 1.08]	0.98 [0.95; 1.01]	-0.07 [-0.11; -0.03]§
Iran†*	1.08 [1.02; 1.14]	1.13 [1.05; 1.21]	0.05 [-0.03; 0.13]
Jordan†*	1.10 [1.03; 1.17]	1.12 [1.02; 1.22]	0.02 [-0.06; 0.11]
Lebanon†	1.09 [0.99; 1.18]	1.09 [0.97; 1.19]	0.00 [-0.08; 0.08]
Macedonia†	1.11 [1.08; 1.15]	1.14 [1.08; 1.21]	0.03 [-0.04; 0.10]
Malawi†	1.11 [1.07; 1.15]	1.20 [1.13; 1.27]	0.09 [0.01; 0.16]§
Montenegro†	1.14 [1.07; 1.21]	1.13 [1.05; 1.22]	-0.01 [-0.09; 0.07]
Mozambique†	1.10 [1.05; 1.15]	1.14 [1.08; 1.21]	0.04 [-0.03; 0.12]
Serbia†	1.14 [1.12; 1.17]	1.24 [1.18; 1.30]	0.10 [0.04; 0.16]§
Palestine†	1.13 [1.05; 1.20]	1.17 [1.08; 1.26]	0.04 [-0.04; 0.13]
Tanzania†	1.11 [1.06; 1.15]	1.17 [1.09; 1.25]	0.06 [-0.02; 0.14]

Table 4.10 **Sex ratios for IMR, for countries with outlying sex ratios and higher-than-expected female IMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990. §: Change significantly different from zero.

Country	Excess female IMR (per 1000 livebirths)	
	1990	2012
Azerbaijan*	0.2 [-3.8; 4.2]	2.1 [0.2; 4.2]
Bahamas†	1.4 [0.4; 2.5]	0.9 [-0.1; 1.9]
Bahrain†*	3.2 [2.3; 4.2]	1.1 [0.6; 1.8]
China†	3.6 [0.8; 6.6]	0.9 [0.1; 1.7]
Egypt†*	6.9 [4.9; 9.0]	2.1 [1.7; 2.6]
India†*	9.4 [7.0; 11.7]	8.8 [7.4; 10.4]
Iran†*	5.0 [2.8; 7.3]	1.4 [0.5; 2.5]
Jordan†*	3.5 [1.8; 5.3]	1.6 [0.4; 3.1]
Lebanon†	3.4 [1.5; 5.9]	0.8 [0.1; 2.1]
Macedonia†	3.3 [2.3; 4.3]	0.4 [0.0; 0.7]
Malawi†	5.2 [0.0; 10.5]	0.6 [-2.1; 3.1]
Montenegro†	1.3 [0.5; 2.2]	0.3 [0.0; 0.7]
Mozambique†	6.8 [0.5; 13.1]	2.5 [-0.9; 5.9]
Serbia†	2.0 [1.5; 2.5]	-0.1 [-0.4; 0.1]
Palestine†	3.0 [0.8; 5.3]	1.2 [0.0; 2.7]
Tanzania†	5.2 [1.0; 9.4]	1.8 [-0.5; 4.2]

Table 4.11 **Excess female IMR, for countries with outlying sex ratios and higher-than-expected female IMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990.

Country	Ratio of estimated-to-expected female IMR		
	1990	2012	Change 1990–2012
Azerbaijan*	1.00 [0.95; 1.06]	1.08 [1.01; 1.16]‡	0.08 [0.00; 0.16]§
Bahamas†	1.08 [1.02; 1.15]‡	1.07 [1.00; 1.16]	-0.01 [-0.08; 0.07]
Bahrain†*	1.20 [1.14; 1.27]‡	1.17 [1.08; 1.26]‡	-0.04 [-0.11; 0.04]
China†	1.10 [1.02; 1.19]‡	1.09 [1.01; 1.17]‡	-0.01 [-0.09; 0.06]
Egypt†*	1.13 [1.09; 1.17]‡	1.14 [1.12; 1.17]‡	0.02 [-0.03; 0.06]
India†*	1.12 [1.09; 1.16]‡	1.25 [1.21; 1.29]‡	0.13 [0.07; 0.18]§
Iran†*	1.14 [1.07; 1.20]‡	1.11 [1.04; 1.20]‡	-0.02 [-0.10; 0.06]
Jordan†*	1.14 [1.07; 1.22]‡	1.12 [1.03; 1.23]‡	-0.02 [-0.10; 0.07]
Lebanon†	1.15 [1.06; 1.27]‡	1.13 [1.02; 1.27]‡	-0.02 [-0.11; 0.06]
Macedonia†	1.12 [1.08; 1.16]‡	1.06 [1.00; 1.12]‡	-0.06 [-0.12; 0.01]
Malawi†	1.04 [1.00; 1.08]‡	1.02 [0.95; 1.08]	-0.02 [-0.09; 0.05]
Montenegro†	1.10 [1.04; 1.17]‡	1.06 [0.99; 1.15]	-0.04 [-0.11; 0.04]
Mozambique†	1.05 [1.00; 1.09]‡	1.04 [0.98; 1.11]	0.00 [-0.07; 0.07]
Serbia†	1.10 [1.07; 1.13]‡	0.97 [0.93; 1.02]	-0.13 [-0.18; -0.07]§
Palestine†	1.10 [1.03; 1.19]‡	1.08 [1.00; 1.17]	-0.03 [-0.11; 0.05]
Tanzania†	1.06 [1.01; 1.11]‡	1.05 [0.99; 1.13]	0.00 [-0.07; 0.07]

Table 4.12 **Ratios of estimated-to-expected female IMR, for countries with outlying sex ratios and higher-than-expected female IMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990. ‡: Ratio of estimated-to-expected female mortality is significantly different from one. §: Change significantly different from zero.

Country	Sex ratio CMR		
	1990	2012	Change 1990–2012
Bangladesh†	0.85 [0.82; 0.89]	1.04 [0.98; 1.11]	0.19 [0.13; 0.26]§
Egypt†	0.86 [0.82; 0.90]	1.12 [1.09; 1.15]	0.26 [0.21; 0.30]§
India†*	0.72 [0.69; 0.74]	0.74 [0.70; 0.77]	0.02 [-0.02; 0.06]
Iran†	0.89 [0.81; 0.97]	1.01 [0.91; 1.12]	0.12 [0.05; 0.20]§
Morocco†	0.96 [0.90; 1.03]	1.12 [1.03; 1.22]	0.16 [0.09; 0.24]§
Nepal†*	0.81 [0.76; 0.86]	0.95 [0.87; 1.04]	0.14 [0.08; 0.21]§
Niger†	0.98 [0.94; 1.01]	0.97 [0.90; 1.04]	-0.01 [-0.07; 0.06]
Pakistan†*	0.80 [0.76; 0.85]	0.87 [0.81; 0.94]	0.07 [0.01; 0.13]§
Tunisia†	0.97 [0.86; 1.07]	1.07 [0.93; 1.19]	0.10 [0.02; 0.18]§
Yemen†	0.93 [0.87; 0.99]	1.01 [0.92; 1.09]	0.08 [0.01; 0.15]§

Table 4.13 **Sex ratios for CMR, for countries with outlying sex ratios and higher-than-expected female CMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990. §: Change significantly different from zero.

Country	Excess female CMR (per 1000 livebirths)	
	1990	2012
Bangladesh†	7.7 [5.7; 9.8]	0.7 [0.2; 1.2]
Egypt†	4.1 [3.0; 5.3]	0.2 [0.1; 0.3]
India†*	13.6 [12.1; 15.1]	5.0 [4.3; 5.9]
Iran†	2.5 [1.4; 3.7]	0.4 [0.2; 0.7]
Morocco†	1.5 [0.3; 2.7]	0.3 [0.0; 0.7]
Nepal†*	9.9 [6.8; 13.3]	1.4 [0.7; 2.3]
Niger†	9.3 [0.3; 18.4]	1.6 [-2.0; 5.7]
Pakistan†*	8.0 [6.0; 10.0]	3.3 [1.8; 4.8]
Tunisia†	1.4 [0.2; 2.8]	0.3 [0.0; 0.6]
Yemen†	2.9 [0.3; 5.6]	0.8 [-0.7; 2.1]

Table 4.14 **Excess female CMR, for countries with outlying sex ratios and higher-than-expected female CMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990.

Country	Ratio of estimated-to-expected female CMR		
	1990	2012	Change 1990–2012
Bangladesh†	1.17 [1.12; 1.22]‡	1.10 [1.03; 1.17]‡	-0.07 [-0.15; 0.00]
Egypt†	1.19 [1.13; 1.25]‡	1.08 [1.05; 1.12]‡	-0.10 [-0.17; -0.05]§
India†*	1.40 [1.35; 1.45]‡	1.50 [1.42; 1.58]‡	0.10 [0.02; 0.19]§
Iran†	1.23 [1.12; 1.35]‡	1.20 [1.08; 1.34]‡	-0.03 [-0.12; 0.06]
Morocco†	1.09 [1.02; 1.17]‡	1.08 [0.99; 1.18]	-0.01 [-0.09; 0.07]
Nepal†*	1.23 [1.15; 1.31]‡	1.21 [1.08; 1.34]‡	-0.02 [-0.13; 0.08]
Niger†	1.04 [1.00; 1.09]‡	1.03 [0.96; 1.10]	-0.01 [-0.08; 0.06]
Pakistan†*	1.25 [1.18; 1.32]‡	1.21 [1.11; 1.32]‡	-0.04 [-0.13; 0.06]
Tunisia†	1.14 [1.02; 1.30]‡	1.14 [1.02; 1.31]‡	0.00 [-0.09; 0.09]
Yemen†	1.07 [1.01; 1.15]‡	1.06 [0.96; 1.19]	-0.01 [-0.10; 0.10]

Table 4.15 **Ratios of estimated-to-expected female CMR, for countries with outlying sex ratios and higher-than-expected female CMR in 1990 or 2012.** Data are estimates (90% uncertainty interval). *: Sex ratio outlying for 2012. †: Sex ratio outlying for 1990. ‡: Ratio of estimated-to-expected female mortality is significantly different from one. §: Change significantly different from zero.

Country	Sex ratio U5MR	Ratio of estimated-to-expected female U5MR
Afghanistan	1.07 [1.02; 1.12]	1.06 [1.01; 1.11]
Bahrain	1.07 [1.00; 1.15]	1.14 [1.07; 1.22]
Bangladesh	1.15 [1.10; 1.20]	1.06 [1.01; 1.11]
China	1.15 [1.07; 1.22]	1.08 [1.02; 1.16]
Egypt	1.10 [1.08; 1.12]	1.13 [1.11; 1.16]
Guinea-Bissau	1.16 [1.11; 1.22]	0.95 [0.90; 1.00]
India	0.92 [0.90; 0.95]	1.30 [1.26; 1.34]
Iran	1.11 [1.04; 1.18]	1.13 [1.06; 1.20]
Jordan	1.12 [1.03; 1.20]	1.12 [1.04; 1.21]
Kazakhstan	1.36 [1.26; 1.47]	0.92 [0.85; 0.99]
Mongolia	1.48 [1.36; 1.62]	0.84 [0.77; 0.92]
Nepal	1.13 [1.07; 1.19]	1.08 [1.02; 1.15]
Pakistan	1.09 [1.04; 1.15]	1.06 [1.01; 1.12]
Uganda	1.20 [1.15; 1.26]	0.94 [0.90; 0.99]
Uzbekistan	1.33 [1.23; 1.44]	0.92 [0.84; 1.00]

Table 4.16 **Sex ratios for U5MR in countries with outlying sex ratios in 2012.** Data are estimates (90% uncertainty interval). Countries are ordered alphabetically. All countries in this table also have outlying sex ratios in 1990.

Country	Excess female U5MR (per 1000 livebirths)	Number of excess female U5MR	Ratio of excess female deaths to total deaths (%)
Afghanistan	5.2 [0.6; 9.9]	2,810 [330; 5,390]	2.7
Bahrain	1.1 [0.6; 1.8]	11 [6; 18]	5.9
Bangladesh	2.1 [0.5; 3.8]	3,330 [790; 5,880]	2.6
China	1.0 [0.3; 1.9]	8,690 [2,330; 16,100]	3.3
Egypt	2.4 [1.9; 2.8]	2,250 [1,860; 2,660]	5.6
Guinea-Bissau	-6.5 [-14.2; -0.4]	-203 [-450; -10]	-2.6
India	13.5 [11.9; 15.4]	166,000 [144,000; 190,000]	11.7
Iran	1.8 [0.8; 3.0]	1,340 [590; 2,190]	5.2
Jordan	1.9 [0.7; 3.4]	188 [63; 333]	5.0
Kazakhstan	-1.3 [-2.6; -0.1]	-217 [-442; -22]	-3.4
Mongolia	-4.1 [-7.4; -1.9]	-137 [-248; -61]	-7.6
Nepal	2.9 [0.7; 5.2]	852 [227; 1,520]	3.5
Pakistan	4.7 [0.5; 8.9]	11,100 [1,000; 21,400]	2.7
Uganda	-3.8 [-7.8; -0.5]	-2,820 [-5,880; -290]	-2.7
Uzbekistan	-2.7 [-8.8; 0.0]	-872 [-2,850; -11]	-3.5

Table 4.17 **Excess female U5MR, and related outcomes for under 5s in countries with outlying sex ratios in 2012.** Data are estimates (90% uncertainty interval). Countries are ordered alphabetically. All countries in this table also have outlying sex ratios in 1990.

Country	IMR	CMR	U5MR
Azerbaijan		*	
Belarus			*
Cote d'Ivoire		*	*
Eritrea		*	*
Ethiopia	*		*
Guinea-Bissau			*†
Guyana	*		*
Kazakhstan	*†		*†
Mauritania	*		*
Mongolia	*†		*†
Philippines	*		*
Russian Federation	*		*
Rwanda		*	
Tanzania		*	
Thailand	*		*
Turkmenistan	*		*
Uganda		*†	*†
Ukraine	*		*
Uzbekistan	*		*†
Vietnam			*

Table 4.18 **Countries with lower-than-expected female mortality for 1990 or 2012, by age group.** * : Sex ratio outlying in 1990. †: Sex ratio outlying in 2012. Countries are ordered alphabetically.

Age group	**[0, 1)**	**[1, 5)**
Median error	-0.00	-0.00
Median absolute error	0.10	0.16
% of left-out obs. below 90% PI	4.4	3.2
% of left-out obs. above 90% PI	3.6	2.9
Expected proportions (%)	**5**	**5**

Table 4.19 **Validation results for left-out observations by age group.** Errors are defined as the difference between a left-out observation and the posterior median of its predictive distribution. PI=prediction interval. Obs.=observations.

Age group	**[0, 1)**		**[1, 5)**		**[0, 5)**	
Year	**2000**	**2005**	**2000**	**2005**	**2000**	**2005**
Median error	-0.00	-0.00	0.00	0.00	-0.00	-0.00
Median absolute error	0.01	0.01	0.01	0.01	0.01	0.01
Below 90% UI (%)	0.0	0.0	0.0	0.0	0.0	0.0
Above 90% UI (%)	2.1	1.0	0.5	0.5	2.1	1.5
Expected proportions (%)	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**

Table 4.20 **Summary of differences in sex ratio estimates in observation years 2000 and 2005 based on training set and full data set.** Errors are defined as the differences between estimates based on the full dataset and the training set. The proportions refer to the proportions (%) of countries in which the median sex ratio estimates based on the full data set fall below or above their corresponding 90% uncertainty intervals (UIs) based on the training dataset. The results are broken down by age groups and observation years.

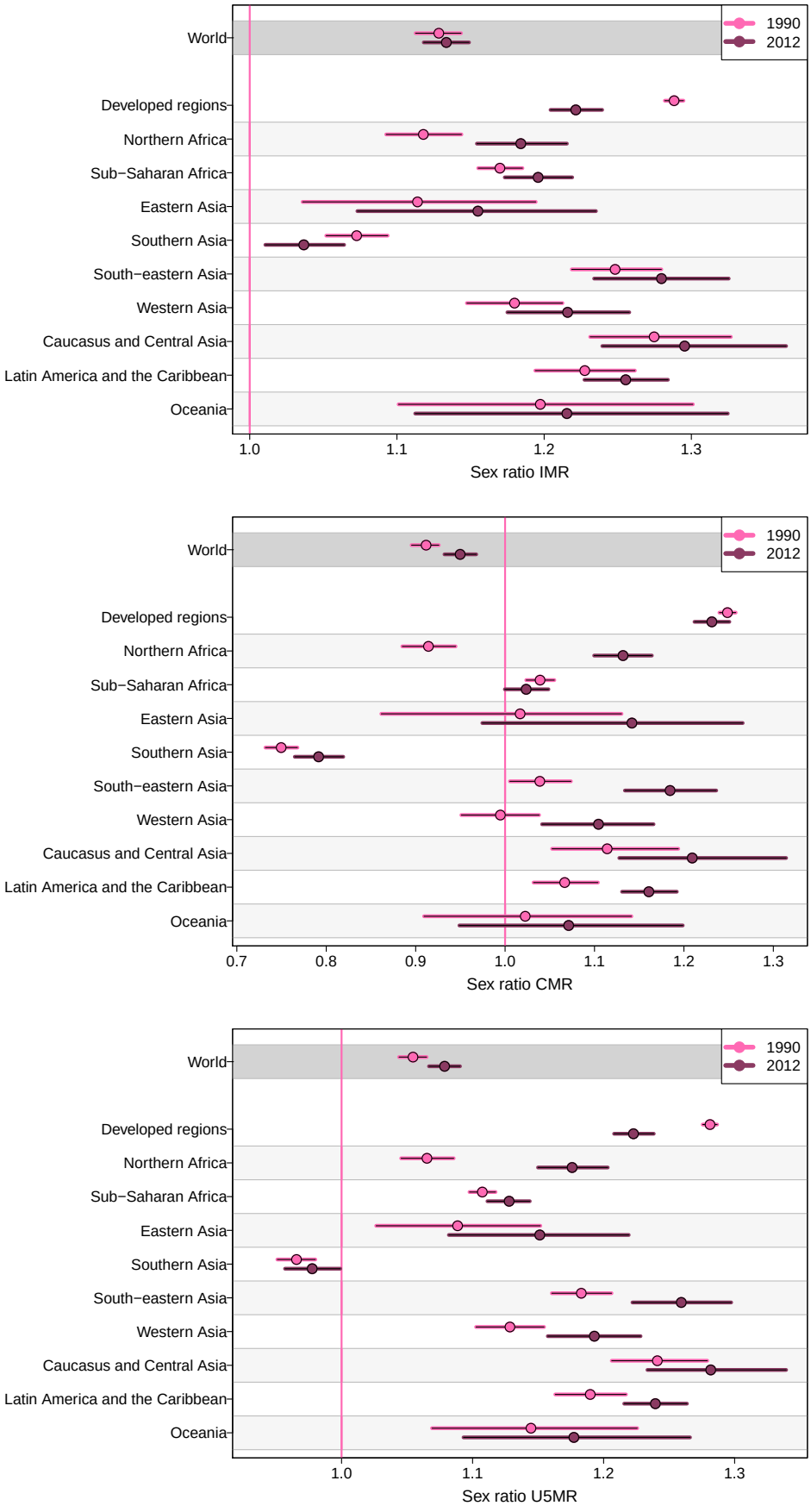

Fig. 4.2 **Sex ratios by age group, year, and regions.** Error bars are 90% uncertainty intervals. IMR=infant mortality rate; CMR=child mortality rate; U5MR=under-5 mortality rate.

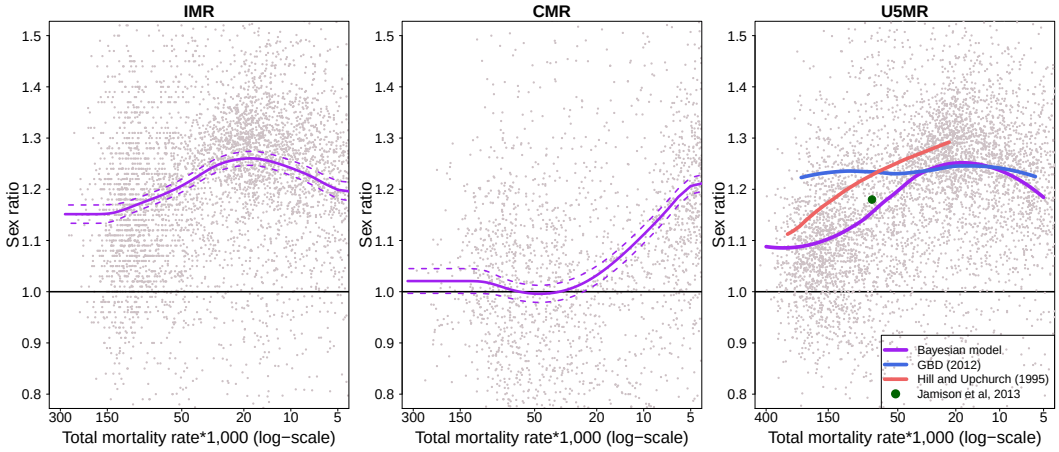

Fig. 4.3 **Overview of the global relation between sex ratios and total mortality levels.** Sex ratios are plotted against decreasing total mortality (grey dots) and the estimated global relation between expected sex ratios and total mortality for the infant mortality rate (A) and child mortality rate (B) are shown in purple. Shaded areas are 90% uncertainty intervals. For under-5 mortality (C), the purple line shows the relation between sex ratios and total mortality based on the relations for IMR and CMR for all included country-years, blue curve is from [134], red curve is from [135], and green dot is from [147].

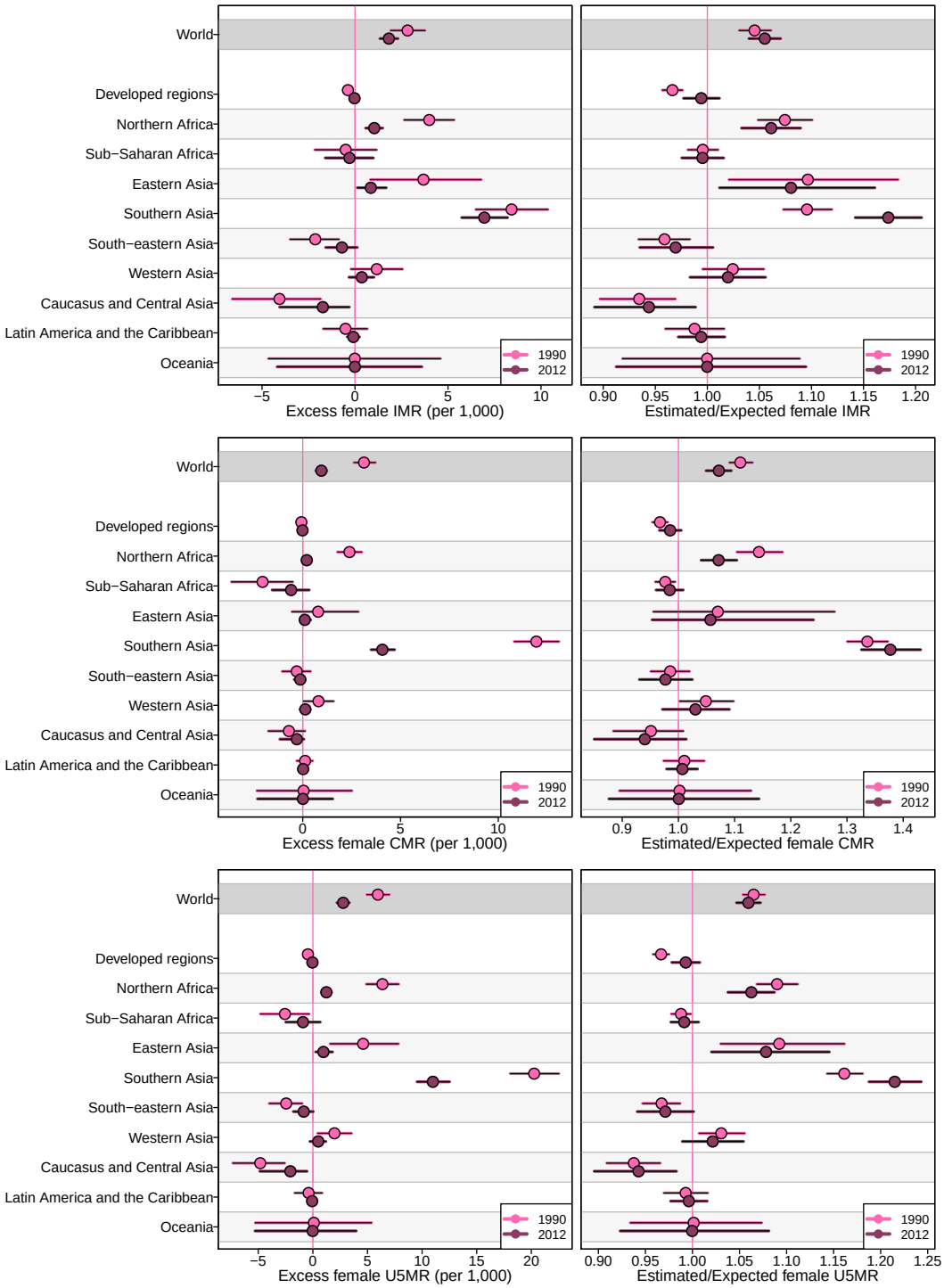

Fig. 4.4 **Overview of excess female mortality (left) and the ratio of estimated-to-expected mortality (right) for the world and MDG regions in 1990 and 2012, for IMR, CMR, and U5MR respectively.** Error bars are 90% uncertainty intervals. IMR=infant mortality rate. CMR=child mortality rate. U5MR=under-5 mortality rate.

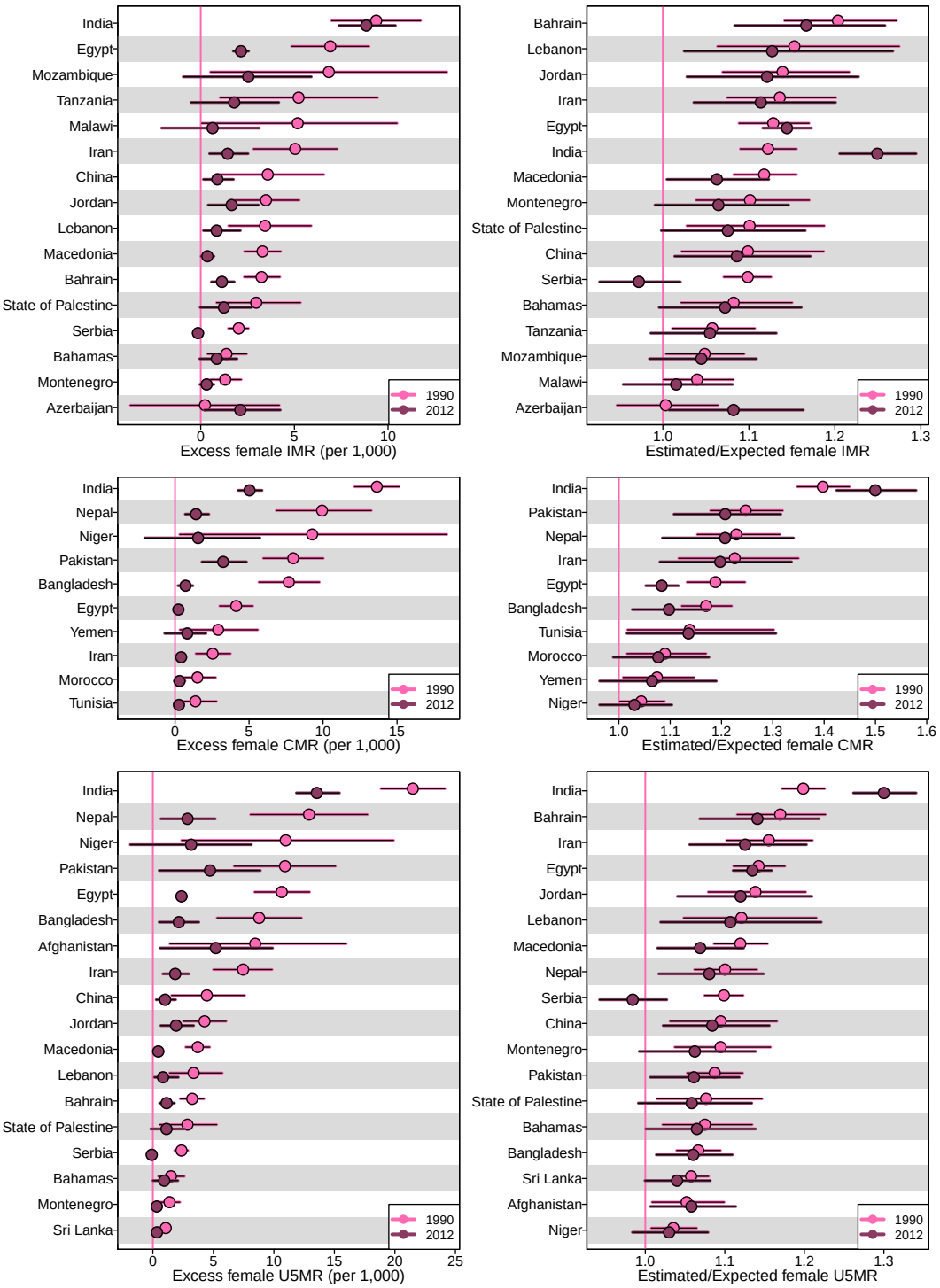

Fig. 4.5 **Overview of excess female mortality (left) and the ratio of estimated-to-expected female mortality (right) for countries with outlying sex ratios and higher-than-expected female mortality in 1990 or 2012.** Countries are ordered by decreasing point estimates for the year 1990. Error bars are 90% uncertainty intervals. IMR=infant mortality rate. CMR=child mortality rate. U5MR=under-5 mortality rate.

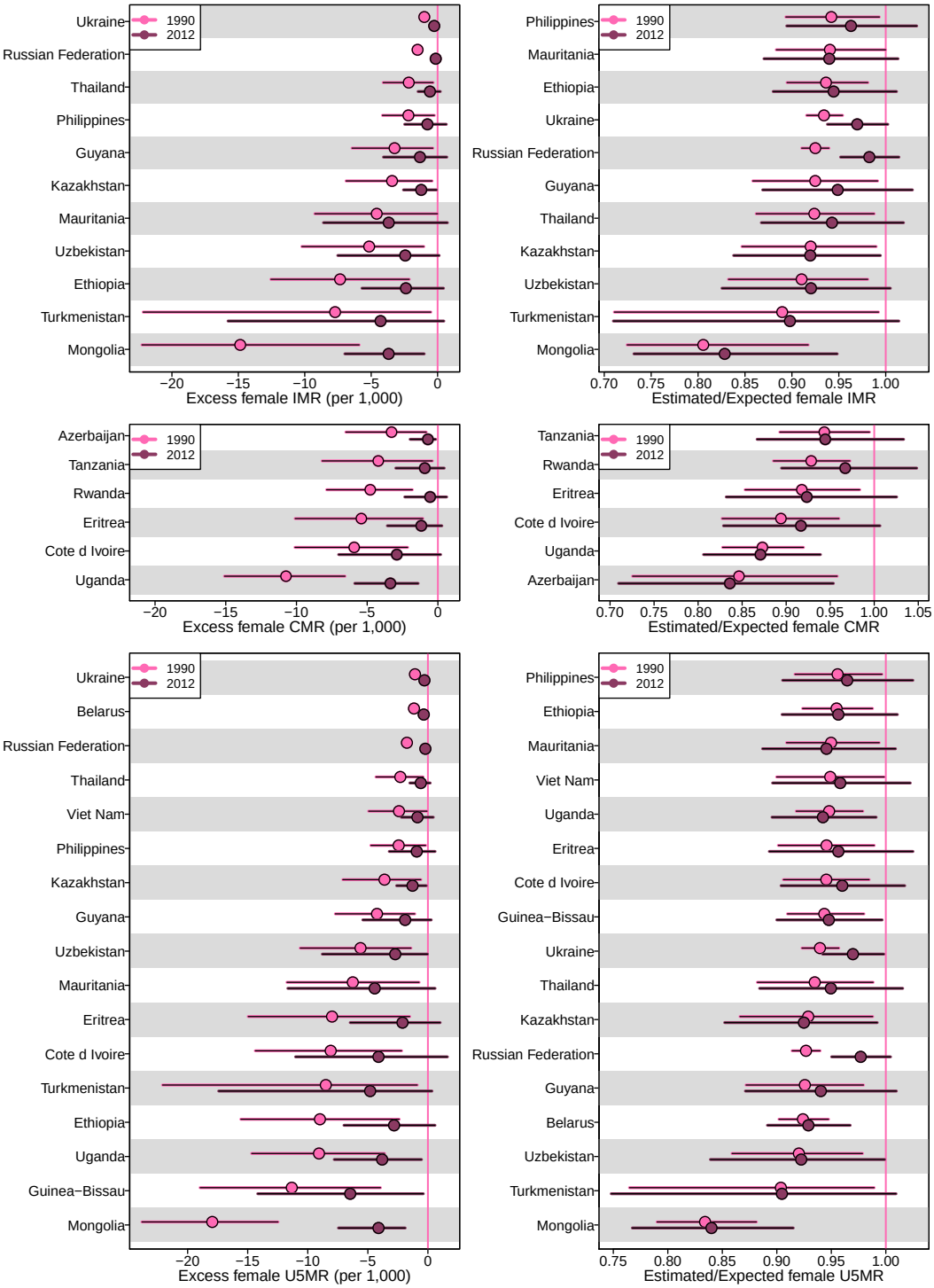

Fig. 4.6 **Overview of excess female mortality (left) and the ratio of estimated-to-expected female mortality (right) for countries with outlying sex ratios and lower-than-expected female mortality in 1990 or 2012.** Countries are ordered by decreasing point estimates for the year 1990. Error bars are 90% uncertainty intervals. IMR=infant mortality rate. CMR=child mortality rate. U5MR=under-5 mortality rate.

4.6 Discussion

We know of no other study to assess the relation between sex ratios and overall mortality levels using data from all countries, while accounting for data quality issues and countries with outlying levels. Our findings suggest that sex ratios are expected to be greater than one for high levels of total infant mortality but around one for high levels of total child mortality. Both ratios increase as total mortality decreases but there is evidence that the IMR sex ratio decreases again at very low total IMR, consistent with previous findings for some high-income countries [113]. The findings reconfirm the previous study [113] that at the early stage of improvement of basic health care condition (i.e. when the national mortality initially decreases from a high level), the cause of deaths for infants and children shifts from infectious diseases to the complications of childbirth and prematurity. When the medical and health care conditions further improve (i.e. the national mortality further declines to a very low level), a greater reduction in male mortality for infants can be attributed to improved obstetric practices and neonatal care. Our estimated global relation between sex ratios and total mortality differs from the one constructed by Hill and Upchurch in 1995, which was based on life tables from 1820 to 1964 from northwestern Europe (Figure 4.3) [135]. Although findings from both studies suggest that sex ratios tend to increase as overall mortality decreases, the Hill and Upchurch estimates for sex ratios are greater than those estimated by our model, referred to hereon in as the Bayesian model. The difference between the Hill-Upchurch curve and the Bayesian model might be explained by the use of a more recent and comprehensive dataset that captures data since 1950. More generally, whereas Hill and Upchurch included data for only five selected countries where they judged treatment of male and female infants to be equal and unchanging over time, to establish a so-called discrimination-free standard, we elected to avoid such an a-priori judgment on discrimination by comparing countries to the global pattern. In another study [147], the expected sex ratio for U5MR for India in 2005 was estimated at 1.18 based on the average value from a set of DHS surveys from low-income and

middle-income countries in 2011, which gives an expected value more comparable to our estimate for the expected sex ratio for India in 2005 than the Hill-Upchurch one. Finally, findings from a previous global study also suggested lower average sex ratios at given levels of mortality than depicted by the Hill-Upchurch curve [135]. There is evidence that vaccination against diphtheria, pertussis, and tetanus is related to decreased sex ratios of mortality in high-mortality countries, which might to some degree account for the lower sex ratios seen in contemporary high-mortality countries compared with the historical experience of western countries [148]; different prevailing patterns of infectious disease morbidity and mortality might also play a role [112].

Important differences exist between our findings and those of the Global Burden of Disease (GBD) 2010 study [134]. We inferred a relation between estimated sex ratios and total U5MR for the GBD study by fitting a Loess smoother to its U5MR and sex ratio estimates, which were published for the years 1970, 1980, 1990, 2000, and 2010. The resulting relation differs from both our global relation as well as the Hill-Upchurch relation because it does not suggest a change in sex ratios with decreasing mortality, which contradicts findings from previous studies [113–115]. Important differences also exist between our country-specific sex ratio estimates and those published in the GBD 2010 study. Figure 4.7 gives an overview of the differences between sex ratio estimates from our model (here referred to as UN IGME estimates) to estimates from the GBD 2010 study [134]. GBD point estimates for U5MR sex ratios were obtained from sex-specific U5MR estimates. Uncertainty intervals could not be constructed from the published estimates. Figure 4.7 shows that GBD estimates tend to be higher than UN IGME estimates.

Figure 4.8 shows estimates for those countries with absolute differences greater than 0.15 in the year 2010 (five countries in total). Figure 4.9 shows country estimates for India and Jordan, where the estimates are in disagreement as to whether the sex ratio in 2010 was greater or smaller than one. To be specific, the GBD study estimates the sex ratio for U5MR for India for 2010 to be 1.05, which is much

higher than our estimate of 0.91. It is not clear to us from the GBD's methodological explanations how such high estimates could be obtained for India in particular, in view of the fact that the vast majority of observed sex ratios from various studies are below one.

We used the estimated global relation between total mortality and sex ratios to calculate excess female mortality and to assess which countries have unusually high or low sex ratios compared with the global standard. Whereas excess female mortality has decreased in most countries with outlying sex ratios, the ratios of estimated-to-expected female mortality did not change much. Exceptions were Serbia, where we saw decreases in the ratio for the IMR, Egypt and Bangladesh, where we saw decreases in the ratio for the CMR, and India, where ratios of estimated-to- expected female mortality increased significantly for all age groups. Further investigation is needed to better understand what causes the outlying levels and trends. Although for India and a few other countries, findings from previous studies have suggested male preference [116–131], and pinpointed to causes of outlying levels such as male preference in the provision of vaccinations [149], information about factors that might have caused outlying sex ratios in other countries is very scarce. Explanations could include biological factors–eg, an unusual cause of death distribution in the country as compared with other countries with similar levels of mortality. However, detailed data for causes of death needed to assess this explanation are absent for most developing countries. We hope that the identification of country-years with outlying sex ratios will generate additional research on this important topic.

Although we feel our study improves on previous studies by accounting for data quality issues, in particular, by down-weighting observations that are deemed less informative of true sex ratios, additional data quality issues (eg, in the under-reporting of birth or deaths or changes in the definitions of livebirths) might also affect estimates of sex ratios of mortality. Also, country-years with outlying sex ratios might go unnoticed in countries with scarce data because of the large uncer-

tainty surrounding the estimates in these countries. Finally, sex-selective abortion is a related issue affecting several of the countries that have outlying sex ratios of mortality, but is beyond the scope of this study. For a complete assessment of skewed under-5 population sex ratios in countries where sex discrimination might be present, sex-selective distortions of sex ratios at birth need to be taken into account as well [43]. Further analysis, focusing on a comprehensive assessment of under-5 sex ratios in the population could provide more insights into such issues.

This study provides a response to the call for disaggregation of under-5 mortality rates by sex from international monitoring initiatives [150, 151]. The country-specific annual estimates and projections of sex ratios, the assessment of excess female mortality and deaths, as well as the degree of uncertainty around them, provide the global health and development community a new platform for monitoring sex equity and evidence-based policy making and programming.

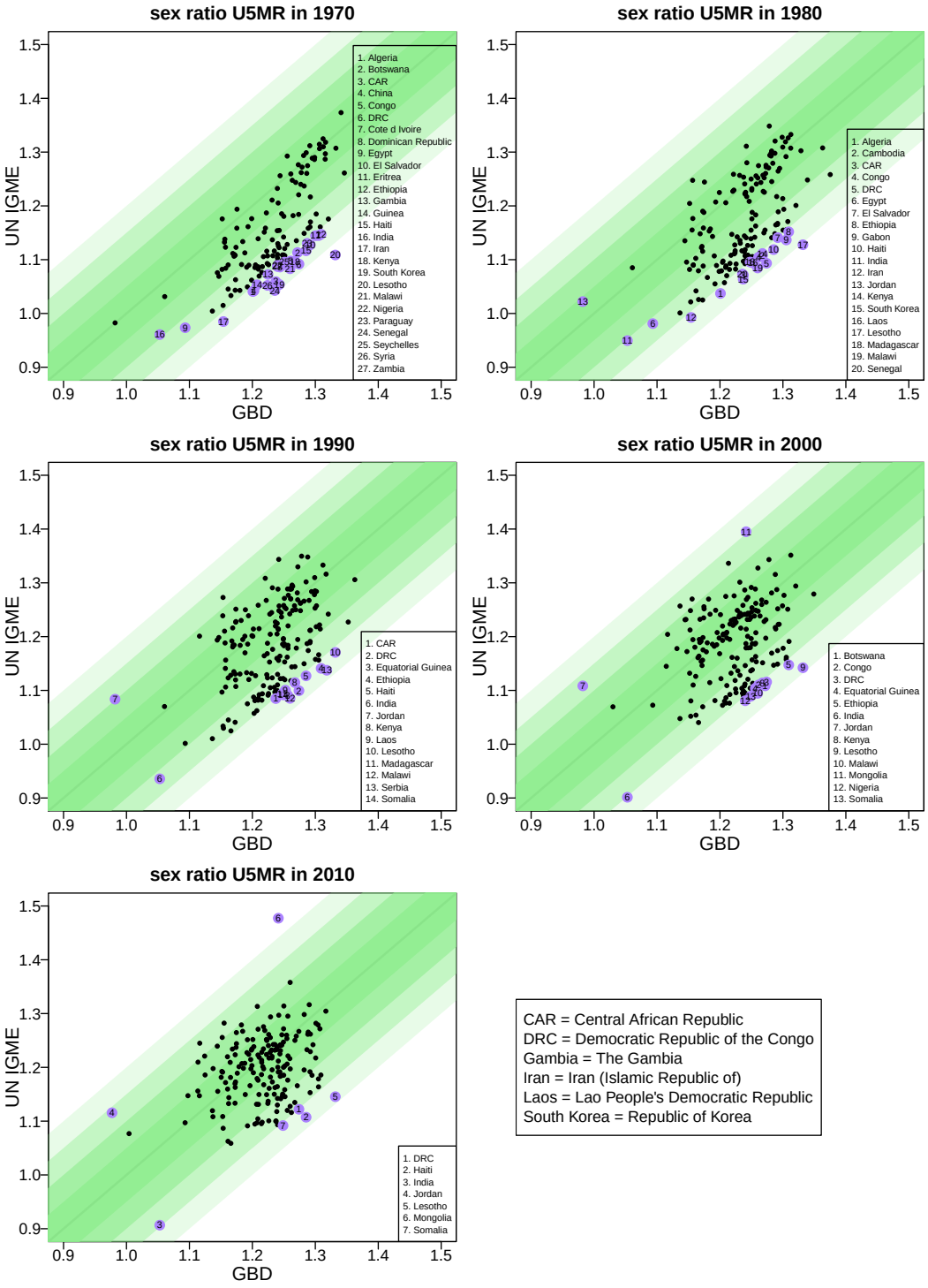

Fig. 4.7 **Comparison of UN IGME and GBD sex ratio estimates for 1970, 1980, 1990, 2000, and 2010.** UN IGME estimates are plotted against GBD estimates. Green shades from dark to light refer to absolute differences of up to 0.05, 0.10, 0.15, and 0.20 respectively. Two types of estimates are highlighted in purple: (1) Estimates with absolute differences that are greater than 0.15; (2) Estimates where the GBD sex ratios is below one while the UN IGME estimate is above one, or vice versa. The highlighted countries are listed in the legend of each plot in short form. The full country names (if available) are listed in the right bottom of the plot.

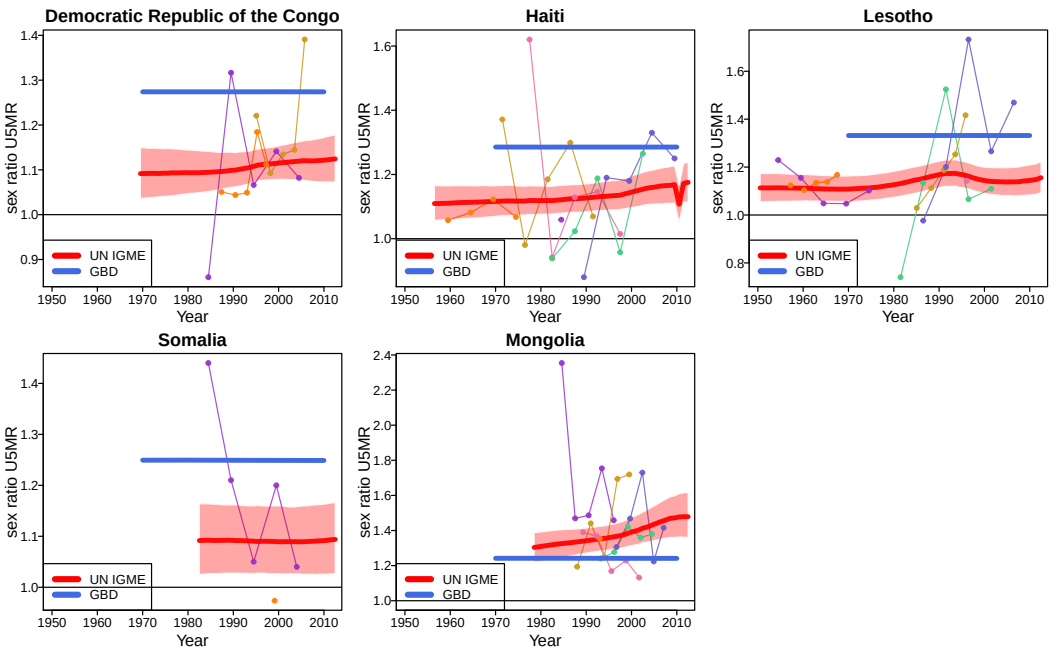

Fig. 4.8 **UN IGME and GBD sex ratio estimates for U5MR for Democratic Republic of the Congo, Haiti, Lesotho, Somalia, and Mongolia.** Selected countries are those with absolute differences between UN IGME and GBD estimates at 0.15 and above in 2010. Red lines and shades indicate UN IGME median estimates and 90% uncertainty intervals. Blue lines indicate GBD estimates. Dots refer to observations used by UN IGME, where different colors indicate different data series.

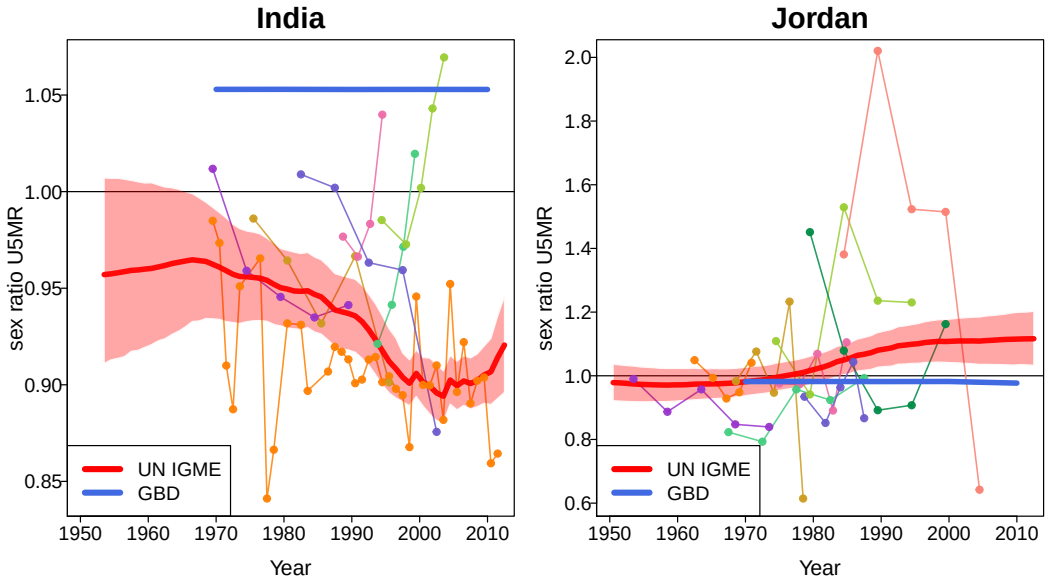

Fig. 4.9 **UN IGME and GBD U5MR sex ratio estimates for U5MR for India and Jordan.** Selected countries are those with one estimate of sex ratio above one, and the other one below one in 2010. Red lines and shades indicate UN IGME median estimates and 90% uncertainty intervals. Blue lines indicate GBD estimates. Dots refer to observations used by UN IGME, where different colors indicate different data series.

Chapter 5

A systematic assessment of national and regional under-5 mortality by economic status for low- and middle-income countries

This work currently under revise and review as:

Chao F, You D, Pedersen J, Hug L, Alkema L. A systematic assessment of national and regional under-5 mortality by economic status for low- and middle-income countries.

Contributors FC and LA developed the Bayesian statistical model. FC carried out the analysis and drafted the initial manuscript. DY proposed the study and oversaw database construction. JP developed the methodology and software to construct the wealth quintile input database. FC and LH assessed and compiled the database. All authors reviewed model results and edited the manuscript.

Abstract

The progress to achieve the fourth Millennium Development Goal (MDG 4) in reducing under-5 mortality rate (U5MR) since 1990 has been remarkable. However,

work remains to be done in the Sustainable Development Goal era. The U5MR estimates at the national level can hide disparities within countries. We assessed disparities in U5MR by household economic status in low- and middle- income countries.

We estimated country-year-specific U5MR by wealth quintile on the basis of household wealth indices for 137 low- and middle-income countries from 1990 to 2016, using a Bayesian statistical model. We estimated the relation between quintile-specific and national-level U5MR. We examined the levels and trends of disparities in U5MR on absolute and relative scales between the poorest and the richest quintiles, and among all quintiles.

In 2016, for all low- and middle-income countries (excluding China), the aggregated U5MR for children in the poorest households ($U5MR_{Q1}$) was 64.6 (90% UI 61.1; 70.1) deaths per 1000 livebirths, 31.3 (29.5; 34.2) deaths per 1000 livebirths among children in the richest households ($U5MR_{Q5}$), and in between those outcomes for the middle quintiles. Between 1990 and 2016, the largest absolute decline in the U5MR occurred in the two poorest quintiles at 77.6 (71.2; 82.6) and 77.9 (72.0; 82.2) deaths per 1000 livebirths for the poorest and the 2nd poorest quintile respectively. The difference between the U5MR for the poorest and for the richest decreased significantly by 38.8 (32.9; 43.8) deaths per 1000 livebirths between 1990 and 2016. The ratio of the poorest to the richest U5MR, however, remained at similar levels; the ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ was 2.03 (1.94; 2.11) in 1990, 1.99 (1.91; 2.08) in 2000, and 2.06 (1.92; 2.20) in 2016. During 1990–2016, around half of the total under-5 deaths were from the poorest two quintiles (48.5% in 1990 and 2000, 49.5% in 2016) and only less than one third were from the richest two quintiles (30.4% in 1990, 30.5% in 2000, 29.9% in 2016). For all the regions, differences between the $U5MR_{Q1}$ and $U5MR_{Q5}$ decreased significantly, with the decreases ranging from 20.6 (15.9; 25.1) deaths per 1000 livebirths in Eastern Europe and Central Asia to 59.5 (48.5; 70.4) deaths per 1000 livebirths in South Asia. In 2016, the ratios of $U5MR_{Q1}$ to $U5MR_{Q5}$ were found to be significantly above

two in East Asia and Pacific (excluding China) at 2.49 (2.15; 2.87) and in South Asia at 2.41 (2.05; 2.80). Eastern and Southern Africa had the smallest ratio in 2016 at 1.62 (1.48; 1.76). Our model suggested that the expected ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ increases as national-level U5MR decreases.

For all low- and middle-income countries combined (excluding China), the absolute disparities in under-5 mortality between the poorest and the richest households have narrowed significantly since 1990 in terms of differences of U5MR between the poorest and the richest, while the relative differences have remained stable. To further narrow the rich-and-poor gap of under-5 mortality on the relative scale, targeted interventions that focus on the poorest populations are needed.

5.1 Introduction

Since 1990, the world as a whole has made substantial progress in reducing child mortality. However, continued efforts are needed to ensure further progress and to reduce the disparity in child survival across populations. Globally, the reduction in the under-5 mortality rate (U5MR, the probability of a child dying before age five) was more than 50% in 1990–2016 with a significant acceleration in recent years [7, 152]. Despite the encouraging advancement in reducing child mortality, progress has been uneven across and within countries [153]. The fourth Millennium Development Goal (MDG 4) [154], which was to reduce U5MR by two thirds between 1990 and 2015, was not achieved in the great majority of countries. Far too many children still face drastically low odds of surviving their first five years. To continue past efforts to reduce child mortality and to complete the unfinished MDG agenda for improving child survival, the Sustainable Development Goals (SDGs) call for ending preventable newborn and child deaths by 2030, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1000 livebirths and U5MR to at least as low as 25 per 1000 livebirths. Moreover, SDGs call for reliable data disaggregated by multiple dimensions including income [9]. It is important to better understand who and where the most disadvantaged and vulnerable children

are at the beginning of the SDG era. The trends in such disparities across countries over time can help to understand how the benefits of development reach different segments of the population.

Monitoring U5MR by household economic status is challenging. Currently, countries with good vital registration do not combine mortality data with registry-based economic data, and countries that rely on surveys for mortality estimates usually do not combine mortality surveys with in-depth socioeconomic surveys such as household income and expenditure surveys. Estimates of U5MR by household economic strata, or disparities of U5MR between rich and poor, have been published previously for either one country [155–160], or multiple countries [161–171]. Before this study, the Health Equity Monitor by the World Health Organization provided the most comprehensive information on U5MR by household wealth quintile for country-years with available data from Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS), including 71 countries [167]. However, none of the studies provided time trends covering the period from 1990 to 2016 or included all low- and middle-income countries.

In this study, we estimated levels and trends in U5MR by wealth quintile, which is a measure of household economic status, for 137 low- and middle-income countries from 1990 to 2016. In our model, the relation between ratios among quintile-specific U5MR and national-level U5MR was assessed using all available survey data and was modeled with a flexible splines regression model. We identified regions and countries with the largest and smallest disparities in U5MR, on absolute and relative scales.

5.2 Data

The quintile-specific U5MR refers to the probability of those children born in households of a specific wealth quintile group to die before reaching age five. The data used in this study are observed U5MRs by wealth quintile from Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS) conducted

between 1990 and 2016 in 99 low- and middle-income countries (Figure 5.1, Table 5.2). As of August 2017, the database contained information from 319 surveys, with the range of one to nine available surveys per country.

DHS and MICS employ a wealth index (also known as the asset index) composed of a set of variables asked in household questionnaires that describe household assets and utility service [172]. The wealth index is used as a proxy for household welfare. The variables constituting the wealth index vary across surveys, reflecting different conditions in different countries as well as technological advances. The wealth index for a given survey is constructed using a principle component analysis of the wealth-related variables available for that survey; the index is given by the object scores for the first principal component. Typically, the quintiles are constructed so that each quintile contains 20 percent of the population of individuals. Under this approach the number of birth in the poorest households tends to be higher than in the wealthier quintiles because fertility tends to be higher among women in the poorer households. In our study, the division into quintiles was based on the product of the sampling weight and the number of births to include equal numbers of births in each quintile.

DHS and MICS surveys collect retrospective information on child mortality through birth histories. For surveys that included full birth histories which collect detailed information on each child including date of birth and date of death, we calculated quintile-specific U5MR in the five years prior to the study, as opposed to for a longer retrospective period, to reduce the effect of household wealth changing over time and potential recall bias. The detailed description of the direct calculation method is in the UN Inter-agency Group for Child Mortality Estimation (UN IGME) report [152]. For surveys that collected summary birth histories which only gather information on the number of children ever born and the number of children died or still survive, a time-since-first-birth indirect method was used to estimate under-5 mortality for each quintile [173]. In the calculation, mortality rates are based on births and deaths that occurred to mothers who had their first birth five to nine years

before the time of the survey. The sampling errors were calculated by the Jackknife method (see Section 3.3.1 for full details) which takes into account the multi-stage cluster and/or stratified sampling design of DHS and MICS surveys.

Table 5.1 summarizes the observations by source type for each wealth quintile group. In particular, there are 41 data points from 38 countries with reference year from 2010 onward. The percentage of the total number of under-5 deaths that were covered by the 38 counties with data since 2010 increased steadily from 32% in 1990 to 41% in 2016. Please refer to Appendix 6.4 for the full list of data series for the 99 countries.

Data source type	**Number of data series**
DHS Direct	224
MICS Direct	29
MICS Indirect	66
total	**319**

Table 5.1 **Distribution of observations by source type for each wealth quintile.** Observations are grouped by source types. "Direct" refers to observation obtained from full birth histories. "Indirect" refers to observations obtained from summary information and demographic methods. DHS: Demographic and Health Surveys; MICS: Multiple Indicator Cluster Surveys.

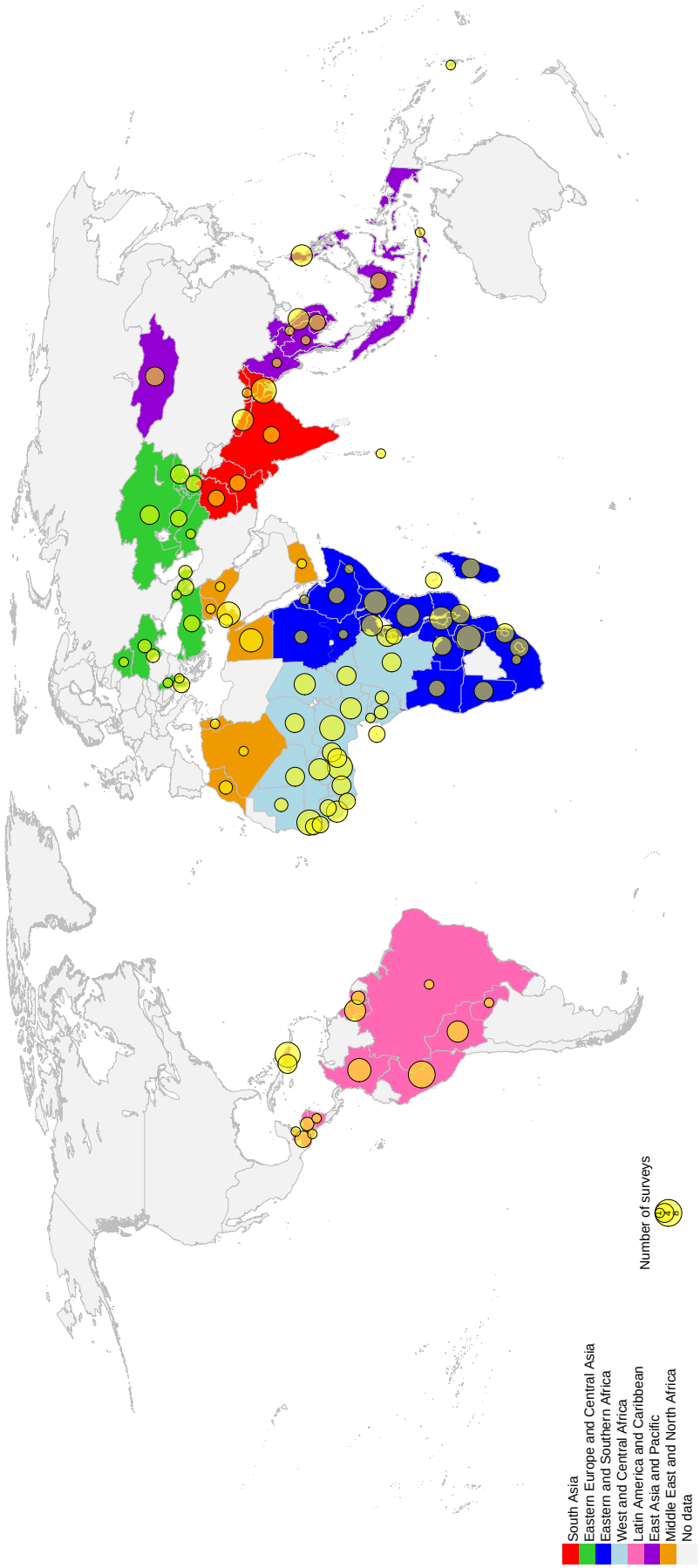

Fig. 5.1 **Wealth quintile-specific U5MR data availability.** Countries are colored by regions. Circle size is proportional to the number of data points available for each country.

5.3 Methods: overview

5.3.1 Statistical analysis

We developed a statistical model to estimate levels and trends in the U5MR by wealth quintile over time. The model took as an input the ratio of the quintile-specific U5MR to the national-level U5MR from empirical data, and the national-level (i.e. all quintiles combined) U5MR estimates with reference period from 1990 to 2016 published by the UN Inter-agency Group for Child Mortality Estimation (UN IGME) [152]. The model produced disaggregated estimates of U5MR by the five wealth quintiles.

In our model, the U5MRs for the 1st, 2nd, 4th, and 5th quintiles were modeled relative to the U5MR for the 3rd quintile and referred to as Q3-disparity ratios with the 3rd quintile serving as the reference point (see Section 5.4.1). This approach was used (i) to exchange information within countries over time and across countries on the expected levels of the Q3-disparity ratios, and (ii) to incorporate the constraint that the sum of quintile-specific under-5 deaths is equal to the total number of under-5 deaths.

National-level U5MR (excluding crisis-related deaths) was used to predict the expected Q3-disparity ratios based on an expected (and empirically observed) relation between the ratios and national-level U5MR, using a flexible (penalized B-splines) regression model. The splines were used in order to capture the potentially non-linear relation between the expected Q3-disparity ratios and the national-level U5MR (see Figure 5.2). The final country-specific Q3-disparity ratios were modeled as the product of the expected ratios (based on the national-level U5MR in the country-year) and a country-year-specific multiplier. The multiplier represents the deviation of the actual country-specific ratio away from its expected level, as indicated by country-specific data. The multiplier was modeled on the log-scale by a time series model of a first order autoregressive process (ie AR(1)) structure, with quintile-specific autoregressive parameters and global distortion variance. The

UNICEF Region	[30] Low-income country	[69] Middle-income country
South Asia	[2] Afghanistan; Nepal	[5] Bangladesh; Bhutan; India; Maldives; Pakistan
Eastern Europe and Central Asia	[0]	[15] Albania; Armenia; Azerbaijan; Belarus; Georgia; Kazakhstan; Kyrgyzstan; Republic of Moldova; The former Yugoslav Republic of Macedonia; Serbia; Tajikistan; Turkmenistan; Turkey; Ukraine; Uzbekistan
Eastern and Southern Africa	[13] Burundi; Comoros; Eritrea; Ethiopia; Madagascar; Mozambique; Malawi; Rwanda; Somalia; South Sudan; United Republic of Tanzania; Uganda; Zimbabwe	[8] Angola; Kenya; Lesotho; Namibia; Sudan; Swaziland; South Africa; Zambia
West and Central Africa	[14] Benin; Burkina Faso; Central African Republic; Democratic Republic of the Congo; Guinea; Gambia; Guinea-Bissau; Liberia; Mali; Niger; Senegal; Sierra Leone; Chad; Togo	[9] Cote d'Ivoire; Cameroon; Congo; Gabon; Ghana; Equatorial Guinea; Mauritania; Nigeria; Sao Tome and Principe
Latin America and Caribbean	[1] Haiti	[13] Belize; Bolivia (Plurinational State of); Brazil; Colombia; Dominican Republic; Guatemala; Guyana; Honduras; Nicaragua; Peru; Paraguay; El Salvador; Suriname
East Asia and Pacific (excluding China)	[0]	[10] Indonesia; Cambodia; Lao People's Democratic Republic; Myanmar; Mongolia; Philippines; Thailand; Timor-Leste; Viet Nam; Vanuatu
Middle East and North Africa	[0]	[9] Algeria; Egypt; Iraq; Jordan; Morocco; State of Palestine; Syrian Arab Republic; Tunisia; Yemen

Table 5.2 **Low- and middle-income countries (excluding China) with data by UNICEF regions.** Countries are categorized by UNICEF regions. The red numbers in brackets represent the numbers of countries in each group.

UNICEF Region	[1]Low-income country	[37]Middle-income country
South Asia	[0]	[1] Sri Lanka
Eastern Europe and Central Asia	[0]	[6] Bulgaria; Bosnia and Herzegovina; Croatia; Montenegro; Romania; Russian Federation
Eastern and Southern Africa	[0]	[3] Botswana; Djibouti; Mauritius
West and Central Africa	[0]	[1] Cabo Verde
Latin America and Caribbean	[0]	[12] Argentina; Costa Rica; Cuba; Dominica; Ecuador; Grenada; Jamaica; Saint Lucia; Mexico; Panama; Saint Vincent and the Grenadines; Venezuela (Bolivarian Republic of)
East Asia and Pacific (excluding China)	[1] Democratic People's Republic of Korea	[11] Fiji; Micronesia (Federated States of); Kiribati; Marshall Islands; Malaysia; Nauru; Papua New Guinea; Solomon Islands; Tonga; Tuvalu; Samoa
Middle East and North Africa	[0]	[3] Iran (Islamic Republic of); Lebanon; Libya

Table 5.3 **Low- and middle-income countries (excluding China) without data by UNICEF regions.** Countries are categorized by UNICEF regions. The red numbers in brackets represent the numbers of countries in each group.

country-year-specific levels of the multiplier were assumed to fluctuate around one.

We simultaneously estimated the expected Q3-disparity ratios and the final country-specific ratios (see Section 5.4.2). We used the observed ratio of the quintile-specific U5MR to the national-level U5MR as data input for model fitting to reduce the effect of level biases in U5MR data [174]. The data quality model incorporated sampling variance that takes into account survey structures.

We used a Markov Chain Monte Carlo (MCMC) algorithm to generate samples from the posterior distribution of the parameters [141] (see Section 5.4.4). This approach produced a set of trajectories of ratios of Q3-disparity ratios, or equivalently, ratios of quintile-specific to national-level U5MR for each country.

Estimates of the final Q3-disparity ratios were combined with estimates of national-level U5MR to obtain country-year-quintile-specific U5MR (see Section 5.4.1), accounting for the uncertainty in the national-level U5MR [152]. Estimates for countries without data followed from the model and its parameter estimates and were based on the expected Q3-disparity ratios (determined by the national-level U5MR for that country), the uncertainty in country-specific deviations based on simulations of the country-year-specific multiplier (that captured the variability unexplained by the expected Q3-disparity ratios), and the uncertainty in national-level U5MR. The quintile-specific U5MR and corresponding deaths were adjusted to account for crisis-related under-5 deaths [152]. Aggregated U5MR estimates by quintile (see Section 5.4.8) were derived by applying the proportions of quintile-specific under-5 deaths within a region to the aggregated UN IGME U5MR in a region [152]. We constructed aggregated results for all low- and middle-income countries (excluding China) using the World Bank income group classification [175]. We computed 90% uncertainty intervals (UIs) for all indicators of interest using the 5th and 95th percentiles of the posterior distributions (90% UIs are the standard choice in UN IGME reporting as opposed to the more standard 95% intervals given the inherent uncertainty in child mortality related outcomes).

Model performance was assessed through an out-of-sample validation (see Sec-

tion 5.4.9).

5.3.2 Equity analyses

We examined the household economic disparities in U5MR on the absolute and relative scales at national, regional, and aggregated levels of 137 low- and middle-income countries. Since absolute and relative measures can lead to different conclusions about the size of and changes in disparities, examination of both absolute and relative measures is important to present a complete picture in disparity [176]. We calculated two absolute indicators of inequality: the difference between the U5MR for the poorest and the richest quintile, $U5MR_{Q1} - U5MR_{Q5}$, and the slope index of inequality, which captures inequity across all five quintile groups. The slope index is the slope of a regression of quintile-specific U5MR on its cumulative proportion of the livebirths up to the midpoint of each quintile from the poorest to the richest [162, 177]. It represents the change in the quintile-specific U5MR (per 1000 livebirths) when the position of the economic status increase from poor to rich by one unit [178]. We also calculated two relative inequality indicators: the ratio of the U5MR for the poorest to the richest quintile, $U5MR_{Q1}/U5MR_{Q5}$, and the concentration index. The concentration index captures the inequality across all the quintiles and is calculated as twice the area between the mortality concentration curve (the cumulative proportion of under-5 deaths against the cumulative proportion of livebirths, beginning with the poorest quintile) and the diagonal [162]. The concentration index ($\times 100$) is expressed in a scale ranging from -100 to 100; a value of 0 represents perfect equality, whereas a value equal to 100 or -100 indicated that only the richest or the poorest households bear the burden of under-5 mortality.

5.4 Methods: technical details

The contents of this section were taken from the Online Appendix of the original paper (which is currently under review).

5.4.1 Wealth quintile-specific U5MR model

Our goal is to estimate the wealth quintile-specific U5MR $Q_{w,c,t}$ for wealth quintile w, country c and year t. Here we use w as an index to denote the wealth quintile group $w = 1,\ldots,5$. This notation is equivalent to the notation $Q1,\ldots,Q5$ in the main paper. Only in this section, Q refers to the under-5 mortality rate. The wealth quintile-specific U5MRs are assumed to relate to the national-level U5MR as follows:

$$\begin{aligned} Q_{\text{total},c,t} &= D_{\text{total},c,t}/B_{\text{total},c,t}, \\ Q_{w,c,t} &= D_{w,c,t}/(B_{\text{total},c,t}/5), \\ \frac{D_{\text{total},c,t}}{B_{\text{total},c,t}} &= \frac{\sum_{w=1}^{5} D_{w,c,t}}{(B_{\text{total},c,t}/5)\cdot 5}, \\ Q_{\text{total},c,t} &= \sum_{w=1}^{5} Q_{w,c,t}/5. \end{aligned}$$

where $Q_{\text{total},c,t}$ is the national-level U5MR, $D_{\text{total},c,t}$ is the total number of under-5 deaths, $B_{\text{total},c,t}$ is the total number of livebirths, and $D_{w,c,t}$ is the number of under-5 deaths from the w-th wealth quintile group. All notations are referring to country c in year t.

In order to incorporate the constraint that the wealth quintile-specific U5MRs sum up to five times the national-level U5MR, we estimated the Q3-disparity ratios $S_{w,c,t} = Q_{w,c,t}/Q_{3,c,t}$ for $w = 1,2,4,5$. After estimating those ratios, the wealth quintile-specific U5MRs are recovered as follows:

$$\begin{aligned} S_{1,c,t} + S_{2,c,t} + S_{4,c,t} + S_{5,c,t} &= (Q_{1,c,t} + Q_{2,c,t} + Q_{4,c,t} + Q_{5,c,t})/Q_{3,c,t}, \\ &= (\sum_{w=1}^{5} Q_{w,c,t} - Q_{3,c,t})/Q_{3,c,t}, \\ &= (5\cdot Q_{\text{total},c,t} - Q_{3,c,t})/Q_{3,c,t}, \\ &= 5\cdot Q_{\text{total},c,t}/Q_{3,c,t} - 1. \end{aligned}$$

Hence,

$$\begin{aligned} Q_{3,c,t} &= 5 \cdot Q_{\text{total},c,t} / (S_{1,c,t} + S_{2,c,t} + S_{4,c,t} + S_{5,c,t} + 1), \\ Q_{w,c,t} &= S_{w,c,t} \cdot Q_{3,c,t}, \text{ for } w = 1,2,4,5. \end{aligned}$$

We used the 3rd wealth quintile group (i.e. $w = 3$) as the reference group in the ratios because it is the group where we expected the proportion of deaths to be closest to 20%; national-level U5MR (excluding crisis-related deaths) was used to predict the expected Q3-disparity ratios based on an expected (and empirically observed) relation between the ratios and national-level U5MR, using a flexible (penalized B-splines) regression model. Figure 5.2 shows the relationship between $S_{w,c,t}$ and the national-level U5MR $Q_{\text{total},c,t}$ for $w = 1,2,4,5$ in the four plots respectively. The national-level U5MR inputs $Q_{\text{total},c,t}$ used are the median estimates (excluding crisis-related under-5 deaths, and including HIV-related under-5 deaths) from the UN Inter-agency Group for Child Mortality Estimation (UN IGME) 2017 results [152]. The loess curves in the 1st and 2nd plots increase as the national-level U5MR decreases, implying that as the national-level U5MR is decreasing, survival among children in the 3rd wealth quintile is improving more quickly as compared to survival among the poorest two groups. Similarly, the decreasing trend of the loess curve in the 4th plot indicate that as the national-level U5MR is declining over time, the decrease of the U5MR in the 4th richest wealth quintile is faster than that in the 3rd wealth quintile. For the richest wealth quintile, the loess curve suggests a survival advantage for children in the richest wealth quintile at any value of national-level U5MR, with the relative difference between the U5MR in the 3rd and 5th wealth quintile increasing as the U5MR decreases until a national-level U5MR of about 50 deaths per 1,000 livebirths, followed by a decrease of the relative difference.

The relation between national-level U5MR $Q_{\text{total},c,t}$ and $S_{w,c,t}$ is incorporated

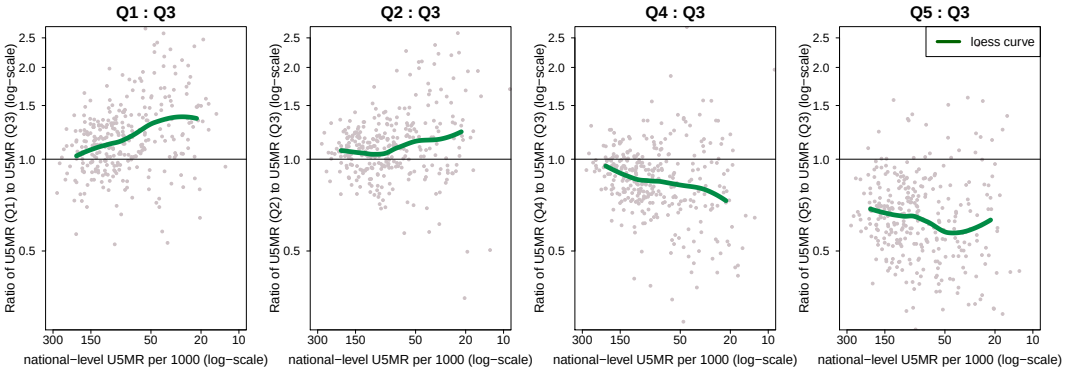

Fig. 5.2 **Q3-disparity ratios against national-level U5MR – data trend.** The grey dots are observed Q3-disparity ratios $S_{w,c,t}$ (i.e. $= Q_{w,c,t}/Q_{3,c,t}$) for $w = 1,2,4,5$ respectively for the four plots. The green curves are loess curves between the 5th and 95th percentiles of the national-level U5MR.

into the model for $S_{w,c,t}$:

$$S_{w,c,t} \quad = \quad U_{w,c,t} \cdot P_{w,c,t}, \text{ for } w = 1,2,4,5,$$

where $U_{w,c,t}$ is the expected Q3-disparity ratio (as illustrated by the green loess curves in Figure 5.2) and $P_{w,c,t}$ is a quintile-country-year-specific multiplier. The specification of $U_{w,c,t}$ is explained in more detail below.

We used an AR(1) process to model the $P_{w,c,t}$'s on the log-scale:

$$\log(P_{w,c,t}) \quad \sim \quad N(\rho_w \cdot \log(P_{w,c,t-1}), \sigma^2_\varepsilon),$$

With wealth quintile-specific autoregressive parameter ρ_w (allowing for a wealth quintile-specific rate of convergence back to zero on the log-scale) and distortion variance σ^2_ε.

Specification of the expected Q3-disparity ratio $U_{w,c,t}$ We used flexible penalized B-spline regression models [142, 143] to estimate the relation between national-level U5MR and the expected Q3-disparity ratios (based on data from the 99 low- and middle-income countries). While other semi- or non-parametric models could be considered, the B-splines set-up is relatively easy to implement, flexible and performed well in validation exercises (see later in Section 5.5.5).

The B-spline regression models are denoted by function $f_w(\cdot)$, for $w = 1,2,4,5$. The function $f_w(q)$ for some national-level U5MR value q was specified as follows:

$$f_w(q) \quad = \quad \sum_{k=1}^{K} B_k(q)\alpha_{w,k}, \text{ for } w = 1,2,4,5,$$

where $B_k(q)$ refers to the k-th B-spline evaluated at q and $\alpha_{w,k}$ to the k-th spline coefficient for ratio w. We set:

$$\log(U_{w,c,t}) = f_w(\widetilde{Q}_{\text{total},c,t}), \text{ for } w = 1,2,4,5,$$

where $\widetilde{Q}_{\text{total},c,t}$ is the $Q_{\text{total},c,t}$ rounded to three decimal places (to reduce the number of splines evaluations).

The B-splines used in the regression models are illustrated in Figure 5.3. We used symmetric third-order polynomials, equally spaced on the log-transformed national-level U5MR scale (knots are set to be 0.3 apart). The resulting splines add up to unity at any level of national-level U5MR. To avoid extreme extrapolations, splines are combined for national-level U5MR less than 20 per 1000 livebirths, and for national-level U5MR greater than the 95-th percentile of $Q_{\text{total},c,t}$.

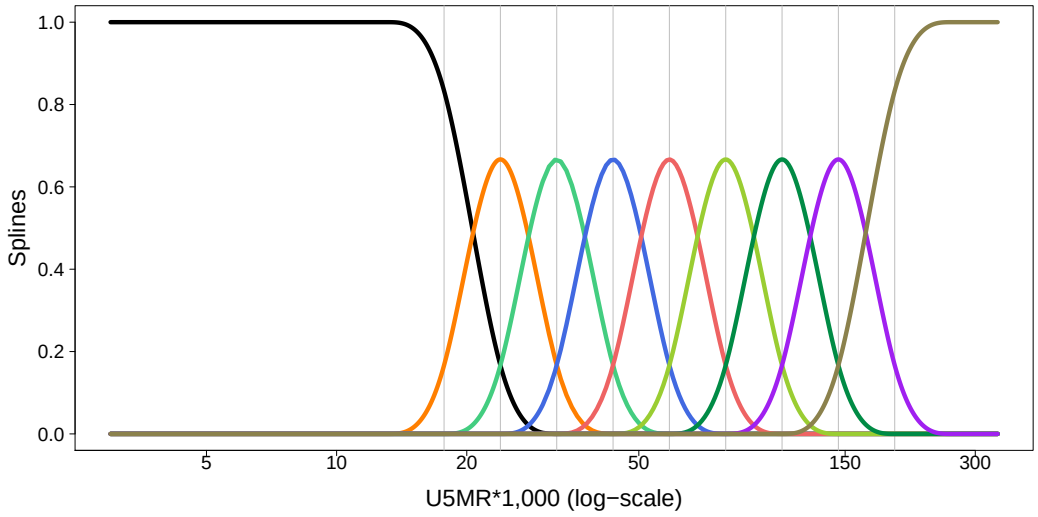

Fig. 5.3 **B-splines used in the regression model for the expected Q3-disparity ratios.** B-splines plotted against the log-transformed U5MR. The grey vertical lines indicate knots.

When fitting the splines model to observations, first-order differences in ad-

jacent splines coefficients were penalized to guarantee smoothness of the global relation between national-level mortality and expected ratios. The remainder of this subsection discusses the implementation details.

The splines regression model is specified as follows:

$$\begin{aligned} f_w(\tilde{\boldsymbol{q}}) &= \widetilde{\boldsymbol{B}}\boldsymbol{\alpha}_w, \\ \tilde{\boldsymbol{q}} &= (q_1,\ldots,q_j,\ldots,q_J)'. \end{aligned}$$

$\tilde{\boldsymbol{q}}$ represents the vector of unique values $\tilde{Q}_{\text{total},c,t}$ (rounded to three digits). Here, $J = 334$ since there are 334 unique values for $\tilde{Q}_{\text{total},c,t}$. $\widetilde{\boldsymbol{B}} = \boldsymbol{B}(\tilde{\boldsymbol{q}})$ the matrix of splines evaluated at each entry of $\tilde{\boldsymbol{q}}$, and $\boldsymbol{\alpha}_w$ the vector of splines coefficients with length equal to number of knots K. The splines equation can be written as follows [143–145]:

$$\begin{aligned} \widetilde{\boldsymbol{B}}\boldsymbol{\alpha}_w &= \beta_w + \boldsymbol{Z}\times\boldsymbol{\delta}_w, \qquad (5.1) \\ \boldsymbol{Z} &= \widetilde{\boldsymbol{B}}\boldsymbol{D}'(\boldsymbol{D}\boldsymbol{D}')^{-1}, \\ D_{i,j} &= \begin{cases} -1 & \text{if} \quad i=j, \\ 1 & \text{if} \quad i=j-1, \\ 0 & \text{o.w.} \end{cases} \end{aligned}$$

where the elements of difference matrix $\boldsymbol{D}$ has dimension $H\times K$, with $H = K-1$. The first part in Eq.(5.1), β_w describes the average constant level in the expected relative difference, and the second part $\boldsymbol{Z}\times\boldsymbol{\delta}_w$ describes the fluctuations around the linear trend. The dimension of matrix $\boldsymbol{Z}$ is $J\times H$. $\boldsymbol{\delta}_w = (\delta_{w,1},\ldots,\delta_{w,H})'$. First-order differences are penalized by imposing:

$$\delta_{w,h} \sim N(0,\sigma^2_{\delta_w}), \text{ for } w = 1,2,4,5, \text{ and } h = 1,\ldots,H,$$

where variance $\sigma^2_{\delta_w}$ determines the extent of smoothing. Vague prior distributions are used for the splines model parameters.

The expected Q3-disparity ratios U_w are modeled independently for different

w's. The hierarchical structure is not used in this case mainly due to two reasons. Firstly, U_w capture different relations for w's, and hence it is not valid to exchange information across w's. Secondly, U_w is modeled by global functions using data from all available country-years. Thus, there is enough information to estimate each U_w independently without the need for the hierarchical structures.

5.4.2 Data model

Instead of using the observed wealth quintile-specific U5MR in the data model, we used the observed ratio of wealth quintile-specific U5MR to the national-level U5MR to remove the national-level survey biases [174]. Let $r_{w,i} = q_{w,i}/q_{\text{total},i}$, the i-th observed ratio of the w-th wealth quintile-specific U5MR to the national-level U5MR, which is from country $c[i]$, in year $t[i]$. The data model is:

$$\log(r_{w,i}) \quad \sim \quad N(\log(R_{w,c[i],t[i]}), \gamma_{w,i}^2),$$

where $R_{w,c,t} = Q_{w,c,t}/Q_{\text{total},c,t}$ and $\gamma_{w,i}$ is the sampling error for the i-th observation.

In general, the sampling error of the wealth quintile-specific data points from full birth history is smaller than the sampling error from summary birth history, and hence more informative and assigned more weight in the estimation process. Figure 5.4 shows the distribution of the the sampling errors for the ratio of wealth quintile-specific U5MR to the national-level U5MR for all wealth quintile groups.

5.4.3 Model summary

Notations Table 5.4 summarizes the notations and indices used in this project.

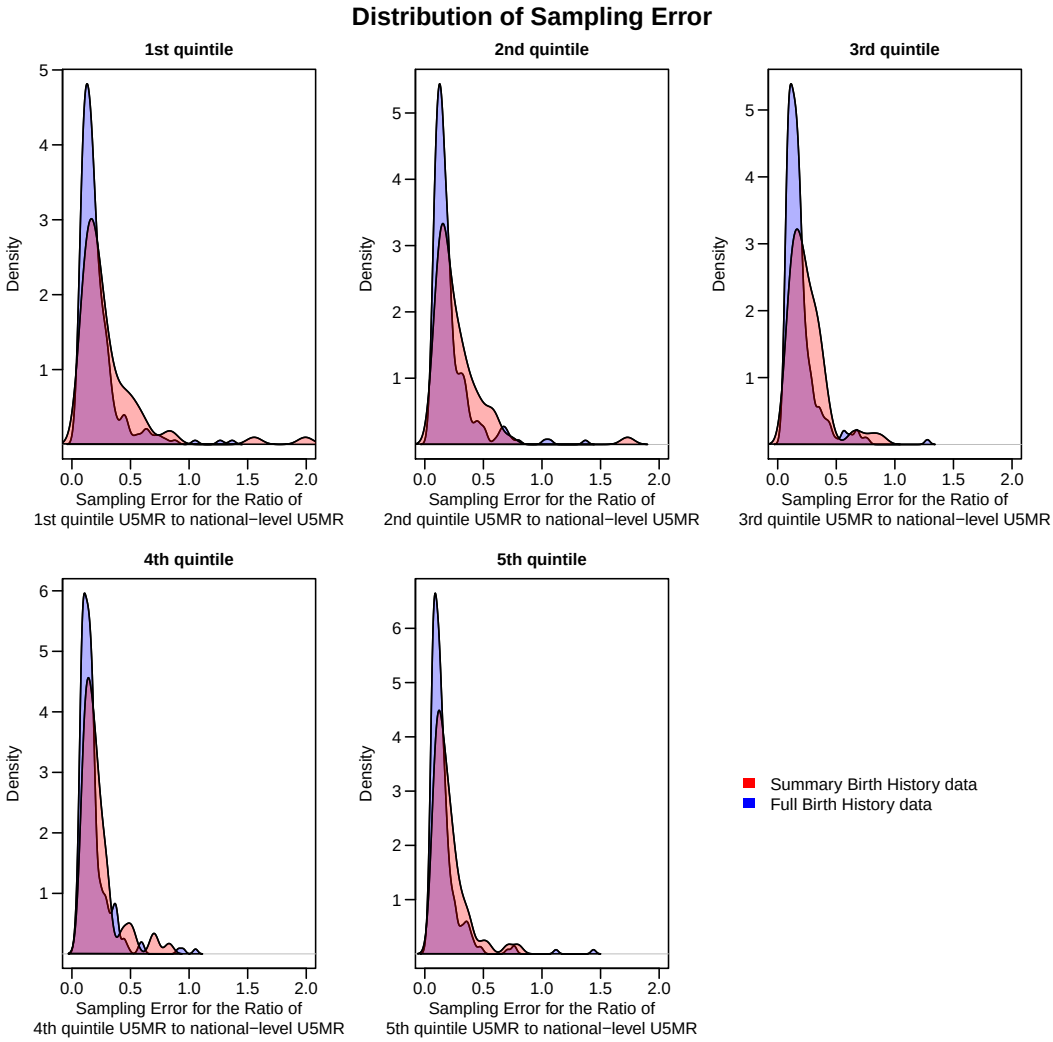

Fig. 5.4 **Sampling error distribution for full birth history and summary birth history data, by wealth quintile.**

Symbol	Description
t	Indicator for year, $t = 1981, \ldots, 2016$.
c	Indicator for country, $c = 1, \ldots, 99$.
w	Indicator for wealth quintile groups, $w = 1, \ldots, 5$. $w = 1$ refers to the 1st (i.e. the poorest) wealth quintile group, and $w = 5$ refers to the 5th (i.e. the richest) wealth quintile group.
i	Indicator for the i-th observation within a certain wealth quintile group.
$r_{w,i}$	The i-th observed ratio of the w-th wealth quintile-specific U5MR to the national-level U5MR.
$\gamma_{w,i}$	The i-th sampling error for $r_{w,i}$.
$q_{w,i}$	The i-th observed wealth quintile-specific U5MR from the w-th wealth quintile group.
$q_{\text{total},i}$	The i-th national-level U5MR from DHS and MICS surveys.
$Q_{\text{total},c,t}$	The national-level U5MR for country c year t, is the median estimates (excluding crisis-related deaths) from the UN Inter-agency Group for Child Mortality Estimation (UN IGME) 2017 results [152].
$\widetilde{Q}_{\text{total},c,t}$	The $Q_{\text{total},c,t}$ rounded to three decimal places.
$Q_{w,c,t}$	The true wealth quintile-specific U5MR for wealth quintile w, with $w = 1, \ldots, 5$, country c in year t.
$S_{w,c,t}$	The true Q3-disparity ratio (i.e. $= Q_{w,c,t}/Q_{3,c,t}$) of the U5MR from the w-th wealth quintile to the 3rd wealth quintile for $w = 1,2,4,5$ respectively, for country c in year t.
$U_{w,c,t}$	The expected Q3-disparity ratio of the U5MR from the w-th wealth quintile to the 3rd wealth quintile for $w = 1,2,4,5$ respectively, for country c in year t.
$P_{w,c,t}$	The relative difference between $S_{w,c,t}$ and $U_{w,c,t}$ for $w = 1,2,4,5$, for country c in year t.
$R_{w,c,t}$	The true ratio of the w-th wealth quintile-specific U5MR to the national-level U5MR for country c in year t, i.e. $= Q_{w,c,t}/Q_{\text{total},c,t}$.
ρ_w	Autoregressive parameter for AR(1) time series model for $\log(P_{w,c,t})$, for $w = 1,2,4,5$.
σ_ε^2	Variance of distortion terms in AR(1) time series model for $\log(P_{w,c,t})$.

Table 5.4 **Notation summary.**

Wealth quintile-specific U5MR model

$$
\begin{aligned}
Q_{w,c,t} &= S_{w,c,t} \cdot Q_{3,c,t}, \text{ for } w = 1,2,4,5 \\
Q_{3,c,t} &= 5 \cdot Q_{\text{total},c,t} / (S_{1,c,t} + S_{2,c,t} + S_{4,c,t} + S_{5,c,t} + 1), \\
S_{w,c,t} &= U_{w,c,t} \cdot P_{w,c,t}, \text{ for } w = 1,2,4,5, \\
\log(U_{w,c,t}) &= f_w(\widetilde{Q}_{\text{total},c,t}), \text{ for } w = 1,2,4,5, \\
f_w(\tilde{\boldsymbol{q}}) &= \widetilde{\boldsymbol{B}}\boldsymbol{\alpha}_w, \text{ for } w = 1,2,4,5, \\
\delta_{(w,h)} &\sim N(0, \sigma^2_{\delta_w}), \text{ for } w = 1,2,4,5, \text{ and } h = 1,\ldots,H, \\
\log(P_{w,c,t}) &\sim N(\rho_w \cdot \log(P_{w,c,t-1}), \sigma^2_\varepsilon), \text{ for } w = 1,2,4,5, \\
R_{w,c,t} &= Q_{w,c,t} / Q_{\text{total},c,t}, \text{ for } w = 1,\ldots,5, \\
\log(r_{w,i}) &\sim N(\log(R_{w,c[i],t[i]}), \gamma^2_{w,i}), \text{ for } w = 1,\ldots,5.
\end{aligned}
$$

Prior distributions Vague priors are assigned to hyper-parameters:

$$
\begin{aligned}
\beta_w &\sim U(-5,5), \text{ for } w = 1,2,4,5, \\
\rho_w &\sim U(0,1), \text{ for } w = 1,2,4,5, \\
\sigma_{\delta_w} &\sim U(0,0.5), \text{ for } w = 1,2,4,5, \\
\sigma_\varepsilon &\sim U(0,0.5).
\end{aligned}
$$

5.4.4 Computing

We obtained posterior samples of all the model parameters and hyper parameters using a MCMC algorithm, implemented in the open source softwares `R 3.2.2` [179] and `JAGS 4.0.1` (Just another Gibbs Sampler) [16], using `R`-packages `coda` [19], `rjags` [18], and `R2jags` [95]. Results were obtained from 4 chains with a total number of 490,000 iterations in each chain, while the first 1,300,500 iterations were discarded as burn-in, and thinning for every 10 iterations, the final posterior sample size for each parameter is 3,600. Convergence of the MCMC algorithm and the sufficiency of the number of samples obtained were checked through visual

inspection of trace plots and convergence diagnostics of Gelman and Rubin [14]. Software programs and data are available from the authors.

5.4.5 Uncertainty intervals of wealth quintile-specific U5MR

Computation of final results Throughout the project, we presented our results in the format of "point estimate [lower bound; upper bound]". E.g. the quintile-specific U5MR and under-5 deaths are presented as $Q^{P.E.}_{w,c,t}[Q^{L}_{w,c,t};Q^{U}_{w,c,t}]$ and $D^{P.E.}_{w,c,t}[D^{L}_{w,c,t};D^{U}_{w,c,t}]$ respectively. The rest of this section will explain how we derived each of the component in the result.

We constructed the uncertainty intervals of wealth quintile-specific U5MR and under-5 deaths using the posterior samples of the Q3-disparity ratios $S_{w,c,t}$ (ratio of other wealth quintiles to the 3rd wealth quintile-specific U5MR). The g-th posterior sample of the Q3-disparity ratios is $S^{(g)}_{w,c,t}$. This sample is combined with the g-th posterior sample of national-level U5MR $Q(c.f.)^{(g)}_{c,t}$ (excluding crisis-related deaths; from the UN IGME 2017 results [152]) to include national-level U5MR uncertainty in the estimated wealth quintile-specific U5MR from the w-th wealth quintile group in country c year t:

$$\begin{aligned} R^{(g)}_{3,c,t} &= 5/(S^{(g)}_{1,c,t}+S^{(g)}_{2,c,t}+S^{(g)}_{4,c,t}+S^{(g)}_{5,c,t}+1), \\ R^{(g)}_{w,c,t} &= S^{(g)}_{w,c,t}\cdot R^{(g)}_{3,c,t}, \text{ for } w=1,2,4,5, \\ Q(c.f.)^{(g)}_{w,c,t} &= R^{(g)}_{w,c,t}\cdot Q(c.f.)^{(g)}_{c,t}, \text{ for } w=1,\ldots,5, \end{aligned}$$

where $Q(c.f.)^{(g)}_{w,c,t}$ is g-th posterior sample of the crisis-free U5MR for the w-th wealth quintile. Before computing the number of under-5 deaths for each wealth quintile, we adjusted the country-years affected by crisis events to include the crisis-related deaths in the final results.

Adjusting the U5MR in years with crisis-related deaths To include crisis deaths in the resulting wealth quintile-specific U5MR estimates, we followed the procedure used by the UN IGME for adjusting national-level U5MR [7, 152], based on the as-

sumption that the national-level crisis mortality rate is equally added among wealth quintiles. To include crisis deaths in the wealth quintile-specific U5MR estimates, we added the crisis-specific U5MR to the fitted model results described above. No uncertainty of crisis deaths is included in the final adjusted wealth quintile-specific U5MR results. As suggested in [7, 152], we assumed that the relative uncertainties in the wealth quintile-specific U5MR before and after adjusting for crisis deaths are the same. In total, 18 different crises from 9 countries were taken into account into the estimation of wealth quintile-specific U5MR. After adjustment, the posterior samples of the wealth quintile-specific U5MR including crisis death $\left\{Q_{w,c,t}^{(g)}, g = 1,\ldots,G\right\}$ were generated.

Posterior samples for the number of under-5 deaths per wealth quintile (including crisis-related deaths) $D_{w,c,t}^{(g)}$, inclusive of uncertainty in the national-level under-5 death (including crisis-related deaths), were obtained as follows:

$$D_{w,c,t}^{(g)} = R_{w,c,t}^{(g)} \cdot \frac{D(total)_{c,t}^{(g)}}{5}, \text{ for } w = 1,\ldots,5.$$

The samples of number of national-level under-5 deaths for each country-year $\left\{D(total)_{c,t}^{(g)}, g = 1,\ldots,G\right\}$ were from the UN IGME 2017 results [152].

The 90% uncertainty intervals for $Q_{w,c,t}$ and $D_{w,c,t}$, denoting as $[Q_{w,c,t}^{L}; Q_{w,c,t}^{U}]$ and $[D_{w,c,t}^{L}; D_{w,c,t}^{U}]$ respectively, are the 5-th and 95-th percentiles of the corresponding posterior samples:

$$\begin{aligned}
Q_{w,c,t}^{L} &= \text{percentile}_{5\%}\left\{Q_{w,c,t}^{(1)},\ldots,Q_{w,c,t}^{(G)}\right\},\\
Q_{w,c,t}^{U} &= \text{percentile}_{95\%}\left\{Q_{w,c,t}^{(1)},\ldots,Q_{w,c,t}^{(G)}\right\},\\
D_{w,c,t}^{L} &= \text{percentile}_{5\%}\left\{D_{w,c,t}^{(1)},\ldots,D_{w,c,t}^{(G)}\right\},\\
D_{w,c,t}^{U} &= \text{percentile}_{95\%}\left\{D_{w,c,t}^{(1)},\ldots,D_{w,c,t}^{(G)}\right\}.
\end{aligned}$$

5.4.6 Point estimates of wealth quintile-specific U5MR

We constructed the point estimates of wealth quintile-specific U5MR and under-5 deaths by re-scaling the medians of $R_{w,c,t}$, the ratio of wealth quintile-specific to

national-level U5MR, such that $\sum_{w=1}^{5} R_{w,c,t} = 5$ for $\forall c, \forall t$. The point estimates of $R_{w,c,t}$ are combined with the point estimates of national-level U5MR $Q(total)_{c,t}^{P.E.}$ and under-5 deaths $D(total)_{c,t}^{P.E.}$ (both with adjustment on crisis-related deaths) to derive the point estimates of quintile-specific U5MR and under-5 deaths:

$$R_{w,c,t}^{M} = \text{median}\left\{R_{w,c,t}^{(1)}, \ldots, R_{w,c,t}^{(G)}\right\}, \text{ for } w = 1, \ldots, 5,$$

where $R_{w,c,t}^{(g)}$ is the g-th posterior sample of $R_{w,c,t}$ as explained in Section 5.4.5. Then we re-scaled each $R_{w,c,t}^{M}$ to $R_{w,c,t}^{P.E.}$ for $w = 1, \ldots, 5$:

$$R_{w,c,t}^{P.E.} = 5 \cdot \frac{R_{w,c,t}^{M}}{\sum_{w=1}^{5} R_{w,c,t}^{M}}.$$

The point estimates of $Q_{w,c,t}^{P.E.}$ and under-5 deaths $D_{w,c,t}^{P.E.}$ were derived as:

$$\begin{aligned} Q_{w,c,t}^{P.E.} &= R_{w,c,t}^{P.E.} \cdot Q(total)_{c,t}^{P.E.}, \\ D_{w,c,t}^{P.E.} &= R_{w,c,t}^{P.E.} \cdot \frac{D(total)_{c,t}^{P.E.}}{5}. \end{aligned}$$

5.4.7 Imputing results for countries without data

38 out of the 137 low- and middle-income countries (excluding China) do not have wealth quintile-specific data. For these countries, the results were imputed as follows. Firstly, we imputed $\log(P_{w,c,t})$ for any country without data based on the posterior samples of parameters related. Let $P*_{w,t}^{(g)}$ be the g-th imputed sample for any country without data (hence drop the index c) in time t, and $\sigma_{\varepsilon}^{(g)}$, $\rho^{(g)}$ be the g-th posterior sample from the model:

$$\begin{aligned} \log(P*_{w,t=1}^{(g)}) &\sim N(0, \frac{(\sigma_{\varepsilon}^{(g)})^2}{1-(\rho^{(g)})^2}), \\ \log(P*_{w,t}^{(g)}) &= \rho_{w}^{(g)} \cdot \log(P*_{w,t-1}^{(g)}) + \varepsilon_{t}^{(g)}, \text{ for } w = 1,2,4,5, \text{ for } t = 2, \ldots, T, \end{aligned}$$

where

$$\varepsilon_{t}^{(g)} \sim N(0, (\sigma_{\varepsilon}^{(g)})^2), \text{ for } t = 2, \ldots, T.$$

Secondly, for a given country-year, the crisis-free national-level U5MR (rounded to three digits) was used to identify the posterior samples of $\log(U_{w,c,t})$

$$\log(U_{w,c,t}^{(1,\ldots,G)}) \quad = \quad f_w(\widetilde{Q}(c.f.)_{c,t}), \text{ for } w = 1,2,4,5.$$

Hence, we computed the imputed $S_{w,c,t}^{(g)} = P*_{w,t}^{(g)} \cdot U_{w,c,t}^{(g)}$. We then followed the same steps as described in Section 5.4.5 to calculate the 90% UI and in Section 5.4.6 to compute the point estimates of wealth quintile-specific U5MR and under-5 deaths.

5.4.8 Computation of aggregated results

Aggregate estimates for 137 low- and middle-income countries were based on the totals for the number of livebirths by region. The 137 countries were low- and middle-income countries based on the World Bank country income classification in 2017[1]. We did not include China. Estimates for countries without data were obtained from the fitted model. The 137 low- and middle-income countries are listed in Table 5.2 and Table 5.3 by UNICEF region and data availability. The wealth quintile-specific under-5 deaths from region r for the w-th wealth quintile group for year t, denoted by $DR_{w,r,t}$, is computed as:

$$DR_{w,r,t} \quad = \quad \sum_{c \in \{region[c]=r\}} D_{w,c,t}, \text{ for } w = 1,\ldots,5.$$

The wealth quintile-specific U5MR from region r for the w-th wealth quintile group for year t, denoted by $QR_{w,r,t}$, is computed as:

$$QR_{w,r,t} \quad = \quad QR(total)_{r,t} \cdot \frac{DR_{w,r,t} \cdot 5}{DR(total)_{r,t}}, \text{ for } w = 1,\ldots,5,$$

where

$$DR(total)_{r,t} \quad = \quad \sum_{c \in \{region[c]=r\}} D(total)_{c,t}.$$

[1]The World Bank country classification based on income can be downloaded at: `https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups`

$QR(total)_{r,t}$ is the aggregated U5MR from region r in year t from the UN IGME 2017 results [152].

Rounding

We kept three significant figures for all reported estimates and uncertainty intervals, including those for the number of wealth quintile-specific under-5 deaths.

5.4.9 Model validation

Model performance was assessed through out-of-sample validation. In the first exercise, we left out all observations that were obtained after a certain survey year leaving out around 20% observations [97]. Based on the current database, all data that were collected in the year 2011 and onward were left out. We fitted the model to the training data set, and obtained point estimates and uncertainty intervals that would have been constructed based on the available data set in the year 2011. We also assessed the model performance using the traditional approach of leaving out data at random, i.e. leaving out 20% of the data randomly, and repeated this exercise 30 times.

We calculated median errors and median absolute errors for the left-out observations, where errors are defined as $e_{a,i} = r_{w,i} - \widehat{r}_{w,i}$, with $\widehat{r}_{w,i}$ the posterior median of the predictive distribution based on training data set for the left-out observation $r_{w,i}$. Coverage is given by $1/n \cdot \sum 1[r_{w,i} \geq l_{w,i}] \cdot 1[r_{w,i} \leq u_{w,i}]$, where n refers to the number of left-out observations, and $l_{w,i}$ and $u_{w,i}$ correspond to the lower and upper bounds of the respective prediction interval (PI) for the left-out observation $r_{w,i}$. The validation measures were calculated for 100,000 sets of left-out observations, where each set consisted of only one randomly selected left-out observation from each country. The reported validation results were based on the mean of the outcomes from the 100,000 sets of left-out observations for the validation exercise based on leaving out all data since 2011, and the mean of the 100,000 times 30 training-set specific outcomes for the exercise with randomly left-out data.

For the validation based on leaving out recent data only, point estimates based on the full data set were compared to point estimates and uncertainty intervals obtained from the training data set. For this calculation, errors are defined as $e_{w,c,t} = R_{w,c,t} - R^{(train)}_{w,c,t}$, where $R_{w,c,t}$ is the posterior median for country c in year t for the w-th wealth quintile based on the full data set, and $R^{(train)}_{w,c,t}$ is the posterior median for the same country-year and wealth quintile based on the training data set. Coverage was computed in a similar manner as for the left-out observations, based on the lower and upper bounds of the 95% uncertainty interval of $R^{(train)}_{w,c,t}$ from the training data set.

5.5 Results

5.5.1 Quintile-specific U5MR for all low- and middle-income countries combined

For all the 137 low- and middle-income countries (excluding China) combined, in 2016, the U5MR for the poorest quintile ($U5MR_{Q1}$) was 64.6 (90% UI 61.1; 70.1) deaths per 1000 livebirths, 31.3 (29.5; 34.2) for the richest quintile ($U5MR_{Q5}$), and in between those outcomes for the middle quintiles (Table 5.5 and Figure 5.5). The U5MR decreased significantly for all quintiles between 1990 and 2016, with greater point estimates of average yearly absolute and percentage declines observed in 2000–2016 as compared to declines observed in 1990–2000. The largest absolute declines (Table 5.6) between 1990 and 2016 occurred in the two poorest quintiles with 77.6 (71.2; 82.6) deaths per 1000 livebirths in the 1st quintile (Q1) and 77.9 (72.0; 82.2) in the 2nd quintile (Q2). The corresponding percentage declines between 1990 and 2016 for Q1 and Q2 were 54.6% (50.6; 57.3) and 57.3% (53.6; 59.7) respectively (Table 5.7), which are similar to the levels of the percentage decline in other quintiles. Due to the greater absolute decline in U5MR in the poorest quintile than in the richest quintile, the difference between $U5MR_{Q1}$ and $U5MR_{Q5}$ decreased significantly from 72.0 (67.7; 76.5) deaths per 1000 livebirths in 1990, to

57.4 (53.9; 61.1) in 2000, and 33.2 (29.9; 37.6) in 2016 (Table 5.8). Similarly, the absolute disparity of U5MR among all the five quintiles, measured by the slope index of inequality, narrowed significantly over time, and shifted significantly closer to zero from -14.1 (-14.9; -13.3) deaths per 1000 livebirths in 1990, to -11.2 (-11.9; -10.6) in 2000, and -6.6 (-7.3; -6.0) in 2016. The relative disparity between the poorest and the richest U5MRs, however, remained at similar levels; the ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ was 2.03 (1.94; 2.11) in 1990, 1.99 (1.91; 2.08) in 2000, and 2.06 (1.92; 2.20) in 2016. The relative disparity across all quintiles, measured by the concentration index, also had minor fluctuations only between 1990 and 2016.

While the absolute burden of under-5 deaths declined for all low- and middle-income countries (excluding China) combined, the distribution of under-5 deaths across quintiles remained stable since 1990 (Table 5.9 and Figure 5.5). During 1990–2016, around half of the total under-5 deaths were children born in the poorest two quintiles (48.5% (48.0; 49.1) in 1990, 48.5% (47.9; 49.0) in 2000, and 49.5% (48.6; 50.4) in 2016) and only less than one third were from the richest two quintiles (30.4% (29.9; 30.9) in 1990, 30.5% (30.0; 31.0) in 2000, 29.9% (29.0; 30.6) in 2016). In 2016 alone, among the total 5.41 (5.17; 5.81) million under-5 deaths in low- and middle-income countries (excluding China), an estimated 1.41 (1.33; 1.53) million children died in the poorest households, compared to 0.68 (0.65; 0.75) million in the richest quintile.

5.5.2 Quintile-specific U5MR for regions

$U5MR_{Q1}$ and $U5MR_{Q5}$ levels varied across regions over time (Table 5.10, Table 5.11, Table 5.12, Table 5.13, Table 5.16, Table 5.17, Figure 5.6, Figure 5.7, Figure 5.8, and Figure 5.9). In 2016, at the regional level, $U5MR_{Q1}$ ranged from 19.4 (17.4; 22.9) deaths per 1000 livebirths in Eastern Europe and Central Asia to 119.9 (104.3; 141.6) deaths per 1000 livebirths in West and Central Africa (Table 5.10), and $U5MR_{Q5}$ ranged from 9.9 (8.6; 12.0) deaths per 1000 livebirths in Eastern Europe and Central Asia to 59.8 (52.6; 70.3) deaths per 1000 livebirths in

West and Central Africa (Table 5.11). In 2016, the ratios of $U5MR_{Q1}$ to $U5MR_{Q5}$ (Table 5.13) were found to be significantly above two in East Asia and Pacific (excluding China) at 2.49 (2.15; 2.87) and in South Asia at 2.41 (2.05; 2.80). Eastern and Southern Africa had the smallest ratio in 2016 of 1.62 (1.48; 1.76) and its concentration index (Table 5.15) was the closest to zero at -9.4 (-10.8; -8.0) per 100. Among all regions studied here, West and Central Africa and South Asia had the largest absolute differences between $U5MR_{Q1}$ and $U5MR_{Q5}$ in 2016 given by 60.1 (49.2; 75.1) and 38.4 (30.9; 46.2) deaths per 1000 livebirths respectively (Table 5.12). The region with the smallest absolute disparity in 2016 was Eastern Europe and Central Asia, with the difference between $U5MR_{Q1}$ and $U5MR_{Q5}$ at 9.6 (7.3; 12.5) deaths per 1000 livebirths, and the slope index of inequality at -1.9 (-2.4; -1.5) deaths per 1000 livebirths (Table 5.14).

From 1990 to 2016 across all regions, $U5MR_{Q1}$ and $U5MR_{Q5}$ decreased significantly. For both $U5MR_{Q1}$ and $U5MR_{Q5}$, based on point estimates, greater average yearly absolute declines were seen after 2000 than during the period 1990–2000 in Eastern Europe and Central Asia, Eastern and Southern Africa, and West and Central Africa (Table 5.16). Due to substantial absolute declines in both $U5MR_{Q1}$ and $U5MR_{Q5}$, the levels of $U5MR_{Q1}$ and $U5MR_{Q5}$ in 2016 were less than half of those in 1990 for all regions except for West and Central Africa with a 47.5% decline (90% UI 37.2; 54.6) in $U5MR_{Q1}$ (Table 5.17). Absolute declines in $U5MR_{Q1}$ were greater than those in $U5MR_{Q5}$ in all regions during 1990–2016. Consequently, differences between $U5MR_{Q1}$ and $U5MR_{Q5}$ decreased significantly for all regions, with the decreases ranging from 20.6 (15.9; 25.1) deaths per 1000 livebirths in Eastern Europe and Central Asia to 59.5 (48.5; 70.4) deaths per 1000 livebirths in South Asia. For all regions, the U5MR in the poorest quintile was the highest among all quintiles in 2016 and $U5MR_{Q5}$ the lowest (Figure 5.6). Similarly, in 1990, $U5MR_{Q5}$ was the lowest quintile-specific U5MR for all regions and $U5MR_{Q1}$ the highest, except for Eastern and Southern Africa, and West and Central Africa, where the U5MR in Q2 was lower than $U5MR_{Q1}$. On relative scale, the changes

of the ratios of $U5MR_{Q1}$ to $U5MR_{Q5}$ were significantly different from zero in two African regions only: the ratios increased between 1990 and 2016 in Eastern and Southern Africa, and West and Central Africa (Table 5.13 and Figure 5.7).

5.5.3 Expected relation between ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ and national-level U5MR

Figure 5.10 shows the model results of the average relative difference $U_{w,c,t}$ given the national-level U5MR for that country-year $Q_{\text{total},c,t}$. From left to right, the four plots show the model results of $U_{w,c,t}$ for $w = 1,2,4,5$ respectively. Comparing to the loess curves in green, within the 95% bounds of national-level U5MR, the model estimates and loess curves produce similar results.

Our model suggested an inverse relation between the ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ and national-level U5MR (Figure 5.11). The expected ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ (derived from the expected Q3-disparity ratios) is around 1.58 (1.47; 1.70) for very high levels of national-level U5MR (greater than 200 deaths per 1000 livebirths). The ratio increases to its maximum at 2.04 (1.79; 2.33) as national-level U5MR decreases to around 20 deaths per 1000 livebirths.

5.5.4 Country-level results

Generally, U5MR was the highest in Q1 and the lowest in Q5 but exceptions exist. Specifically, the $U5MR_{Q1}$ was greater than 90% of the average of $U5MR_{Q1}$ and $U5MR_{Q2}$ in 1990 for all the 99 countries with data except for Chad, and Niger. The $U5MR_{Q5}$ was smaller than 110% of the average of $U5MR_{Q4}$ and $U5MR_{Q5}$ for all countries in 1990 and 2016. The country disparity ranks of slope inequality index and concentration index in 2016 roughly agree with the ranks using the difference and ratio from the two extreme quintiles (Figure 5.12 and Figure 5.13), suggesting that disparities between the poorest and the richest household are informative of the disparities across all quintile groups.

The levels of absolute and relative disparities between the poorest and the richest quintiles in U5MR varied greatly among the 99 low- and middle-income countries with empirical data (Table 5.18, Table 5.19, and Table 5.20). In 2016, the difference between $U5MR_{Q1}$ and $U5MR_{Q5}$ and the ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ ranged widely across countries (Figure 5.14). The differences between $U5MR_{Q1}$ and $U5MR_{Q5}$ ranged from 2.8 (1.2; 4.2) deaths per 1000 livebirths in Belarus to 82.6 (56.0; 116.4) deaths per 1000 livebirths in Nigeria (table 3). The ratios of $U5MR_{Q1}$ to $U5MR_{Q5}$ ranged from 1.09 (0.91; 1.32) in Chad to 3.06 (2.32; 3.99) in Peru. In 2016, nine countries (Chad, Equatorial Guinea, Iraq, Lesotho, Liberia, Niger, Sierra Leone, South Sudan, and Zimbabwe) had ratios below 1.5. Among the nine countries, Chad, Iraq, and South Sudan also had small absolute differences between $U5MR_{Q1}$ and $U5MR_{Q5}$ (below 15 deaths per 1000 livebirths). Eleven countries (Bolivia (Plurinational State of), Brazil, Cambodia, Egypt, India, Indonesia, Lao People's Democratic Republic, Morocco, Peru, Philippines, and Turkey) had ratios above 2.5 in 2016. Of these 11 countries, all except Cambodia and Lao People's Democratic Republic had ratios above 2.5 in 1990 as well. Among the 11 countries with the highest ratios in 2016, Bolivia (Plurinational State of), India, and Lao People's Democratic Republic also had the largest absolute disparities, with the differences between $U5MR_{Q1}$ and $U5MR_{Q5}$ higher than 30 deaths per 1000 livebirths (Figure 5.14).

5.5.5 Validation results

Validation results suggested that our model was reasonably well calibrated, with conservative uncertainty intervals (i.e., wider than expected).

Leaving out data based on survey year

We left out all observations collected since the year 2011: 264 observations were left out, corresponding to 17.9% of all observations. Table 5.21 summarizes the results related to the left-out observations for the validation exercise based on 90%

and 80% prediction intervals (PIs). Median errors were very close to zero for left-out observations in all the wealth quintile groups. Coverage of 90% PIs were higher than expected: 100%, 96.1%, 100%, 98.2%, 92.6% for the 5 wealth quintile groups respectively. Coverage of 80% PIs were higher than expected at 93.6%, 89.7%, 97.3%, 84.7%, and 90.5% for each wealth quintile group.

Table 5.22 shows the results for the comparison between estimates obtained from the full data set, and estimates based on the training set. Median errors and the median absolute errors were close to zero. The proportion of updated estimates that fell outside the uncertainty intervals constructed based on the training set was well below 5%, as desired.

Leaving out data randomly

Table 5.23 shows the results of the validation exercises whereby data were left out at random. Median of error and median of absolute error are close to zero for all the wealth quintile groups. The proportions of left-out data falling outside the 90% and 80% PIs are lower than expected for all the wealth quintile groups. This means that the PIs of the model are more conservative than expected. No systematic biases are observed for PIs.

Wealth quintile	U5MR (deaths per 1000 livebirths)		
	1990	2000	2016
1st quintile	142.2 (138.6; 146.2)	115.3 (112.2; 118.5)	64.6 (61.1; 70.1)
2nd quintile	135.9 (132.6; 139.4)	108.9 (106.2; 112.0)	58.0 (54.9; 63.1)
3rd quintile	120.6 (118.0; 123.5)	97.3 (95.2; 99.6)	51.1 (48.6; 55.3)
4th quintile	104.1 (101.4; 107.0)	83.2 (81.1; 85.7)	42.5 (40.2; 46.1)
5th quintile	70.2 (68.0; 72.5)	57.8 (56.1; 59.7)	31.3 (29.5; 34.2)

Table 5.5 Estimates and 90% uncertainty intervals for quintile-specific U5MR in 1990, 2000, and 2016, for all the low- and middle-income countries (excluding China).

Wealth quintile	U5MR absolute decline (deaths per 1000 livebirths)		
	average decline per year		total decline
	1990–2000	2000–2016	1990–2016
1st quintile	2.7 (2.3; 3.1)	3.2 (2.8; 3.4)	77.6 (71.2; 82.6)
2nd quintile	2.7 (2.3; 3.1)	3.2 (2.8; 3.4)	77.9 (72.0; 82.2)
3rd quintile	2.3 (2.1; 2.6)	2.9 (2.6; 3.1)	69.4 (64.6; 73.0)
4th quintile	2.1 (1.8; 2.4)	2.5 (2.3; 2.7)	61.6 (57.2; 65.1)
5th quintile	1.2 (1.0; 1.4)	1.7 (1.5; 1.8)	38.9 (35.4; 41.4)

Table 5.6 Estimates and 90% uncertainty intervals for quintile-specific U5MR annual absolute decline during 1990–2000 and 2000–2016, and total absolute decline during 1990–2016, for all the low- and middle-income countries (excluding China).

Wealth quintile	U5MR percentage decline (%)		
	average decline per year		total decline
	1990–2000	2000–2016	1990–2016
1st quintile	2.1% (1.8; 2.4)	3.6% (3.1; 3.9)	54.6% (50.6; 57.3)
2nd quintile	2.2% (1.9; 2.5)	3.9% (3.4; 4.2)	57.3% (53.6; 59.7)
3rd quintile	2.1% (1.9; 2.3)	3.9% (3.5; 4.3)	57.6% (54.1; 59.8)
4th quintile	2.2% (1.9; 2.5)	4.1% (3.6; 4.5)	59.2% (55.6; 61.6)
5th quintile	1.9% (1.6; 2.2)	3.8% (3.2; 4.1)	55.4% (51.2; 58.0)

Table 5.7 **Estimates and 90% uncertainty intervals for quintile-specific U5MR annual percentage decline during 1990–2000 and 2000–2016, and total percentage decline during 1990–2016, for all the low- and middle-income countries (excluding China).**

Inequality index	1990	2000	2016
Ratio ($U5MR_{Q1}$: $U5MR_{Q5}$)	2.03	1.99	2.06
	(1.94; 2.11)	(1.91; 2.08)	(1.92; 2.20)
Difference ($U5MR_{Q1} - U5MR_{Q5}$)	72.0	57.4	33.2
(deaths per 1000 livebirths)	(67.7; 76.5)	(53.9; 61.1)	(29.9; 37.6)
Concentration index	-12.3	-12.2	-13.3
($\times 100$)	(-12.9; -11.6)	(-12.8; -11.5)	(-14.3; -12.2)
Slope inequality index	-14.1	-11.2	-6.6
(deaths per 1000 livebirths)	(-14.9; -13.3)	(-11.9; -10.6)	(-7.3; -6.0)

Table 5.8 **Estimates and 90% uncertainty intervals for ratio of and difference between $U5MR_{Q1}$ and $U5MR_{Q5}$ in 1990, 2000, and 2016, for all the low- and middle-income countries (excluding China).** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile.

Wealth quintile	percentage of quintile-specific to total under-5 deaths (%)		
	1990	2000	2016
1st quintile	24.8% (24.3; 25.4)	24.9% (24.3; 25.5)	26.1% (25.1; 27.1)
2nd quintile	23.7% (23.2; 24.2)	23.6% (23.1; 24.1)	23.4% (22.7; 24.2)
3rd quintile	21.0% (20.7; 21.4)	21.0% (20.7; 21.4)	20.7% (20.2; 21.2)
4th quintile	18.2% (17.7; 18.6)	18.0% (17.6; 18.4)	17.2% (16.5; 17.8)
5th quintile	12.2% (11.9; 12.6)	12.5% (12.2; 12.9)	12.7% (12.1; 13.3)

Table 5.9 **Estimates and 90% uncertainty intervals for proportion of quintile-specific to total under-5 deaths in 1990, 2000, and 2016, for all the low- and middle-income countries (excluding China).**

Region	$U5MR_{Q1}$ (deaths per 1000 livebirths)		
	1990	2000	2016
South Asia	167.8 (160.4; 175.6)	124.8 (118.1; 131.6)	65.7 (58.0; 73.9)
Eastern Europe and Central Asia	61.3 (57.4; 65.6)	48.0 (44.8; 51.6)	19.4 (17.4; 22.9)
Eastern and Southern Africa	173.4 (165.9; 181.7)	149.0 (143.8; 155.1)	73.6 (67.5; 83.7)
West and Central Africa	228.2 (215.6; 241.5)	200.7 (191.9; 210.4)	119.9 (104.3; 141.6)
Latin America and Caribbean	76.9 (71.2; 83.0)	47.5 (43.8; 51.2)	24.9 (22.3; 28.2)
East Asia and Pacific	98.5 (92.6; 105.0)	70.1 (66.2; 74.6)	39.2 (34.6; 45.4)
Middle East and North Africa	91.1 (85.9; 96.8)	61.5 (57.9; 65.0)	34.9 (30.9; 40.4)

Table 5.10 **Estimates and 90% uncertainty intervals for $U5MR_{Q1}$ in 1990, 2000, and 2016, by region.** $U5MR_{Q1}$ is the U5MR for Q1. Q1 is the 20% poorest quintile. Q=Quintile.

Region	$U5MR_{Q5}$ (deaths per 1000 livebirths)		
	1990	2000	2016
South Asia	69.8 (66.1; 73.8)	51.8 (48.4; 55.3)	27.2 (23.8; 31.7)
Eastern Europe and Central Asia	31.1 (28.3; 34.4)	24.6 (22.2; 27.2)	9.9 (8.6; 12.0)
Eastern and Southern Africa	124.5 (118.3; 131.7)	105.2 (100.8; 110.3)	45.5 (41.4; 52.0)
West and Central Africa	128.3 (121.3; 136.3)	108.9 (103.7; 114.5)	59.8 (52.6; 70.3)
Latin America and Caribbean	34.6 (30.4; 39.6)	21.0 (18.4; 23.9)	11.3 (9.7; 13.3)
East Asia and Pacific	42.2 (38.2; 46.6)	28.8 (26.2; 31.9)	15.7 (13.6; 18.6)
Middle East and North Africa	42.7 (38.7; 47.0)	28.9 (26.3; 31.6)	16.9 (14.8; 19.9)

Table 5.11 **Estimates and 90% uncertainty intervals for $U5MR_{Q5}$ in 1990, 2000, and 2016, by region.** $U5MR_{Q5}$ is the U5MR for Q5. Q5 is the 20% richest quintile. Q=Quintile.

Region	Difference ($U5MR_{Q1} - U5MR_{Q5}$) (deaths per 1000 livebirths)			
	1990	2000	2016	Change (1990–2016)
South Asia	98.0 (89.7; 106.4)	73.1 (65.4; 80.5)	38.4 (30.9; 46.2)	-59.5 (-70.4; -48.5)
Eastern Europe and Central Asia	30.2 (25.0; 35.6)	23.4 (19.3; 27.7)	9.6 (7.3; 12.5)	-20.6 (-25.1; -15.9)
Eastern and Southern Africa	48.9 (38.9; 59.0)	43.8 (37.4; 50.4)	28.1 (23.0; 34.7)	-20.8 (-31.1; -9.6)
West and Central Africa	99.9 (85.5; 114.2)	91.8 (82.7; 101.4)	60.1 (49.2; 75.1)	-39.8 (-57.3; -19.1)
Latin America and Caribbean	42.3 (34.2; 50.3)	26.5 (21.3; 31.5)	13.6 (10.2; 17.4)	-28.6 (-35.7; -21.2)
East Asia and Pacific	56.3 (48.4; 64.5)	41.3 (36.2; 46.7)	23.5 (19.2; 28.4)	-32.9 (-40.8; -24.6)
Middle East and North Africa	48.4 (41.0; 55.9)	32.6 (27.9; 37.1)	18.0 (14.5; 22.3)	-30.4 (-37.5; -22.9)

Table 5.12 **Estimates and 90% uncertainty intervals for difference between $U5MR_{Q1}$ and $U5MR_{Q5}$ in 1990, 2000, and 2016, by region.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile.

Region	Ratio ($U5MR_{Q1} : U5MR_{Q5}$)			
	1990	2000	2016	Change (1990–2016)
South Asia	2.40 (2.24; 2.58)	2.41 (2.21; 2.62)	2.41 (2.05; 2.80)	0.01 (-0.38; 0.41)
Eastern Europe and Central Asia	1.97 (1.75; 2.23)	1.95 (1.73; 2.21)	1.97 (1.67; 2.32)	0.00 (-0.26; 0.28)
Eastern and Southern Africa	1.39 (1.30; 1.49)	1.42 (1.35; 1.49)	1.62 (1.48; 1.76)	0.23 (0.07; 0.38)
West and Central Africa	1.78 (1.64; 1.92)	1.84 (1.74; 1.95)	2.00 (1.82; 2.21)	0.23 (0.00; 0.47)
Latin America and Caribbean	2.22 (1.88; 2.62)	2.26 (1.91; 2.67)	2.21 (1.80; 2.71)	-0.01 (-0.38; 0.40)
East Asia and Pacific	2.34 (2.06; 2.64)	2.43 (2.17; 2.73)	2.49 (2.15; 2.87)	0.15 (-0.19; 0.51)
Middle East and North Africa	2.13 (1.89; 2.41)	2.13 (1.90; 2.37)	2.06 (1.80; 2.36)	-0.07 (-0.37; 0.23)

Table 5.13 **Estimates and 90% uncertainty intervals for ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ in 1990, 2000, and 2016, by region.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile.

Region	Slope inequality index (deaths per 1000 livebirths)		
	1990	2000	2016
South Asia	-19.5 (-21; -18)	-14.6 (-15.9; -13.2)	-7.6 (-9; -6.3)
Eastern Europe and Central Asia	-5.9 (-6.8; -5)	-4.7 (-5.4; -4)	-1.9 (-2.4; -1.5)
Eastern and Southern Africa	-9.3 (-11.1; -7.5)	-8.2 (-9.4; -7.1)	-5.8 (-7; -4.9)
West and Central Africa	-19 (-21.6; -16.4)	-17.7 (-19.5; -16.1)	-11.8 (-14.7; -9.8)
Latin America and Caribbean	-8.2 (-9.6; -6.8)	-5.2 (-6; -4.3)	-2.7 (-3.3; -2.1)
East Asia and Pacific	-10.6 (-12; -9.3)	-7.8 (-8.7; -7)	-4.5 (-5.4; -3.7)
Middle East and North Africa	-9.3 (-10.6; -8)	-6.3 (-7; -5.5)	-3.5 (-4.3; -2.9)

Table 5.14 **Estimates and 90% uncertainty intervals for Slope inequality index (deaths per 1000 livebirths) in 1990, 2000, and 2016, by region.**

Region	Concentration index ($\times$100)		
	1990	2000	2016
South Asia	-15.1 (-16.2; -14)	-15.6 (-16.9; -14.2)	-15.7 (-18.1; -13.2)
Eastern Europe and Central Asia	-12.7 (-14.5; -10.8)	-12.9 (-14.8; -10.9)	-13.3 (-16.1; -10.6)
Eastern and Southern Africa	-5.6 (-6.7; -4.6)	-6 (-6.8; -5.1)	-9.4 (-10.8; -8)
West and Central Africa	-9.6 (-10.8; -8.3)	-10.3 (-11.2; -9.3)	-12.5 (-14; -10.9)
Latin America and Caribbean	-14.5 (-16.9; -12.1)	-15.1 (-17.5; -12.6)	-15.1 (-18.3; -11.9)
East Asia and Pacific	-14.7 (-16.6; -12.9)	-15.7 (-17.4; -14)	-16.4 (-18.6; -14.1)
Middle East and North Africa	-13.5 (-15.4; -11.7)	-13.7 (-15.4; -12)	-13.6 (-15.8; -11.4)

Table 5.15 **Estimates and 90% uncertainty intervals for concentration index in 1990, 2000, and 2016, by region.**

Region	$U5MR_{Q1}$ absolute decline (deaths per 1000 livebirths)			$U5MR_{Q5}$ absolute decline (deaths per 1000 livebirths)		
	average decline per year		total decline	average decline per year		total decline
	1990–2000	2000–2016	1990–2016	1990–2000	2000–2016	1990–2016
South Asia	4.3 (3.4; 5.2)	3.7 (3.1; 4.3)	102.1 (90.8; 112.6)	1.8 (1.4; 2.2)	1.5 (1.2; 1.8)	42.6 (36.9; 47.7)
Eastern Europe and Central Asia	1.3 (1.0; 1.6)	1.8 (1.5; 2.0)	41.9 (37.4; 45.8)	0.7 (0.5; 0.8)	0.9 (0.8; 1.0)	21.3 (18.5; 23.8)
Eastern and Southern Africa	2.4 (1.8; 3.1)	4.7 (4.1; 5.2)	99.9 (87.5; 109.3)	1.9 (1.4; 2.5)	3.7 (3.3; 4.1)	79.1 (70.2; 86.3)
West and Central Africa	2.7 (1.7; 3.9)	5.1 (3.6; 6.1)	108.3 (83.0; 127.9)	1.9 (1.3; 2.6)	3.1 (2.4; 3.6)	68.5 (56.3; 78.3)
Latin America and Caribbean	2.9 (2.5; 3.4)	1.4 (1.2; 1.6)	52.0 (46.1; 57.7)	1.4 (1.1; 1.7)	0.6 (0.5; 0.7)	23.4 (19.7; 27.3)
East Asia and Pacific	2.8 (2.3; 3.4)	1.9 (1.5; 2.3)	59.3 (51.0; 66.7)	1.3 (1.1; 1.6)	0.8 (0.6; 1.0)	26.4 (22.3; 30.5)
Middle East and North Africa	3.0 (2.6; 3.4)	1.7 (1.3; 1.9)	56.2 (49.1; 62.3)	1.4 (1.1; 1.7)	0.7 (0.6; 0.9)	25.8 (21.5; 29.9)

Table 5.16 **Estimates and 90% uncertainty intervals for $U5MR_{Q1}$ and $U5MR_{Q5}$ absolute decline during 1990–2000, 2000–2016, and 1990–2016, by region.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile.

Region	$U5MR_{Q1}$ percentage decline (%)			$U5MR_{Q5}$ percentage decline (%)		
	average decline per year		total decline	average decline per year		total decline
	1990–2000	2000–2016	1990–2016	1990–2000	2000–2016	1990–2016
South Asia	2.9% (2.3; 3.5)	3.9% (3.2; 4.7)	60.9% (55.5; 65.6)	3.0% (2.2; 3.6)	3.9% (3.0; 4.8)	61.0% (54.3; 66.3)
Eastern Europe and Central Asia	2.4% (1.8; 3.0)	5.5% (4.6; 6.1)	68.3% (62.8; 71.6)	2.3% (1.7; 2.9)	5.5% (4.5; 6.2)	68.2% (62.4; 71.9)
Eastern and Southern Africa	1.5% (1.1; 1.9)	4.3% (3.5; 4.8)	57.6% (51.5; 61.4)	1.7% (1.2; 2.1)	5.1% (4.3; 5.6)	63.5% (58.0; 67.0)
West and Central Africa	1.3% (0.8; 1.8)	3.2% (2.1; 4.0)	47.5% (37.2; 54.6)	1.6% (1.1; 2.1)	3.7% (2.7; 4.4)	53.4% (44.9; 59.2)
Latin America and Caribbean	4.7% (4.1; 5.3)	3.9% (3.2; 4.5)	67.6% (63.1; 71.1)	4.9% (4.2; 5.6)	3.5% (2.8; 4.1)	67.5% (62.6; 71.2)
East Asia and Pacific	3.3% (2.8; 3.9)	3.6% (2.7; 4.3)	60.2% (53.5; 65.2)	3.7% (3.1; 4.4)	3.6% (2.7; 4.4)	62.7% (55.9; 67.7)
Middle East and North Africa	3.9% (3.4; 4.4)	3.5% (2.6; 4.2)	61.7% (55.5; 66.2)	3.8% (3.2; 4.5)	3.3% (2.4; 4.0)	60.4% (53.5; 65.5)

Table 5.17 **Estimates and 90% uncertainty intervals for $U5MR_{Q1}$ and $U5MR_{Q5}$ percentage decline during 1990–2000, 2000–2016, and 1990–2016, by region.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile.

Table 5.18 **Estimates and 90% uncertainty intervals for $U5MR_{Q1}$ and $U5MR_{Q5}$ in 1990 and 2016, for the 99 countries with empirical data.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile. §: change of ratio of UMRQ1 to U5MRQ5 is significantly different from zero; ¶: point estimates of ratio ($U5MR_{Q1} : U5MR_{Q5}$) < 1.5 in 2016; †: point estimates of ratio ($U5MR_{Q1} : U5MR_{Q5}$) > 2.5 in 2016. Countries are ordered alphabetically.

Country	$U5MR_{Q1}$ 1990	$U5MR_{Q1}$ 2016	$U5MR_{Q5}$ 1990	$U5MR_{Q5}$ 2016
Afghanistan	201.9 (171.2; 237.2)	90.5 (71.2; 112.3)	117.3 (96.5; 142.0)	45.5 (35.3; 57.6)
Angola	232.3 (195.8; 275.0)	98.7 (48.5; 178.6)	171.0 (140.4; 207.7)	60.9 (29.4; 112.6)
Albania	49.5 (39.5; 60.1)	17.7 (9.3; 33.2)	27.8 (20.5; 36.9)	9.4 (4.8; 18.4)
Armenia	65.5 (53.9; 77.8)	18.7 (13.4; 26.2)	32.5 (24.0; 43.1)	8.9 (5.9; 13.2)
Azerbaijan	113.0 (94.5; 133.3)	40.0 (23.5; 69.4)	64.3 (49.6; 82.0)	20.1 (11.3; 36.2)
Burundi	204.8 (172.8; 241.5)	94.5 (71.1; 123.1)	112.8 (90.8; 138.6)	46.1 (33.7; 62.7)
Benin	198.8 (177.1; 222.5)	116.6 (86.6; 161.5)	127.7 (111.3; 146.9)	67.0 (48.9; 93.8)
Burkina Faso	208.4 (187.5; 229.8)	101.0 (75.5; 133.6)	146.5 (131.0; 163.5)	59.5 (44.4; 79.4)
Bangladesh	172.9 (159.9; 186.7)	45.3 (38.7; 52.5)	96.1 (87.2; 105.6)	22.2 (18.6; 26.3)
Belarus	20.9 (17.1; 25.0)	5.4 (4.3; 6.4)	10.1 (7.4; 13.5)	2.6 (1.9; 3.5)
Belize	51.2 (41.2; 62.9)	20.5 (16.3; 25.1)	25.6 (18.4; 34.8)	9.8 (7.1; 13.3)
Bolivia (Plurinational State of)*	170.8 (154.5; 188.0)	55.1 (37.4; 78.1)	63.6 (55.4; 72.5)	18.6 (12.4; 27.1)
Brazil*	93.9 (80.7; 108.1)	23.1 (17.7; 29.6)	36.4 (27.8; 46.9)	8.7 (6.1; 12.1)
Bhutan	164.6 (135.2; 200.3)	46.9 (32.0; 66.5)	78.3 (58.1; 104.8)	18.8 (11.9; 28.7)
Central African Republic	199.3 (174.5; 227.5)	154.3 (97.6; 242.2)	118.3 (101.1; 137.7)	82.9 (52.1; 132.4)
Cote d'Ivoire	181.9 (162.3; 203.3)	113.8 (83.0; 153.9)	101.0 (88.0; 115.0)	63.8 (45.8; 88.4)
Cameroon	185.6 (165.0; 207.6)	106.5 (79.8; 142.2)	93.2 (80.9; 107.1)	52.0 (38.3; 71.0)
Democratic Republic of the Congo	215.3 (185.1; 249.4)	117.7 (82.2; 164.7)	111.0 (92.4; 133.2)	58.7 (40.0; 84.2)

$U5MR_{Q1}$ and $U5MR_{Q5}$ are in deaths per 1000 livebirths.

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Table 5.18 – continued from previous page

Country	$U5MR_{Q1}$ 1990	$U5MR_{Q1}$ 2016	$U5MR_{Q5}$ 1990	$U5MR_{Q5}$ 2016
Congo	102.5 (84.8; 122.5)	63.2 (43.6; 87.8)	68.1 (53.8; 85.5)	40.0 (27.5; 57.2)
Colombia	47.3 (41.3; 53.6)	21.5 (16.1; 28.4)	24.3 (20.2; 29.1)	10.6 (7.6; 14.4)
Comoros	148.8 (123.5; 177.0)	90.1 (46.9; 181.5)	91.8 (73.4; 112.6)	54.3 (27.8; 110.1)
Dominican Republic	77.8 (68.1; 88.3)	40.0 (29.4; 54.0)	38.0 (31.0; 46.4)	20.1 (14.3; 27.8)
Algeria	63.7 (53.7; 74.5)	33.9 (28.7; 39.8)	34.6 (26.9; 44.0)	17.9 (14.0; 22.6)
Egypt*	123.1 (112.1; 134.7)	33.1 (25.3; 43.5)	45.8 (39.3; 53.3)	12.9 (9.6; 17.6)
Eritrea	150.8 (125.5; 178.7)	52.1 (32.1; 82.9)	97.9 (76.8; 123.2)	27.6 (16.7; 45.6)
Ethiopia	190.5 (164.6; 218.7)	67.2 (52.0; 87.4)	161.3 (138.9; 186.7)	43.6 (33.1; 56.9)
Gabon	104.3 (85.5; 126.4)	57.5 (37.8; 84.7)	64.5 (49.3; 83.4)	32.5 (20.9; 49.1)
Georgia	60.3 (48.9; 72.8)	14.5 (11.5; 18.2)	30.4 (22.1; 40.7)	7.0 (5.0; 9.5)
Ghana	155.8 (140.5; 172.0)	76.3 (56.8; 101.1)	89.0 (77.2; 102.0)	43.1 (31.5; 58.5)
Guinea	272.9 (240.1; 308.6)	115.0 (90.6; 146.8)	162.6 (140.4; 188.9)	57.9 (44.7; 75.6)
The Gambia	183.8 (153.5; 218.9)	78.9 (48.3; 126.8)	113.7 (91.7; 139.8)	42.2 (25.5; 68.7)
Guinea-Bissau	241.0 (204.1; 282.0)	104.8 (70.4; 147.4)	155.1 (129.1; 184.8)	63.1 (42.4; 91.2)
Equatorial Guinea¶	206.6 (169.2; 252.3)	109.0 (70.5; 162.7)	172.9 (137.3; 216.9)	79.3 (50.0; 122.2)
Guatemala	93.2 (81.6; 105.2)	36.1 (28.4; 45.5)	57.2 (46.5; 69.3)	18.7 (13.9; 24.8)
Guyana	68.4 (56.1; 81.8)	37.9 (24.6; 58.4)	45.8 (35.5; 59.3)	24.6 (15.6; 39.4)
Honduras	79.9 (68.2; 92.5)	27.3 (19.6; 37.5)	35.5 (27.8; 44.4)	11.5 (7.8; 16.5)
Haiti	158.0 (140.2; 177.7)	79.4 (59.8; 107.4)	107.0 (91.5; 124.5)	47.5 (35.3; 65.0)
Indonesia*	119.2 (106.5; 133.6)	39.3 (30.3; 50.9)	47.2 (39.3; 56.5)	14.8 (11.0; 19.9)
India*	169.7 (160.0; 179.5)	61.2 (52.2; 70.7)	61.6 (57.2; 66.3)	22.0 (18.2; 26.9)

$U5MR_{Q1}$ and $U5MR_{Q5}$ are in deaths per 1000 livebirths.

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Table 5.18 – continued from previous page

Country	$U5MR_{Q1}$ 1990	$U5MR_{Q1}$ 2016	$U5MR_{Q5}$ 1990	$U5MR_{Q5}$ 2016
Iraq¶	63.0 (52.5; 74.1)	36.8 (26.5; 51.0)	46.3 (37.0; 57.4)	27.2 (19.1; 38.4)
Jordan	45.2 (39.4; 51.6)	23.0 (15.7; 32.8)	26.9 (22.5; 32.1)	13.0 (8.8; 18.8)
Kazakhstan	63.6 (53.4; 74.6)	14.9 (12.3; 17.8)	36.8 (28.8; 46.6)	8.1 (6.2; 10.3)
Kenya	125.4 (112.6; 139.3)	60.4 (48.3; 75.3)	72.1 (63.2; 81.9)	37.1 (29.2; 47.6)
Kyrgyz Republic	82.0 (68.0; 97.0)	28.2 (23.8; 33.1)	46.8 (36.3; 59.3)	14.9 (11.7; 18.7)
Cambodia*	147.3 (129.2; 166.8)	42.8 (26.2; 69.7)	61.0 (50.4; 72.9)	15.5 (9.2; 26.3)
Lao People's Democratic Republic*	196.1 (162.2; 235.0)	87.1 (60.2; 123.6)	84.5 (63.7; 109.0)	31.4 (20.5; 46.9)
Liberia¶	260.1 (219.0; 307.0)	78.0 (56.4; 109.8)	231.6 (192.8; 276.9)	58.9 (42.0; 83.3)
Lesotho¶	102.6 (87.0; 120.0)	103.4 (77.2; 138.1)	70.4 (57.9; 84.7)	71.1 (52.0; 96.4)
Morocco*	106.1 (92.8; 120.4)	38.5 (27.0; 53.7)	42.2 (34.6; 50.8)	14.6 (9.9; 21.2)
Republic of Moldova	42.9 (33.9; 53.3)	21.5 (14.3; 33.0)	23.5 (17.0; 32.0)	11.4 (7.2; 18.4)
Madagascar	187.0 (164.9; 210.5)	62.2 (42.2; 90.8)	96.5 (81.8; 113.5)	27.2 (17.8; 40.7)
Maldives	113.6 (92.9; 136.9)	11.5 (8.4; 15.3)	65.2 (48.3; 87.4)	5.7 (3.9; 8.2)
The former Yugoslav Republic of Macedonia	50.1 (41.7; 58.5)	17.2 (11.9; 28.1)	24.6 (18.3; 32.4)	8.1 (5.2; 13.9)
Mali	278.8 (252.0; 308.2)	132.8 (80.8; 212.2)	170.8 (152.1; 191.3)	68.3 (41.5; 109.8)
Myanmar	139.4 (114.3; 166.4)	66.2 (48.5; 86.9)	77.9 (57.4; 103.3)	32.6 (22.2; 46.4)
Mongolia	138.2 (118.2; 159.9)	26.0 (17.1; 39.0)	71.9 (58.1; 87.9)	11.1 (6.9; 17.1)
Mozambique	267.9 (234.4; 306.3)	86.4 (62.7; 119.7)	184.7 (158.4; 214.4)	53.8 (38.4; 75.1)
Mauritania	146.0 (122.5; 171.8)	104.3 (56.9; 190.9)	84.0 (66.9; 103.5)	58.6 (31.6; 109.6)

$U5MR_{Q1}$ and $U5MR_{Q5}$ are in deaths per 1000 livebirths.

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Table 5.18 – continued from previous page

Country	$U5MR_{Q1}$ 1990	$U5MR_{Q1}$ 2016	$U5MR_{Q5}$ 1990	$U5MR_{Q5}$ 2016
Malawi	242.4 (218.5; 267.4)	65.2 (49.2; 85.5)	175.2 (156.3; 195.8)	41.9 (31.4; 55.5)
Namibia	81.7 (70.7; 93.6)	56.2 (37.8; 83.8)	49.3 (40.9; 58.9)	29.4 (19.3; 45.0)
Niger¶‖	305.4 (272.0; 341.9)	96.5 (67.8; 138.1)	234.0 (205.3; 264.1)	66.9 (46.2; 96.9)
Nigeria	253.5 (225.3; 284.2)	140.1 (101.4; 189.5)	124.5 (109.4; 142.2)	57.5 (41.5; 79.2)
Nicaragua	81.4 (69.8; 94.2)	26.1 (16.1; 43.1)	41.6 (33.1; 51.9)	12.2 (7.1; 20.4)
Nepal	153.9 (136.4; 172.8)	44.1 (35.4; 55.1)	95.0 (81.4; 109.3)	22.2 (17.3; 28.7)
Pakistan	160.0 (142.3; 178.1)	98.4 (74.4; 130.4)	92.2 (79.1; 106.6)	52.0 (38.0; 70.3)
Peru*	118.7 (108.1; 129.3)	23.9 (18.0; 32.1)	39.1 (33.4; 45.1)	7.8 (5.6; 11.0)
Philippines*	87.5 (78.5; 97.1)	41.2 (29.6; 57.1)	30.6 (25.8; 36.0)	14.2 (9.8; 20.3)
Paraguay	58.7 (49.1; 69.7)	26.6 (15.8; 44.1)	29.2 (21.8; 38.1)	12.6 (7.2; 21.7)
State of Palestine	57.6 (47.3; 68.7)	26.2 (18.0; 38.3)	28.9 (21.5; 37.7)	12.6 (8.1; 19.3)
Rwanda§	149.4 (133.0; 167.2)	47.9 (30.1; 75.4)	121.2 (107.3; 136.6)	28.4 (17.7; 45.2)
Sudan	145.2 (122.4; 170.2)	77.0 (59.8; 98.3)	89.4 (71.8; 109.6)	42.5 (32.1; 55.2)
Senegal	179.1 (160.7; 198.3)	65.1 (50.4; 84.7)	86.2 (74.2; 99.7)	27.6 (20.8; 36.7)
Sierra Leone¶‖	280.2 (241.9; 320.9)	130.5 (99.8; 165.9)	212.7 (179.8; 247.8)	97.7 (74.2; 125.2)
El Salvador	76.5 (62.7; 91.7)	21.0 (13.8; 31.3)	40.3 (29.5; 53.4)	10.1 (6.2; 16.1)
Somalia	195.6 (150.1; 252.5)	151.1 (81.3; 282.0)	131.5 (93.4; 182.0)	95.4 (50.6; 183.1)
Serbia	37.3 (31.1; 44.2)	7.9 (6.3; 10.0)	19.4 (14.5; 25.8)	4.0 (2.9; 5.5)
South Sudan¶‖	251.6 (194.2; 317.6)	98.6 (59.5; 160.3)	247.8 (186.4; 322.6)	88.5 (52.5; 145.0)
Sao Tome and Principe	119.1 (96.0; 144.9)	41.9 (26.9; 63.0)	91.0 (70.6; 115.9)	27.2 (17.1; 42.8)
Suriname	64.1 (49.2; 82.1)	28.6 (13.6; 59.4)	28.4 (19.9; 40.1)	12.5 (5.6; 26.8)

$U5MR_{Q1}$ and $U5MR_{Q5}$ are in deaths per 1000 livebirths.

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Table 5.18 – continued from previous page

Country	$U5MR_{Q1}$ 1990	$U5MR_{Q1}$ 2016	$U5MR_{Q5}$ 1990	$U5MR_{Q5}$ 2016
Swaziland	83.4 (69.5; 99.4)	89.3 (59.7; 130.7)	50.4 (40.6; 61.7)	54.3 (35.9; 80.0)
Syria	46.6 (38.2; 55.6)	22.7 (16.5; 33.0)	25.8 (19.3; 34.0)	12.6 (8.5; 19.6)
Chad¶	178.1 (156.7; 201.0)	126.2 (101.3; 155.5)	193.1 (171.0; 217.7)	115.8 (92.3; 141.0)
Togo	170.1 (149.6; 192.8)	99.0 (77.1; 125.7)	85.2 (72.1; 99.7)	40.9 (31.0; 53.1)
Thailand	48.8 (40.4; 57.7)	16.5 (9.7; 28.1)	24.9 (18.3; 33.3)	8.1 (4.5; 14.4)
Tajikistan	124.2 (103.9; 147.0)	54.0 (32.0; 92.1)	88.0 (71.1; 107.9)	33.6 (19.5; 59.1)
Turkmenistan	109.4 (87.2; 135.9)	68.6 (28.7; 147.5)	59.3 (42.7; 79.4)	33.9 (13.8; 74.0)
Timor-Leste	186.4 (152.7; 223.4)	61.0 (39.4; 94.6)	118.8 (91.7; 151.7)	32.2 (20.3; 51.3)
Tunisia	73.6 (58.9; 90.2)	19.0 (12.9; 27.5)	37.2 (26.8; 51.0)	8.9 (5.7; 13.6)
Turkey*	109.4 (96.7; 123.8)	19.6 (16.6; 22.9)	39.4 (31.3; 49.0)	6.8 (5.3; 8.8)
United Republic of Tanzania¶	171.9 (152.4; 193.2)	63.0 (49.8; 80.9)	142.1 (124.5; 161.3)	47.5 (37.3; 61.2)
Uganda	196.1 (175.2; 218.3)	67.4 (54.6; 82.4)	133.3 (117.5; 150.8)	38.7 (30.7; 47.9)
Ukraine	26.2 (21.1; 32.6)	12.4 (10.1; 15.0)	13.0 (9.4; 17.8)	6.1 (4.4; 8.1)
Uzbekistan	80.5 (66.4; 96.7)	29.5 (23.0; 37.4)	59.4 (47.3; 73.9)	19.2 (14.2; 25.2)
Vietnam	72.4 (61.7; 84.4)	31.6 (25.3; 39.8)	30.4 (23.5; 38.6)	13.0 (9.7; 17.6)
Vanuatu	46.8 (36.6; 58.8)	36.6 (23.5; 57.5)	23.0 (16.1; 31.9)	18.0 (10.8; 29.6)
Yemen	160.3 (135.9; 187.4)	76.1 (52.9; 107.6)	76.7 (59.3; 97.7)	32.3 (21.0; 48.9)
South Africa	78.7 (65.1; 94.7)	59.9 (47.5; 73.3)	33.7 (25.2; 44.5)	25.7 (18.4; 34.7)
Zambia	196.4 (176.6; 218.2)	76.8 (55.0; 104.9)	139.6 (123.6; 157.1)	48.5 (34.5; 66.8)
Zimbabwe	82.4 (71.3; 94.1)	67.9 (51.0; 88.9)	59.8 (50.9; 69.7)	41.9 (31.0; 55.0)

Table 5.19 **Estimates and 90% uncertainty intervals for difference ($U5MR_{Q1} - U5MR_{Q5}$) and ratio ($U5MR_{Q1} : U5MR_{Q5}$) in 1990 and 2016, for the 99 countries with empirical data.** $U5MR_{Q1}$ is the U5MR for Q1, $U5MR_{Q5}$ is the U5MR for Q5. Q1 is the 20% poorest quintile, Q5 is the 20% richest quintile. Q=Quintile. §: change of ratio of UMRQ1 to U5MRQ5 is significantly different from zero; ¶: point estimates of ratio ($U5MR_{Q1} : U5MR_{Q5}$) < 1.5 in 2016; †: point estimates of ratio ($U5MR_{Q1} : U5MR_{Q5}$) > 2.5 in 2016. Countries are ordered alphabetically.

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Afghanistan	84.5 (45.7; 124.2)	45.1 (29.9; 61.6)	1.72 (1.34; 2.20)	1.99 (1.62; 2.42)
Angola	61.3 (15.2; 108.2)	37.8 (13.5; 78.2)	1.36 (1.08; 1.72)	1.62 (1.24; 2.12)
Albania	21.7 (8.0; 35.0)	8.3 (2.6; 18.0)	1.78 (1.23; 2.57)	1.88 (1.27; 2.80)
Armenia	33.0 (16.0; 49.3)	9.8 (4.6; 16.2)	2.02 (1.40; 2.93)	2.11 (1.42; 3.19)
Azerbaijan	48.7 (22.7; 74.3)	19.9 (8.6; 38.4)	1.76 (1.29; 2.40)	1.99 (1.43; 2.84)
Burundi	92.0 (51.2; 132.9)	48.4 (27.5; 71.9)	1.82 (1.40; 2.36)	2.05 (1.54; 2.70)
Benin	71.1 (42.4; 98.9)	49.6 (27.7; 78.4)	1.56 (1.30; 1.85)	1.74 (1.39; 2.19)
Burkina Faso	61.8 (37.4; 85.5)	41.5 (23.4; 63.7)	1.42 (1.24; 1.62)	1.70 (1.38; 2.10)
Bangladesh	76.8 (59.9; 93.6)	23.1 (16.0; 30.4)	1.80 (1.58; 2.04)	2.04 (1.66; 2.51)
Belarus	10.8 (4.8; 16.5)	2.8 (1.2; 4.2)	2.07 (1.37; 3.11)	2.08 (1.36; 3.14)
Belize	25.6 (11.1; 39.8)	10.6 (4.7; 16.5)	2.00 (1.34; 2.98)	2.08 (1.37; 3.17)
Bolivia (Plurinational State of)*	107.1 (89.4; 125.3)	36.5 (23.3; 53.6)	2.68 (2.29; 3.15)	2.96 (2.31; 3.77)
Brazil*	57.6 (39.4; 75.4)	14.3 (8.6; 20.8)	2.58 (1.88; 3.57)	2.64 (1.81; 3.89)
Bhutan	86.3 (47.0; 126.3)	28.1 (15.7; 43.8)	2.10 (1.48; 3.00)	2.49 (1.74; 3.56)
Central African Republic	81.0 (55.4; 107.5)	71.4 (38.2; 121.7)	1.68 (1.43; 1.98)	1.86 (1.48; 2.32)
Cote d'Ivoire	80.9 (58.8; 104.7)	50.0 (27.9; 76.8)	1.80 (1.54; 2.13)	1.78 (1.41; 2.25)

Difference is in deaths per 1000 livebirths.
Difference: $U5MR_{Q1} - U5MR_{Q5}$
Ratio: $U5MR_{Q1} : U5MR_{Q5}$

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Table 5.19 – continued from previous page

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Cameroon	92.4 (69.1; 115.8)	54.5 (33.2; 80.2)	1.99 (1.68; 2.35)	2.05 (1.60; 2.59)
Democratic Republic of the Congo	104.2 (70.7; 139.5)	59.0 (35.0; 89.3)	1.94 (1.57; 2.39)	2.01 (1.59; 2.51)
Congo	34.4 (12.7; 56.2)	23.2 (9.5; 39.8)	1.50 (1.16; 1.96)	1.58 (1.22; 2.06)
Colombia	23.0 (15.1; 30.7)	11.0 (6.4; 16.3)	1.95 (1.55; 2.45)	2.04 (1.54; 2.69)
Comoros	57.0 (25.5; 88.4)	35.8 (12.1; 80.9)	1.62 (1.24; 2.11)	1.66 (1.23; 2.20)
Dominican Republic	39.8 (26.0; 52.9)	19.9 (11.7; 30.3)	2.05 (1.59; 2.63)	1.99 (1.53; 2.59)
Algeria	29.1 (14.3; 43.3)	16.0 (8.5; 23.5)	1.84 (1.34; 2.53)	1.89 (1.39; 2.57)
Egypt*	77.3 (63.5; 91.3)	20.1 (13.8; 28.0)	2.69 (2.24; 3.24)	2.55 (2.01; 3.22)
Eritrea	52.9 (17.6; 89.0)	24.4 (10.7; 44.7)	1.54 (1.15; 2.10)	1.88 (1.35; 2.63)
Ethiopia	29.2 (-6.1; 64.4)	23.7 (10.9; 38.7)	1.18 (0.97; 1.44)	1.54 (1.23; 1.94)
Gabon	39.8 (16.7; 63.4)	25.0 (11.0; 42.7)	1.62 (1.22; 2.16)	1.77 (1.31; 2.37)
Georgia	29.9 (13.9; 46.1)	7.5 (3.4; 11.7)	1.98 (1.36; 2.93)	2.08 (1.39; 3.15)
Ghana	66.8 (46.5; 87.2)	33.2 (18.8; 50.0)	1.75 (1.47; 2.09)	1.77 (1.42; 2.22)
Guinea	110.3 (69.3; 151.6)	57.1 (37.4; 81.6)	1.68 (1.39; 2.02)	1.99 (1.61; 2.45)
The Gambia	70.1 (34.0; 108.6)	36.7 (17.8; 65.3)	1.62 (1.26; 2.08)	1.87 (1.44; 2.43)
Guinea-Bissau	85.8 (45.1; 127.8)	41.7 (20.4; 68.6)	1.55 (1.27; 1.90)	1.66 (1.32; 2.09)
Equatorial Guinea¶	33.8 (-14.8; 80.4)	29.7 (2.8; 61.5)	1.20 (0.93; 1.53)	1.37 (1.03; 1.85)
Guatemala	36.0 (18.2; 52.9)	17.4 (9.8; 25.9)	1.63 (1.27; 2.09)	1.93 (1.46; 2.57)
Guyana	22.6 (3.0; 40.4)	13.3 (2.3; 26.5)	1.49 (1.05; 2.07)	1.54 (1.09; 2.17)
Honduras	44.4 (28.8; 60.0)	15.9 (9.6; 23.9)	2.25 (1.69; 3.01)	2.38 (1.76; 3.22)

Difference is in deaths per 1000 livebirths.
Difference: $U5MR_{Q1} - U5MR_{Q5}$
Ratio: $U5MR_{Q1} : U5MR_{Q5}$

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Table 5.19 – continued from previous page

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Haiti	51.0 (25.9; 75.4)	31.9 (16.5; 50.5)	1.48 (1.21; 1.78)	1.67 (1.32; 2.12)
Indonesia*	72.0 (55.0; 89.4)	24.5 (16.9; 33.8)	2.52 (2.01; 3.18)	2.65 (2.07; 3.42)
India*	108.0 (97.7; 118.4)	39.1 (29.5; 49.0)	2.75 (2.51; 3.01)	2.78 (2.19; 3.47)
Iraq¶	16.7 (1.2; 32.2)	9.5 (1.3; 18.9)	1.36 (1.02; 1.82)	1.35 (1.05; 1.76)
Jordan	18.3 (10.5; 26.4)	10.0 (4.5; 17.0)	1.68 (1.34; 2.12)	1.77 (1.32; 2.39)
Kazakhstan	26.8 (12.2; 40.8)	6.8 (3.1; 10.7)	1.73 (1.28; 2.33)	1.85 (1.31; 2.64)
Kenya	53.3 (37.9; 69.3)	23.3 (12.8; 35.0)	1.74 (1.48; 2.05)	1.63 (1.32; 2.01)
Kyrgyz Republic	35.2 (16.6; 53.3)	13.4 (6.8; 19.8)	1.75 (1.30; 2.34)	1.90 (1.38; 2.61)
Cambodia*	86.3 (64.3; 108.4)	27.3 (15.4; 46.1)	2.42 (1.94; 3.01)	2.76 (2.11; 3.57)
Lao People's Democratic Republic*	111.6 (69.5; 156.2)	55.6 (34.3; 83.9)	2.32 (1.68; 3.24)	2.77 (2.02; 3.79)
Liberia¶	28.5 (-33.3; 92.1)	19.1 (2.8; 37.9)	1.12 (0.88; 1.46)	1.32 (1.04; 1.67)
Lesotho¶	32.3 (12.4; 52.4)	32.3 (11.1; 57.9)	1.46 (1.15; 1.84)	1.45 (1.14; 1.86)
Morocco*	63.9 (47.7; 80.2)	23.9 (14.9; 35.7)	2.52 (1.99; 3.19)	2.64 (1.96; 3.56)
Republic of Moldova	19.4 (7.0; 31.3)	10.1 (3.5; 18.9)	1.83 (1.23; 2.65)	1.89 (1.25; 2.78)
Madagascar	90.5 (63.4; 117.5)	35.0 (20.8; 54.7)	1.94 (1.58; 2.36)	2.29 (1.76; 2.97)
Maldives	48.4 (15.9; 79.4)	5.8 (2.4; 9.5)	1.74 (1.19; 2.54)	2.01 (1.34; 3.03)
The former Yugoslav Republic of Macedonia	25.5 (11.9; 37.8)	9.0 (4.0; 16.6)	2.04 (1.38; 2.99)	2.11 (1.42; 3.19)
Mali	108.1 (78.1; 137.5)	64.5 (35.1; 109.1)	1.63 (1.43; 1.86)	1.94 (1.59; 2.38)

Difference is in deaths per 1000 livebirths.
Difference: $U5MR_{Q1} - U5MR_{Q5}$
Ratio: $U5MR_{Q1} : U5MR_{Q5}$

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Table 5.19 – continued from previous page

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Myanmar	61.5 (22.8; 97.7)	33.6 (16.0; 52.7)	1.79 (1.23; 2.61)	2.03 (1.41; 2.93)
Mongolia	66.3 (40.4; 91.6)	14.9 (8.4; 24.4)	1.92 (1.49; 2.47)	2.35 (1.74; 3.20)
Mozambique	83.2 (41.0; 126.9)	32.6 (17.3; 52.3)	1.45 (1.20; 1.76)	1.61 (1.31; 1.96)
Mauritania	62.0 (31.8; 92.4)	45.6 (20.4; 90.3)	1.74 (1.33; 2.29)	1.78 (1.38; 2.28)
Malawi	67.2 (37.2; 97.3)	23.3 (12.5; 36.3)	1.38 (1.20; 1.60)	1.56 (1.28; 1.89)
Namibia	32.5 (18.5; 46.6)	26.8 (14.2; 44.8)	1.66 (1.33; 2.07)	1.91 (1.47; 2.51)
Niger¶	71.4 (29.1; 116.2)	29.6 (11.6; 52.6)	1.31 (1.11; 1.54)	1.44 (1.16; 1.79)
Nigeria	129.0 (96.9; 161.9)	82.6 (56.0; 116.4)	2.04 (1.72; 2.39)	2.44 (2.01; 2.91)
Nicaragua	39.8 (23.9; 55.8)	13.9 (6.6; 25.6)	1.96 (1.48; 2.59)	2.15 (1.53; 3.04)
Nepal	59.0 (36.7; 81.3)	21.9 (13.7; 31.0)	1.62 (1.35; 1.95)	1.99 (1.56; 2.53)
Pakistan	67.8 (43.0; 91.8)	46.4 (27.8; 69.8)	1.73 (1.42; 2.11)	1.89 (1.49; 2.40)
Peru*	79.7 (67.5; 91.8)	16.1 (11.1; 22.3)	3.04 (2.56; 3.61)	3.06 (2.32; 3.99)
Philippines*	57.0 (46.5; 67.4)	27.1 (18.0; 38.9)	2.86 (2.37; 3.47)	2.91 (2.24; 3.76)
Paraguay	29.4 (16.3; 42.5)	14.0 (6.0; 25.9)	2.01 (1.44; 2.85)	2.11 (1.45; 3.09)
State of Palestine	28.7 (13.7; 43.2)	13.6 (6.5; 22.8)	2.00 (1.38; 2.89)	2.08 (1.45; 3.01)
Rwanda§	28.2 (5.7; 49.8)	19.5 (9.6; 34.6)	1.23 (1.04; 1.45)	1.69 (1.36; 2.12)
Sudan	55.8 (23.5; 87.8)	34.5 (19.7; 51.0)	1.62 (1.22; 2.16)	1.81 (1.43; 2.30)
Senegal	92.9 (69.3; 116.5)	37.5 (26.4; 51.6)	2.08 (1.73; 2.50)	2.36 (1.90; 2.92)
Sierra Leone¶	67.5 (21.4; 116.1)	32.8 (10.5; 56.6)	1.32 (1.09; 1.61)	1.34 (1.10; 1.61)
El Salvador	36.3 (15.6; 56.6)	10.9 (4.8; 18.8)	1.90 (1.31; 2.78)	2.08 (1.41; 3.08)

Difference is in deaths per 1000 livebirths.
Difference: $U5MR_{Q1} - U5MR_{Q5}$
Ratio: $U5MR_{Q1} : U5MR_{Q5}$

Continued on next page

Table 5.19 – continued from previous page

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Somalia	64.1 (3.9; 124.4)	55.7 (9.0; 127.7)	1.49 (1.02; 2.18)	1.58 (1.08; 2.29)
Serbia	17.9 (7.3; 28.0)	3.9 (1.5; 6.4)	1.92 (1.29; 2.84)	1.98 (1.30; 3.00)
South Sudan¶	3.9 (-78.0; 81.9)	10.2 (-18.6; 40.8)	1.02 (0.74; 1.39)	1.12 (0.83; 1.49)
Sao Tome and Principe	28.1 (-4.9; 59.9)	14.7 (3.5; 28.6)	1.31 (0.95; 1.78)	1.54 (1.11; 2.12)
Suriname	35.6 (19.1; 53.2)	16.1 (6.3; 35.6)	2.25 (1.55; 3.28)	2.29 (1.57; 3.43)
Swaziland	33.0 (17.1; 50.3)	35.0 (16.9; 59.9)	1.65 (1.30; 2.13)	1.64 (1.31; 2.10)
Syria	20.8 (7.9; 33.0)	10.0 (3.4; 18.2)	1.81 (1.25; 2.60)	1.79 (1.22; 2.63)
Chad¶	-15.1 (-43.3; 13.3)	10.4 (-11.3; 34.9)	0.92 (0.79; 1.07)	1.09 (0.91; 1.32)
Togo	84.8 (60.5; 109.1)	58.1 (40.6; 79.2)	1.99 (1.64; 2.42)	2.42 (1.95; 3.02)
Thailand	23.8 (10.3; 36.6)	8.4 (3.1; 16.5)	1.96 (1.32; 2.90)	2.03 (1.35; 3.13)
Tajikistan	36.2 (10.1; 62.3)	20.4 (7.3; 39.9)	1.41 (1.10; 1.81)	1.61 (1.21; 2.11)
Turkmenistan	50.0 (21.2; 80.6)	34.7 (11.3; 79.5)	1.84 (1.29; 2.72)	2.02 (1.40; 2.96)
Timor-Leste	67.7 (18.2; 114.5)	28.8 (13.1; 50.8)	1.57 (1.13; 2.17)	1.90 (1.38; 2.59)
Tunisia	36.4 (15.9; 56.4)	10.1 (4.4; 16.8)	1.98 (1.34; 2.91)	2.13 (1.42; 3.23)
Turkey*	70.0 (53.0; 87.0)	12.8 (8.7; 16.8)	2.78 (2.13; 3.65)	2.87 (2.03; 4.07)
United Republic of Tanzania¶	29.9 (2.2; 57.5)	15.5 (4.3; 27.6)	1.21 (1.01; 1.44)	1.33 (1.08; 1.61)
Uganda	62.8 (36.4; 89.6)	28.8 (16.8; 42.0)	1.47 (1.25; 1.73)	1.74 (1.39; 2.19)
Ukraine	13.2 (5.7; 20.8)	6.3 (2.8; 9.8)	2.01 (1.35; 3.03)	2.04 (1.35; 3.09)
Uzbekistan	21.1 (3.3; 38.7)	10.3 (2.8; 18.2)	1.36 (1.05; 1.74)	1.54 (1.13; 2.11)
Vietnam	42.0 (27.7; 56.4)	18.6 (11.4; 26.5)	2.38 (1.76; 3.25)	2.44 (1.74; 3.42)

Difference is in deaths per 1000 livebirths.
Difference: $U5MR_{Q1} - U5MR_{Q5}$
Ratio: $U5MR_{Q1} : U5MR_{Q5}$

Continued on next page

Table 5.19 – continued from previous page

Country	Difference 1990	Difference 2016	Ratio 1990	Ratio 2016
Vanuatu	23.8 (11.0; 36.7)	18.6 (7.9; 33.8)	2.04 (1.38; 3.03)	2.03 (1.37; 3.06)
Yemen	83.6 (48.1; 119.1)	43.9 (25.2; 67.9)	2.09 (1.51; 2.91)	2.36 (1.70; 3.28)
South Africa	45.0 (27.8; 62.2)	34.2 (19.9; 49.2)	2.33 (1.68; 3.24)	2.33 (1.64; 3.35)
Zambia	56.8 (32.5; 81.8)	28.3 (15.0; 45.8)	1.41 (1.22; 1.64)	1.58 (1.30; 1.94)
Zimbabwe	22.6 (8.8; 36.4)	26.0 (14.5; 40.3)	1.38 (1.14; 1.67)	1.62 (1.33; 2.01)

Table 5.20 **Estimates and 90% uncertainty intervals for slope inequality index and concentration index in 1990 and 2016, for the 99 countries with empirical data.** §: change of ratio of UMRQ1 to U5MRQ5 is significantly different from zero; ¶: point estimates of ratio ($U5MR_{Q1}$: $U5MR_{Q5}$) < 1.5 in 2016; †: point estimates of ratio ($U5MR_{Q1}$: $U5MR_{Q5}$) > 2.5 in 2016. Countries are ordered alphabetically.

	Slope Inequality Index		Concentration Index	
Country	**1990**	**2016**	**1990**	**2016**
Afghanistan	-8.7 (-12.4; -4.9)	-12.4 (-15.4; -9.1)	-15.3 (-22.2; -8.6)	-8.7 (-11.6; -6)
Angola	-5.4 (-9; -1.9)	-9.4 (-13.5; -5.1)	-12 (-20.2; -4.1)	-7.8 (-15.2; -3.1)
Albania	-11.3 (-16.5; -5.7)	-12.6 (-18.7; -6.4)	-4.5 (-6.7; -2.2)	-1.7 (-3.5; -0.7)
Armenia	-13.2 (-18.3; -7.6)	-14.5 (-20.7; -8.2)	-6.6 (-9.2; -3.7)	-1.9 (-3.1; -1)
Azerbaijan	-10 (-14.5; -5.4)	-12.8 (-17.7; -7.6)	-9.5 (-13.7; -5.1)	-4 (-7.4; -1.9)
Burundi	-9.8 (-13.7; -5.8)	-13 (-17.2; -8.6)	-16.7 (-23.6; -9.8)	-9.3 (-13.5; -5.7)
Benin	-7.6 (-10.3; -4.9)	-10.2 (-13.8; -6.7)	-13.6 (-18.5; -8.7)	-10 (-15.1; -6.1)
Burkina Faso	-5.7 (-7.8; -3.5)	-9.9 (-13.3; -6.6)	-11.3 (-15.6; -6.9)	-8.4 (-12.4; -5.2)
Bangladesh	-10.3 (-12.4; -8.3)	-13.3 (-16.6; -9.9)	-14.9 (-17.9; -11.9)	-4.6 (-5.8; -3.3)
Belarus	-14.1 (-20.3; -7.7)	-14.2 (-20.5; -7.6)	-2.2 (-3.1; -1.2)	-0.6 (-0.8; -0.3)
Belize	-13.1 (-18.7; -7.1)	-14.2 (-20.5; -7.5)	-5.1 (-7.4; -2.7)	-2.1 (-3.1; -1.1)
Bolivia (Plurinational State of)*	-15.9 (-18.3; -13.6)	-18.8 (-22.4; -14.9)	-19.7 (-22.9; -16.5)	-6.9 (-10.1; -4.5)
Brazil*	-17 (-21.4; -12.3)	-18.1 (-24; -12.2)	-10.9 (-13.9; -7.9)	-2.7 (-3.9; -1.8)
Bhutan	-12.5 (-17.4; -7.3)	-16.5 (-21.6; -11.2)	-15.9 (-22.5; -9.3)	-5.4 (-8.1; -3.2)
Central African Republic	-9.2 (-11.7; -6.7)	-11.1 (-14.5; -7.4)	-16.1 (-20.8; -11.4)	-13.7 (-22.9; -7.6)
Cote d'Ivoire	-10.1 (-12.7; -7.6)	-10.7 (-14.3; -6.9)	-15.2 (-19.3; -11.3)	-9.8 (-14.7; -5.8)

Slope inequality index is in deaths per 1000 livebirths.
Concentration index is in ($\times 100$).

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Table 5.20 – continued from previous page

	Slope Inequality Index		Concentration Index	
Country	**1990**	**2016**	**1990**	**2016**
Cameroon	-12.2 (-14.9; -9.5)	-13.2 (-16.9; -9.3)	-17.5 (-21.6; -13.5)	-10.5 (-15; -6.8)
Democratic Republic of the Congo	-10.1 (-13.2; -7)	-11.9 (-15.4; -8.3)	-18.6 (-24.7; -12.5)	-11.3 (-16.8; -6.9)
Congo	-8 (-11.9; -4)	-9.3 (-13.3; -5.3)	-7.3 (-10.9; -3.6)	-5 (-8.1; -2.6)
Colombia	-13 (-16.6; -9.2)	-14.5 (-19.1; -9.8)	-4.6 (-5.9; -3.2)	-2.2 (-3.2; -1.4)
Comoros	-9 (-13; -4.9)	-9.9 (-14.5; -5.2)	-11.3 (-16.7; -5.9)	-7.3 (-15.9; -2.9)
Dominican Republic	-13 (-16.6; -9.1)	-12.8 (-16.8; -8.7)	-7.8 (-10; -5.4)	-3.9 (-5.8; -2.5)
Algeria	-11.9 (-16.7; -6.9)	-12.4 (-17.1; -7.5)	-5.8 (-8.2; -3.3)	-3.1 (-4.4; -1.9)
Egypt*	-16.7 (-19.4; -14)	-16.5 (-20.1; -12.6)	-14.3 (-16.8; -12)	-3.8 (-5.2; -2.6)
Eritrea	-6.8 (-10.8; -2.7)	-11.4 (-16.1; -6.6)	-10.3 (-16.6; -4.1)	-5.1 (-8.9; -2.6)
Ethiopia	-2.4 (-5.5; 0.7)	-8.5 (-12.3; -4.8)	-4.9 (-11.1; 1.4)	-5 (-7.7; -2.7)
Gabon	-9 (-12.9; -4.8)	-11.1 (-15.3; -6.5)	-8.3 (-12.3; -4.4)	-5.2 (-8.5; -2.7)
Georgia	-12.9 (-18.3; -7.2)	-14.3 (-20.3; -7.9)	-6.1 (-8.8; -3.4)	-1.5 (-2.3; -0.8)
Ghana	-10 (-12.7; -7.2)	-11 (-14.6; -7.3)	-12.6 (-16.2; -9.1)	-6.5 (-9.5; -3.9)
Guinea	-8.8 (-11.7; -5.7)	-12.1 (-15.4; -8.7)	-20.6 (-27.8; -13.4)	-10.8 (-15; -7.3)
The Gambia	-7.8 (-11.5; -4)	-11.2 (-15; -7.2)	-13 (-19.7; -6.7)	-7.3 (-12.7; -3.8)
Guinea-Bissau	-7.8 (-10.9; -4.6)	-9.7 (-13.3; -6)	-17 (-24.5; -9.8)	-8.5 (-13.4; -4.6)
Equatorial Guinea¶	-3.5 (-7.6; 0.8)	-7 (-11.9; -2)	-6.7 (-14.8; 1.6)	-6.3 (-12; -1.7)

Slope inequality index is in deaths per 1000 livebirths.
Concentration index is in ($\times$100).

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Table 5.20 – continued from previous page

Country	Slope Inequality Index		Concentration Index	
	1990	2016	1990	2016
Guatemala	-9.1 (-12.6; -5.3)	-12.7 (-16.8; -8.4)	-7.4 (-10.3; -4.3)	-3.6 (-5.1; -2.3)
Guyana	-8.4 (-13.3; -3.1)	-9.2 (-14.2; -3.7)	-5.1 (-8; -1.8)	-3 (-5.4; -1.1)
Honduras	-14.7 (-18.9; -10.3)	-16.2 (-20.7; -11.5)	-8.5 (-11.2; -5.9)	-3 (-4.5; -1.9)
Haiti	-6.9 (-9.8; -3.9)	-9.7 (-13.3; -6)	-10.1 (-14.3; -5.7)	-6.5 (-9.8; -3.7)
Indonesia*	-15.7 (-19; -12.3)	-17.3 (-21.1; -13.4)	-13.2 (-16.1; -10.3)	-4.6 (-6.2; -3.2)
India*	-17.2 (-18.6; -15.9)	-17.9 (-21.4; -14.2)	-21.7 (-23.6; -19.9)	-7.7 (-9.4; -6)
Iraq¶	-7.1 (-11.9; -2.3)	-7 (-11.3; -2.6)	-3.9 (-6.5; -1.2)	-2.2 (-3.9; -0.8)
Jordan	-10 (-13.6; -6.3)	-11.6 (-16.5; -6.6)	-3.6 (-5; -2.3)	-2 (-3.3; -1.1)
Kazakhstan	-10.8 (-15.1; -6.2)	-12.5 (-18.1; -6.8)	-5.6 (-8; -3.2)	-1.4 (-2.1; -0.8)
Kenya	-11.2 (-13.9; -8.5)	-9.8 (-13.2; -6.2)	-11 (-13.7; -8.3)	-4.8 (-6.9; -3)
Kyrgyz Republic	-10.9 (-15.3; -6.1)	-12.8 (-17.9; -7.6)	-7.1 (-10.2; -4)	-2.7 (-3.8; -1.6)
Cambodia*	-13.6 (-16.7; -10.4)	-16.9 (-20.6; -13)	-15.8 (-19.6; -11.9)	-5.2 (-8.7; -3)
Lao People's Democratic Republic*	-12.4 (-16.8; -8)	-16.5 (-20.6; -12.1)	-20 (-27.6; -12.8)	-10.5 (-15.5; -6.7)
Liberia¶	-2.4 (-6.5; 1.7)	-6.4 (-10.3; -2.3)	-6.1 (-16.9; 4.3)	-4.3 (-7.6; -1.5)
Lesotho¶	-7.3 (-11.1; -3.6)	-7 (-10.7; -3.1)	-6.7 (-10.2; -3.3)	-6.5 (-10.9; -2.8)
Morocco*	-15.3 (-18.7; -12)	-17 (-21.3; -12.5)	-12.2 (-15.1; -9.5)	-4.6 (-6.8; -3)
Republic of Moldova	-12 (-17.5; -5.7)	-13 (-19; -6.4)	-4 (-6; -1.9)	-2.1 (-3.6; -0.9)
Madagascar	-10.4 (-13.3; -7.5)	-14.8 (-18.6; -10.9)	-16.7 (-21.4; -11.8)	-6.8 (-10.5; -4.3)

Slope inequality index is in deaths per 1000 livebirths.
Concentration index is in ($\times$100).

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Table 5.20 – continued from previous page

	Slope Inequality Index		Concentration Index	
Country	**1990**	**2016**	**1990**	**2016**
Maldives	-10.2 (-15.6; -4.3)	-13.7 (-19.8; -7.2)	-9.6 (-14.8; -4)	-1.2 (-1.8; -0.6)
The former Yugoslav Republic of Macedonia	-13.6 (-19; -7.5)	-14.7 (-20.7; -8.1)	-5 (-7.1; -2.8)	-1.8 (-3.2; -0.9)
Mali	-7.6 (-9.6; -5.5)	-11 (-14.1; -7.9)	-19.3 (-24.5; -14)	-12.2 (-20.4; -6.8)
Myanmar	-10.4 (-15.5; -4.9)	-13.4 (-18.3; -7.9)	-12 (-17.9; -5.6)	-6.8 (-10.1; -3.8)
Mongolia	-12 (-15.8; -8.1)	-16.5 (-21.3; -11.7)	-13 (-17.4; -8.8)	-2.9 (-4.7; -1.7)
Mozambique	-6.3 (-9.3; -3.2)	-9.1 (-12.5; -5.8)	-15.5 (-23.1; -8)	-6.5 (-10.1; -3.8)
Mauritania	-10.3 (-14.5; -6)	-11.2 (-15.1; -7)	-12 (-17.1; -7)	-9.1 (-17.5; -4.3)
Malawi	-5.1 (-7.3; -2.8)	-9.1 (-12.2; -5.9)	-11.8 (-17.1; -6.5)	-5 (-7.4; -3.1)
Namibia	-9.3 (-12.5; -5.9)	-11.9 (-16; -7.9)	-6.7 (-9.1; -4.3)	-5.4 (-8.7; -3.1)
Niger¶‖	-4.6 (-7.1; -2.2)	-6.9 (-10.1; -3.5)	-15.1 (-23.5; -7.4)	-6.3 (-10.7; -3)
Nigeria	-11.7 (-14.3; -9.1)	-15.6 (-18.4; -12.6)	-25 (-30.9; -19.2)	-16.2 (-22.8; -11.2)
Nicaragua	-12 (-15.7; -7.9)	-14.2 (-19.2; -8.9)	-8.1 (-10.8; -5.3)	-2.8 (-5; -1.4)
Nepal	-8.1 (-10.8; -5.4)	-12.9 (-16.6; -9.1)	-11.4 (-15.4; -7.5)	-4.4 (-6.1; -3)
Pakistan	-9.5 (-12.5; -6.4)	-11.8 (-15.4; -8.2)	-13.1 (-17.4; -8.8)	-9.3 (-13.5; -6)
Peru*	-19.7 (-22.1; -17.2)	-20.4 (-24.6; -16)	-15.8 (-18; -13.7)	-3.1 (-4.3; -2.2)
Philippines*	-18.9 (-21.7; -16)	-18.9 (-22.6; -14.8)	-11 (-12.8; -9.2)	-5.1 (-7.3; -3.5)
Paraguay	-12.6 (-17.1; -7.8)	-14 (-19.4; -8.2)	-5.9 (-8.1; -3.6)	-2.8 (-5; -1.4)
State of Palestine	-12.9 (-18.1; -7.3)	-13.9 (-19.5; -8.3)	-5.7 (-8.1; -3.3)	-2.7 (-4.3; -1.5)
Rwanda§	-3.5 (-6.1; -0.9)	-10 (-13.8; -6.3)	-5.3 (-9.2; -1.3)	-3.9 (-6.7; -2)

Slope inequality index is in deaths per 1000 livebirths.
Concentration index is in ($\times$100).

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Table 5.20 – continued from previous page

Country	Slope Inequality Index 1990	Slope Inequality Index 2016	Concentration Index 1990	Concentration Index 2016
Sudan	-8.4 (-12.5; -4.3)	-10.9 (-14.4; -7.3)	-11.1 (-16.6; -5.6)	-7.1 (-10.1; -4.5)
Senegal	-12.7 (-15.5; -9.8)	-15.5 (-18.6; -12.1)	-17.8 (-21.9; -13.7)	-7.3 (-9.9; -5.2)
Sierra Leone¶	-4.1 (-7.3; -1)	-5.8 (-9; -2.5)	-10.8 (-19.2; -2.6)	-6.6 (-10.8; -2.7)
El Salvador	-12.2 (-17.6; -6.5)	-14.5 (-20.3; -8.2)	-7.2 (-10.6; -3.8)	-2.2 (-3.6; -1.1)
Somalia	-6.8 (-12; -1.2)	-8.3 (-13.5; -2.5)	-12.3 (-22.6; -2.2)	-10.9 (-24; -2.8)
Serbia	-12.7 (-18.5; -6.4)	-13.6 (-19.9; -6.9)	-3.6 (-5.2; -1.8)	-0.8 (-1.2; -0.4)
South Sudan¶	-1.2 (-6.2; 4.2)	-3.6 (-8.5; 1.5)	-3 (-16.1; 10.6)	-3.3 (-8.7; 1.5)
Sao Tome and Principe	-6 (-10.9; -0.8)	-9.4 (-14.6; -4)	-6.3 (-11.6; -0.8)	-3.2 (-5.6; -1.2)
Suriname	-14.8 (-20.1; -9.3)	-15.5 (-21.4; -9.5)	-6.9 (-9.9; -4.1)	-3.1 (-6.8; -1.3)
Swaziland	-9.8 (-14; -5.8)	-9.5 (-13.4; -5.6)	-6.5 (-9.4; -3.7)	-6.7 (-11.1; -3.5)
Syria	-11.5 (-16.8; -5.9)	-11.7 (-17.7; -5.4)	-4.3 (-6.3; -2.2)	-2.1 (-3.5; -0.9)
Chad¶	0.2 (-2.2; 2.6)	-2.7 (-5.9; 0.3)	0.4 (-4.7; 5.5)	-3.4 (-7.7; 0.4)
Togo	-11.1 (-13.8; -8.2)	-14.9 (-18.2; -11.8)	-16 (-20.3; -11.8)	-11.3 (-15.1; -8.1)
Thailand	-12.8 (-18.2; -6.7)	-13.9 (-20.2; -7.4)	-4.8 (-6.9; -2.5)	-1.7 (-3.2; -0.8)
Tajikistan	-7.3 (-11.2; -3.2)	-10.3 (-14.7; -5.6)	-7.8 (-12.2; -3.4)	-4.4 (-8.2; -2)
Turkmenistan	-11.3 (-16.7; -5.7)	-13.4 (-18.9; -7.8)	-9.8 (-14.8; -4.9)	-6.9 (-15.5; -2.5)
Timor-Leste	-7.4 (-11.8; -2.6)	-11.9 (-16.5; -7.2)	-12.9 (-20.9; -4.6)	-5.9 (-9.9; -3.1)
Tunisia	-12.7 (-18.2; -6.8)	-14.6 (-20.6; -8.1)	-7.2 (-10.5; -3.8)	-2 (-3.2; -1)
Turkey*	-17.4 (-21; -13.6)	-19 (-24.2; -13.5)	-12.9 (-15.8; -10)	-2.4 (-3.1; -1.7)
United Republic of Tanzania¶	-3.8 (-6.5; -1)	-6.3 (-9.5; -2.9)	-6.8 (-11.7; -1.9)	-3.6 (-5.7; -1.6)

Slope inequality index is in deaths per 1000 livebirths.
Concentration index is in ($\times$100).

Continued on next page

Table 5.20 – continued from previous page

	Slope Inequality Index		Concentration Index	
Country	**1990**	**2016**	**1990**	**2016**
Uganda	-6 (-8.7; -3.3)	-10.7 (-14.5; -6.9)	-10.5 (-15.3; -5.7)	-5.7 (-8; -3.5)
Ukraine	-13.5 (-19.5; -7.3)	-13.9 (-20.2; -7.5)	-2.6 (-3.9; -1.4)	-1.3 (-1.8; -0.7)
Uzbekistan	-6.9 (-10.8; -2.7)	-9.4 (-14.5; -4.3)	-5 (-8; -2)	-2.3 (-3.6; -1)
Vietnam	-15.8 (-20.2; -11.2)	-16.5 (-21.5; -11.1)	-8.1 (-10.4; -5.7)	-3.6 (-4.9; -2.3)
Vanuatu	-13.3 (-18.8; -7.3)	-13.3 (-19.1; -7.4)	-4.7 (-6.9; -2.6)	-3.7 (-6.4; -1.8)
Yemen	-12.3 (-16.9; -7.5)	-15.2 (-19.9; -10.4)	-15.4 (-21.4; -9.4)	-8.4 (-12.7; -5)
South Africa	-15.1 (-19.5; -10.3)	-15.3 (-20.2; -10.1)	-8.7 (-11.6; -5.8)	-6.6 (-9.1; -4.2)
Zambia	-5.5 (-7.9; -3.1)	-9.1 (-12.5; -5.8)	-10 (-14.5; -5.6)	-5.8 (-9.1; -3.3)
Zimbabwe	-6 (-9.2; -2.9)	-9.4 (-12.8; -6.2)	-4.5 (-6.9; -2.2)	-5.3 (-7.9; -3.3)

Wealth Quintile Group	**1st**	**2nd**	**3rd**	**4th**	**5th**
Median of error	-0.06	-0.08	0.03	0.04	0.04
Median of absolute error	0.13	0.11	0.09	0.11	0.09
Left-out obs. below 90% PI (%)	0.0	3.9	0.0	0.0	1.1
Left-out obs. above 90% PI (%)	0.0	0.0	0.0	1.8	6.3
Expected proportions (%)	**5**	**5**	**5**	**5**	**5**
Left-out obs. below 80% PI (%)	3.9	10.3	1.6	7.2	3.2
Left-out obs. above 80% PI (%)	2.5	0.0	1.1	8.1	6.3
Expected proportions (%)	**10**	**10**	**10**	**10**	**10**

Table 5.21 **Validation results for left-out observations when leaving out data after 2010.** Errors are defined as the difference between a left-out observation and the posterior median of its predictive distribution obtained from the training set. Obs.=observations.

Year			**2005**		
Wealth Quintile Group	**1st**	**2nd**	**3rd**	**4th**	**5th**
Median of Error	-0.00	-0.01	-0.00	0.01	0.01
Median of absolute Error	0.01	0.02	0.00	0.01	0.01
Below 90% UI (%)	0.0	0.0	0.0	0.0	1.0
Above 90% UI (%)	0.0	0.0	0.0	0.0	1.0
Expected proportions (%)	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**
Year			**2010**		
Wealth Quintile Group	**1st**	**2nd**	**3rd**	**4th**	**5th**
Median of Error	0.00	-0.02	-0.00	0.01	0.01
Median of absolute Error	0.01	0.02	0.00	0.01	0.01
Below 90% UI (%)	0.0	0.0	0.0	0.0	1.0
Above 90% UI (%)	0.0	0.0	0.0	0.0	1.0
Expected proportions (%)	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**	**$\leq$5**

Table 5.22 **Validation results for estimates when leaving out data after 2010.** Errors are defined as the differences between estimates based on the full dataset and the training set. The proportions refer to the proportions (%) of countries in which the median ratio estimates based on the full data set fall below or above their corresponding 90% uncertainty intervals based on the training dataset. The results are broken down by wealth quintile groups and year.

Wealth Quintile Group	1st	2nd	3rd	4th	5th
Median of Error	-0.01	-0.01	-0.01	0.01	-0.00
Median of absolute Error	0.10	0.10	0.08	0.09	0.09
Left-out obs. below 90% PI (%)	2.6	1.1	0.7	2.9	3.2
Left-out obs. above 90% PI (%)	2.8	0.9	2.6	1.3	2.4
Expected proportions (%)	**5**	**5**	**5**	**5**	**5**
Left-out obs. below 80% PI (%)	6.0	5.2	3.9	8.7	6.2
Left-out obs. above 80% PI (%)	4.4	3.8	4.7	5.5	4.7
Expected proportions (%)	**10**	**10**	**10**	**10**	**10**

Table 5.23 **Validation results for left-out observations when randomly leaving out 20% of all data.** Errors are defined as the difference between a left-out observation and the posterior median of its predictive distribution. Obs.=observations.

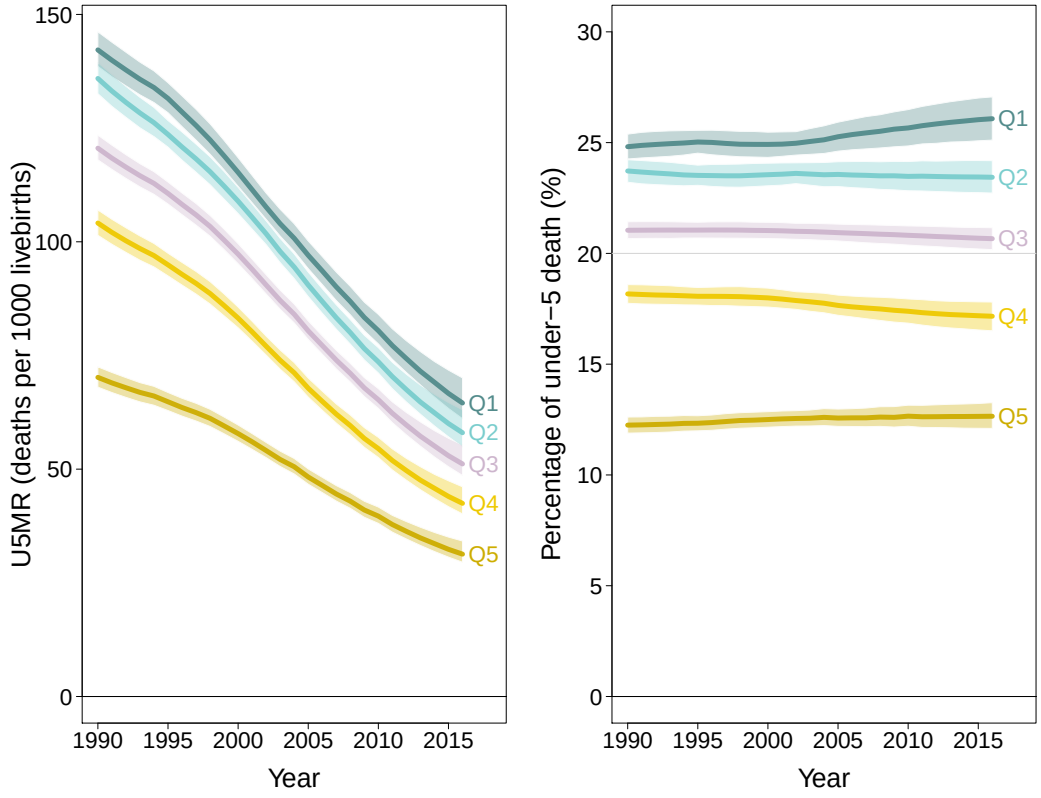

Fig. 5.5 **Quintile-specific U5MR from 1990 to 2016, for all low- and middle-income countries excluding China.** Curves are median estimates. Shaded areas are 90% uncertainty intervals. Q=Quintile. Q1 is the 20% poorest quintile; Q5 is the 20% richest.

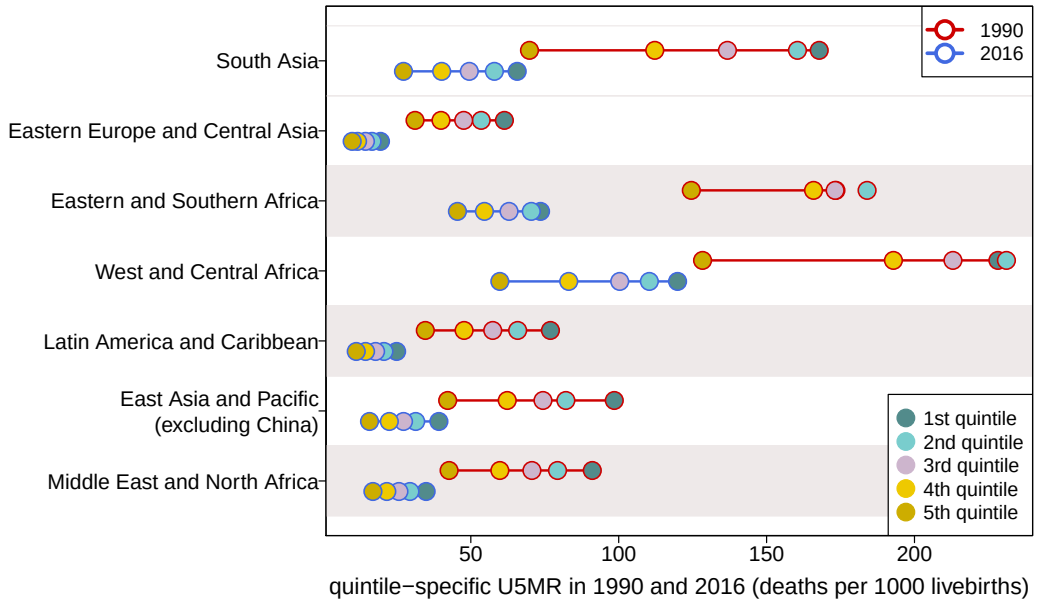

Fig. 5.6 **Point estimates for U5MR in each quintile in 1990 and 2016, by region.** Coloured dots show the point estimates for U5MR in each quintile. The 1st quintile is the 20% poorest quintile; the 5th quintile is the 20% richest. The distance between the 1st and the 5th quintiles represents absolute disparity.

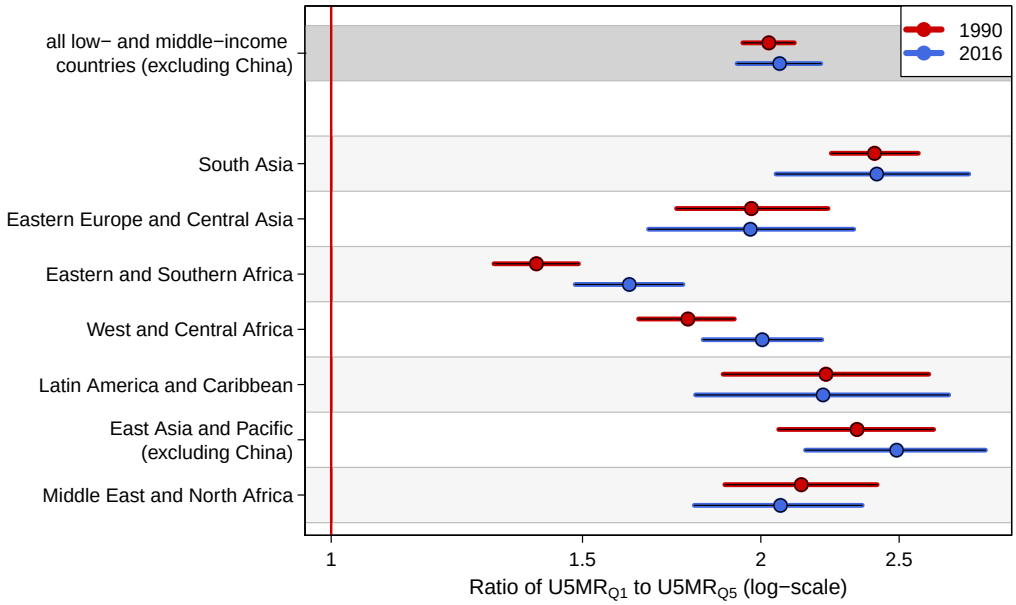

Fig. 5.7 **Ratio of U5MR in 1st quintile to U5MR in 5th quintile- for 1990 and 2016, by region.** Horizontal lines denote 90% uncertainty intervals.

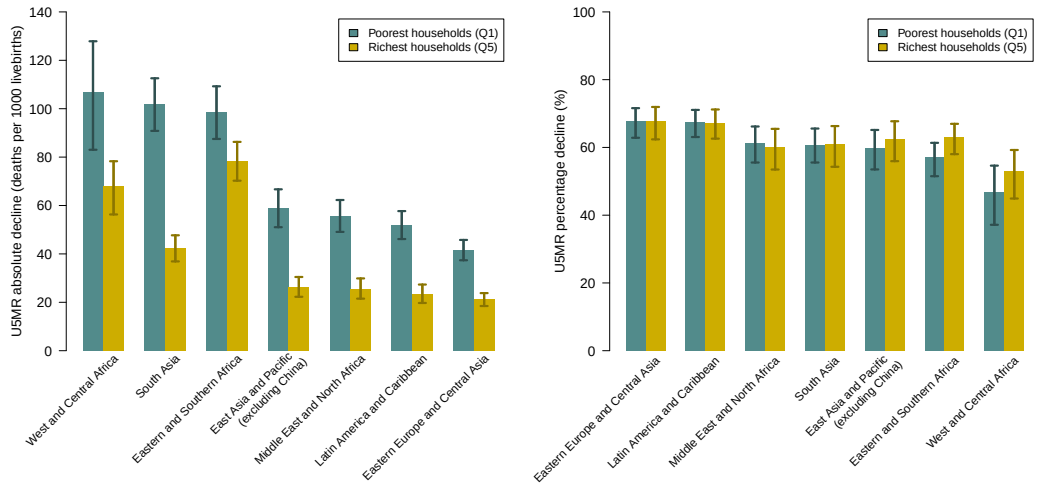

Fig. 5.8 **Absolute decline and percentage decline in U5MR from 1990 to 2016 in the 1st (poorest) and the 5th (richest) quintile, by region.** Vertical line segments on top of bars represent 90% uncertainty intervals.

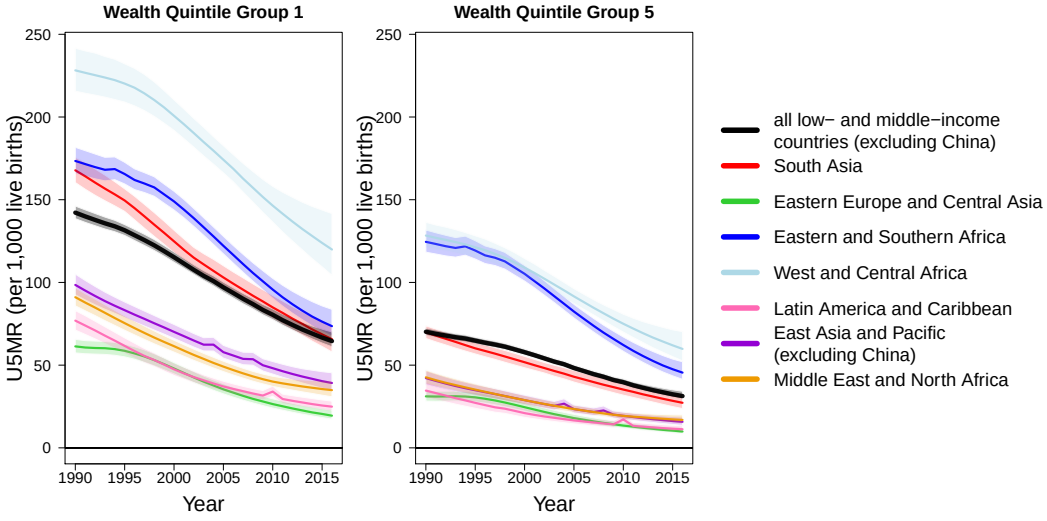

Fig. 5.9 **U5MR for the 1st (poorest) and the 5th (richest) quintile from 1990 to 2016, for overall and regions.** Curves are median estimates. Shaded areas are 90% uncertainty intervals.

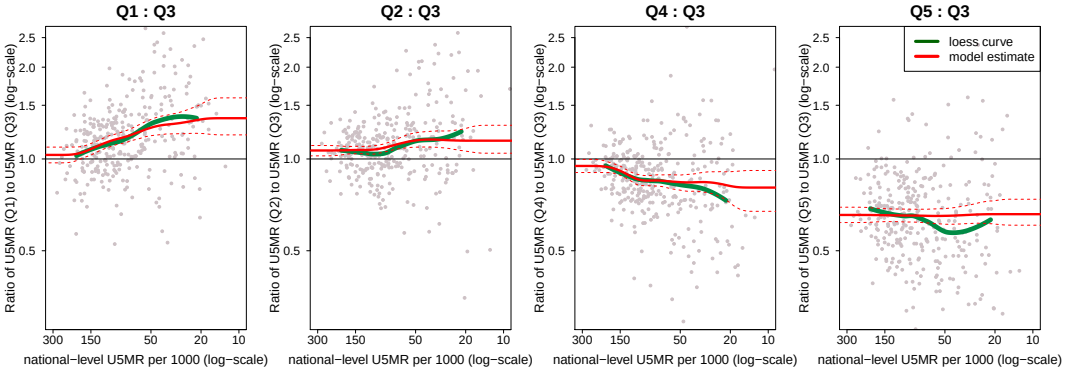

Fig. 5.10 **Q3-disparity ratios against national-level U5MR – model results.** The grey dots are observed Q3-disparity ratios $S_{w,c,t}$ (i.e. $= Q_{w,c,t}/Q_{3,c,t}$) for $w = 1,2,4,5$ respectively for the four plots. The red solid curves are median estimates for the expected Q3-disparity ratios $U_{w,c,t}$ (i.e. $= S_{w,c,t}/P_{w,c,t}$) and dashed lines are the corresponding 5th and 95th percentiles of the uncertainty bounds. The green curves are loess curves between the 5th and 95th percentiles of the national-level U5MR.

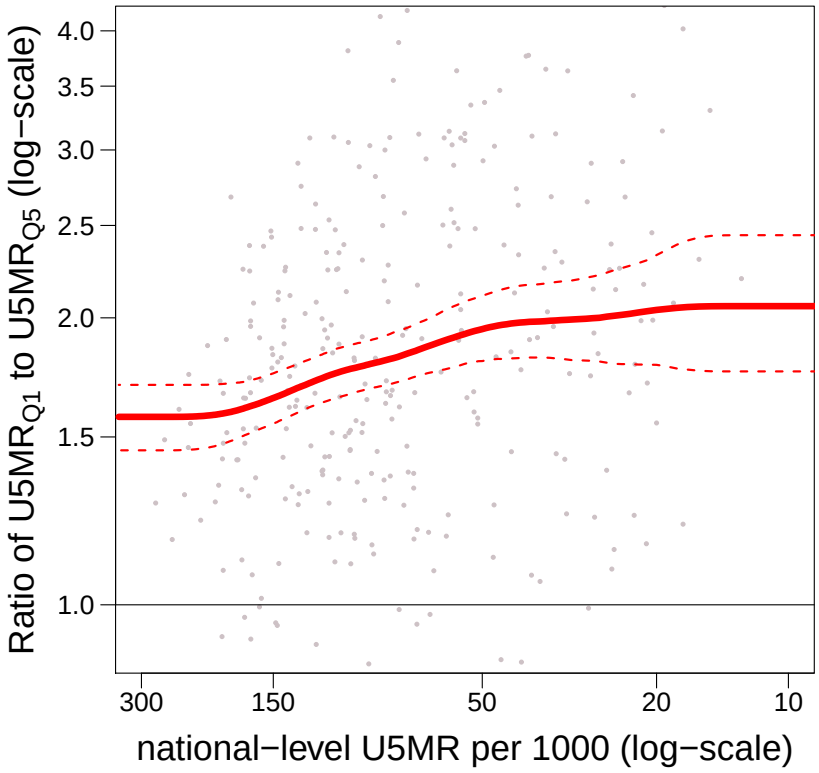

Fig. 5.11 **Overview of the average relation between the ratio of U5MR$_{Q1}$ to U5MR$_{Q5}$ and national-level U5MR.** Observed ratios of U5MR$_{Q1}$ to U5MR$_{Q5}$ are plotted against decreasing national-level U5MR (grey dots) and the model results of the average relation between ratios of U5MR$_{Q1}$ to U5MR$_{Q5}$ and national-level U5MR are in red. Dashed lines represent 90% uncertainty intervals.

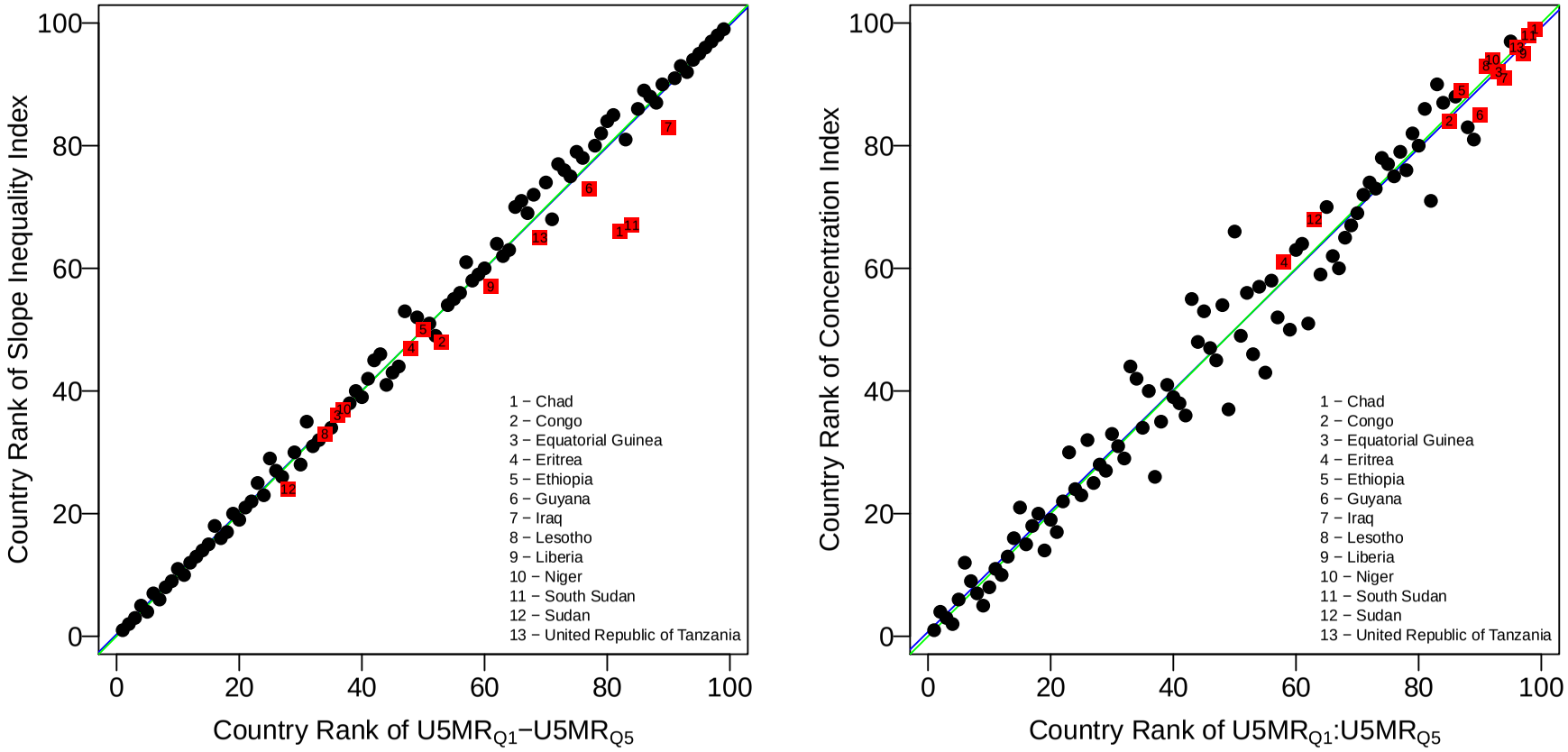

Fig. 5.12 **Country ranks for inequality indices in 2016.** The dots are point estimates of indices ranks (the smaller the ranks, the greater disparity) in 2016 for the 99 countries with empirical data. The green line is the diagonal, indicating equality of two indices. The blue line is the fitted regression line. The red squared dots refer to countries which U5MR from the 1st wealth quintile is not the largest and/or the U5MR from the 5th wealth quintile is not the smallest, among all the wealth quintiles for a country in 2016.

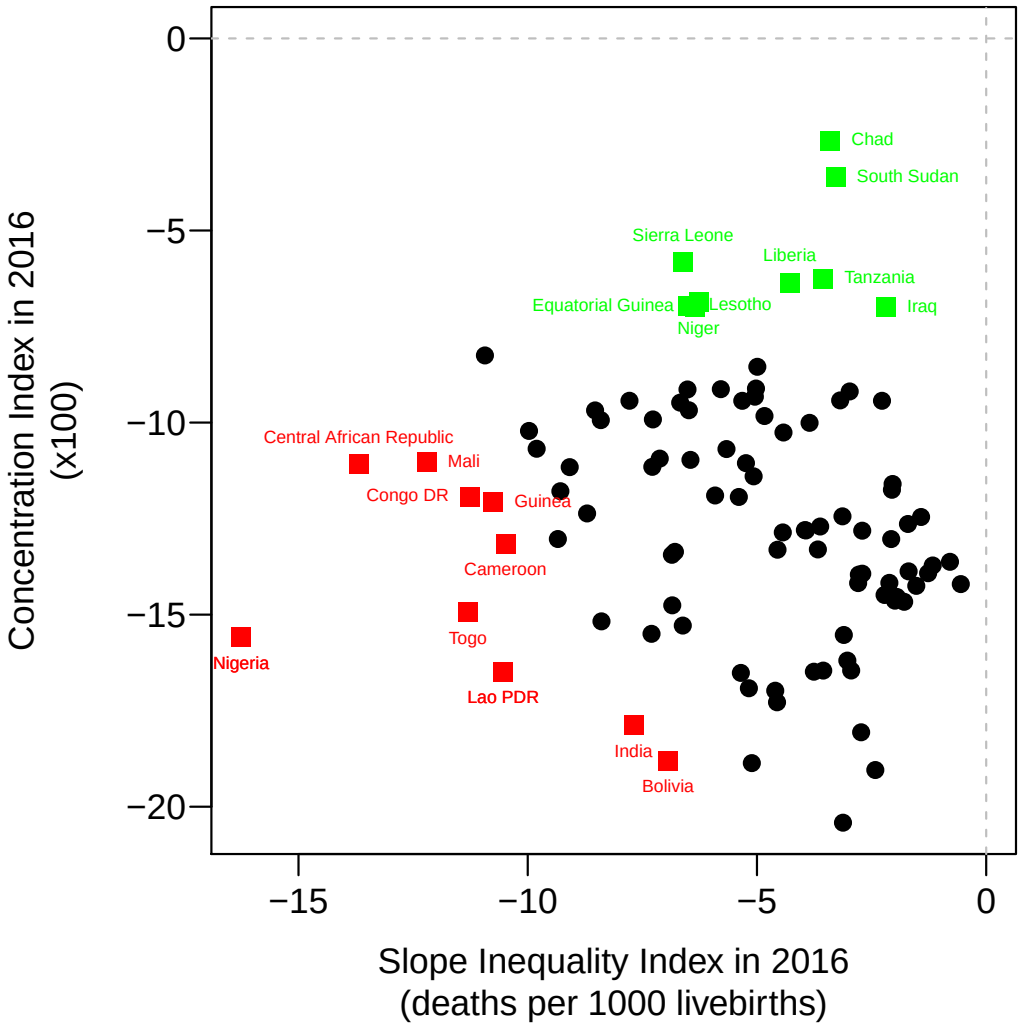

Fig. 5.13 **Slope inequality index and concentration index in 2016, for the 99 countries with empirical data.** The dots are point estimates of indices in 2016 for the 99 countries with empirical data. The green dots highlighted countries with the smallest absolute disparity (based on slope inequality index) and the smallest relative disparity (based on concentration index). The red dots highlighted countries with the largest absolute and relative disparity.

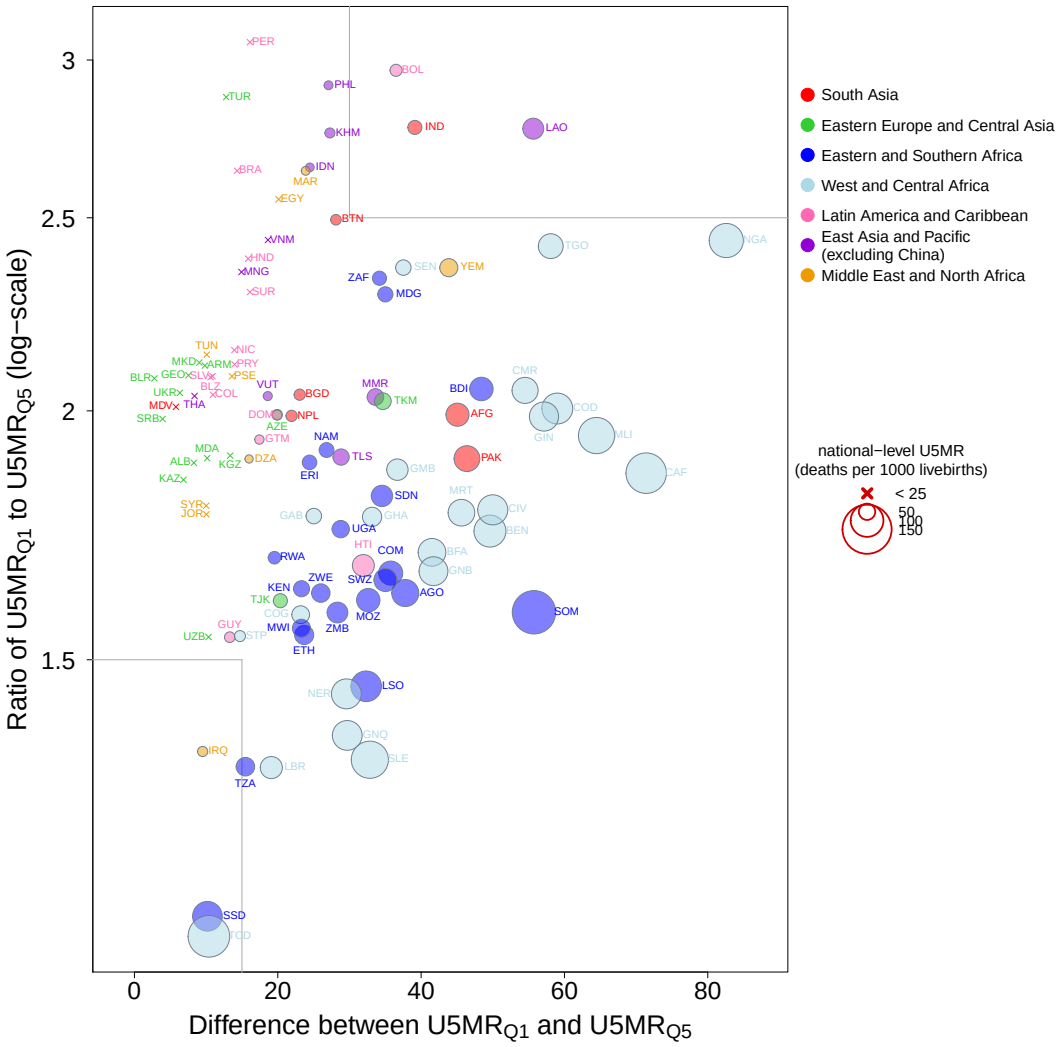

Fig. 5.14 **Ratio of U5MR$_{Q1}$ to U5MR$_{Q5}$ against difference between U5MR$_{Q1}$ and U5MR$_{Q5}$ in 99 low- and middle-income countries with empirical data by national-level U5MR in 2016.** The size of the circle is proportional to the national-level of U5MR (UN IGME 2017 estimates) in 2016 [152]. Circles are color-coded according to the region each country belongs to. Country codes are International Organization for Standardization country codes (see Appendix 6.4 table that lists data sources for 99 countries).

5.6 Discussion

The absolute gap of U5MR between the poorest and the richest households has narrowed significantly for all low- and middle-income countries (excluding China) between 1990 and 2016. The difference of the aggregated U5MR for all low- and middle-income countries (excluding China) between the poorest and the richest household halved between 1990 and 2016. The absolute declines in U5MR for the poorest households in all regions were more than one third higher than those for the richest households. The relative difference between the poorest and the richest U5MRs, however, remained at similar levels between 1990 and 2016, with children in the poorest quintile being twice as likely to die before their fifth birthday, as compared to those in the richest quintile. Similarly, the disparity in U5MR across all quintiles decreased greatly on the absolute scale but remained approximately constant on the relative scale during 1990 and 2016.

We provided estimates and uncertainty intervals for quintile-specific U5MR in 137 low- and middle-income countries based on a statistical model. Our model results confirmed the empirical patterns from previous studies [161, 176] that at high national-level U5MR, the expected ratio of the poor to the rich U5MR tends to be low. As the U5MR at the national level decreases, the expected ratio tends to become higher. The relation confirms the inverse equity hypothesis [180] that small disparities are expected at high mortality levels as most of the population, including the richest households, suffer from poverty and do not have access to basic health care and services. The initial decrease in the national-level U5MR is likely to be driven by a U5MR decrease among the rich, who selectively benefit from improved access to resources [181]. Eventually the poorer groups catch up and when they do, experience faster reductions than the richer groups.

At the regional level, West and Central Africa continued to have the highest quintile-specific U5MR and one of the lowest ratios of $U5MR_{Q1}$ to $U5MR_{Q5}$ during 1990–2016. However, increasing relative disparities have been observed in the region since 1990, as indicated by a significantly positive increase in the ratio of

$U5MR_{Q1}$ to $U5MR_{Q5}$. As the aggregated U5MR for all quintiles combined in this region decreased from 198.7 (192.7; 205.2) deaths per 1000 livebirths in 1990 to 94.7 (83.4; 110.3) deaths per 1000 livebirths in 2016, the ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ increased significantly. Given that U5MR levels are still high in many countries in this region, our model findings on the relation between national-level U5MR and ratio of $U5MR_{Q1}$ to $U5MR_{Q5}$ suggest that relative disparities will be likely to continue to increase after 2016, as national-level U5MR further decreases. Policy interventions with an equity focus, which reach the most disadvantaged and vulnerable children, may help to change these trends. Efforts are needed to reduce high mortality across quintiles as well as to address the increasing relative disparities in West and Central Africa.

In South Asia, the great disparities on both absolute and relative scales were mainly driven by results from India given its large population size among all low- and middle-income countries in the region. For India, its national-level U5MR decreased from 125.8 (121.8; 130.2) deaths per 1000 livebirths to 47.4 (38.8; 47.3) deaths per 1000 livebirths between 1990 and 2016 [152]. In our study, India was identified as a high disparity country on both absolute and relative scales. A further breakdown by smaller age groups can help to better understand the persisting high disparity of U5MR in India. A previous study [182] showed that for India during the period from 1992 to 2006, relative disparities in mortality rates between the first and third years of life were increasing, while the inequality of mortality in the first year of life decreased.

There are several major improvements and advantages in the data processing and modeling approach used in this study. We calculated the U5MR by wealth quintile with an equal number of births in each quintile. This procedure has the benefit of providing a more stable estimate of U5MR for the richest quintile, since more births fall inside this quintile compared to the standard method. The approach differs from the conventional way of deriving quintiles using data from DHS [172, 183] and

MICS[2] surveys, where the number of household members are the same in each quintile. The statistical model incorporates the relation between national-level U5MR and expected Q3-disparity ratios. The model performed reasonably well in validation exercises where data were left out at random and at the end of the observation period (Section 5.5.5); the results suggested that the model-based estimates were unbiased and that uncertainty intervals were conservative (containing the left-out observations more often than expected), hence suggested that the approach worked well to construct estimates for country-years with missing information.

One of the main limitations of our study findings is due to the nature of the data used: we used household assets at the time of the survey as a proxy for household economic status. The household characteristics recorded in surveys only reflect the condition at the time of the interview, while the mortality data recorded a period prior to the time of the survey conducted. In addition, while the set of assets and amenities were tailored in each survey to represent conditions in each country at a specific point in time, variation within each country may in some cases not be covered adequately. The principle component approach used to construct the wealth indices is also not guaranteed to accurately assign low scores to a country's poorest households. This may explain our finding that mortality in the poorest quintile is lower than mortality in richer quintiles for a subset of country-years, hence reflecting problems in the index, rather than reflecting lower mortality among the country's poorest in reality. Lastly, the fact that the wealth index is country-specific implies that absolute country-period specific differences in economic status between the poorest and the wealthiest quintile vary [184]. This limitation is not restricted to the analysis of disparities based on wealth indices – an income or consumption based relative index would face similar problems due to different consumption patterns and prices within and between countries as well as over time. If interest lies in estimating across-country differences in mortality associated with absolute differences

[2]wealth.sps for MICS: The file wealth.sps in `http://www.childinfo.org/files/MICS_syntax_17-03-2009.zip` at `http://www.childinfo.org/mics3_tabulationplan.html`.

in wealth, measures such as a proposed predicted absolute income measure based on households' asset rank, national consumption, and inequality levels can be used [184]. However, any analysis based on absolute differences would not provide a standardized assessment of relative within-country disparities as carried out in this study.

The second main limitation in our study is data availability: we did not have data for 38 out of the 137 countries, and that data at lower levels of U5MR and for more recent years are limited. The lack of data for 38 countries results in estimates for those countries that were purely model-driven. The disparity pattern in these countries may differ from what the model suggested. For this reason, we did not present the country-specific estimates of U5MR by wealth quintile for the 38 countries without any empirical data. We presented aggregated results based on all 137 countries, as opposed to results based on the 99 counties with data, to communicate our best estimates and related uncertainty on all low- and middle-income countries (excluding China). The aggregated results are mainly driven by the 99 countries with available data as they accounted for 97% of all under-5 deaths in the 137 low- and middle-income countries during the period from 1990 to 2016. A comparison of the aggregated results based on the 99 countries with empirical data and the results based on the 137 low- and middle-income countries is carried out. This comparison shows that the overall and regional ratios of quintile-specific to national-level U5MR based on the 137 and 99 countries are approximately the same across quintiles over time. The aggregated quintile-specific U5MR based on the 137 countries are slightly lower than the results based on the 99 countries with empirical data, since countries without data tend to be countries with lower national-level U5MR than those countries with data.

Given data sparsity at low levels of national U5MR (less than 20 deaths per 1000 live births), estimates for the country-years corresponding to those levels of national U5MR were more uncertain and largely based on model extrapolation. Data for countries without information and on disparities at low mortality levels are needed

in order to assess the country-specific situations. Lastly, most of the countries with data only have a limited number of data points. Data are also limited for the most recent period – this study only contains 41 data points from 38 countries with reference year from 2010 onward. Extrapolations using past trends were used to derive trends in most recent years. Efforts are needed to collect reliable, disaggregated, and timely data to better understand trends in mortality disparities.

In the study, we did not incorporate quintile-specific adjustments to reduce the bias associated with retrospective data in countries with high HIV prevalence. Instead we assumed that the observed ratios of quintile-specific to national-level U5MR provide unbiased information of the true ratios. This may result in an underestimate of the relative burden of HIV/AIDS-related child deaths in the poorest quintiles. In addition, we were not able to take into account potential variation of reporting errors across quintiles given the lack of information on the quintile-specific occurrence of such errors.

Despite data limitations, our study provides a systematic assessment of the under-five mortality rate by wealth quintile for all low- and middle-income countries (excluding China) and highlighted that the relative gap in child survival between the poorest and the richest has remained constant during 1990 and 2016. Hence, we should not only acknowledge the progress made in child survival for the poorest subnational population worldwide, but also address the continued existence of within-country disparities and call for greater action to truly close the gap. Identifying current patterns of inequity in under-5 mortality rate in countries is crucial for programming and planning.

Chapter 6

Discussion and conclusion

Given that this PhD research was carried out in Singapore, findings from previous chapters about Singapore are summarized in Section 6.1. Section 6.2 provides an overview of the main findings and contributions of previous chapters. Lastly, future works and follow-up studies are suggested in Section 6.3.

6.1 Research findings for Singapore

In Chapter 3, Singapore is identified as one of the 33 countries at risk of sex-selective abortion and data suggested that the SRB was inflated in the past few decades. The start year of SRB inflation in Singapore was estimated in 1972 [90% UI 1970; 1988] when the total fertility rate declined to 2.8 (Figure 6.1), and the SRB in that year is 1.07 [1.05; 1.08].Then SRB increased for the following decade and reached its maximum at 1.08 [1.07; 1.09] in 1982. It then slowly declined and was estimated to be back around the corresponding regional biological norm of SRB in 2006 [1987; 2035].

Due to the past SRB inflation in Singapore, the annual number of missing female births (AMFBs) during 1972 and 2006 is 63.5 [0; 251.7] on average. The corresponding cumulative number of missing female births (CMFBs) from 1972 to 2006 is 2456.5 [182.0; 7221.3]. To validate the AMBF of Singapore, the AMFBs are compared with the annual number of abortions for Singapore residents during

2003–2006 [185]. The AMFBs account for 0.18% of the total abortions by Singapore residents in 2003 and decreased to 0.02% in 2006.

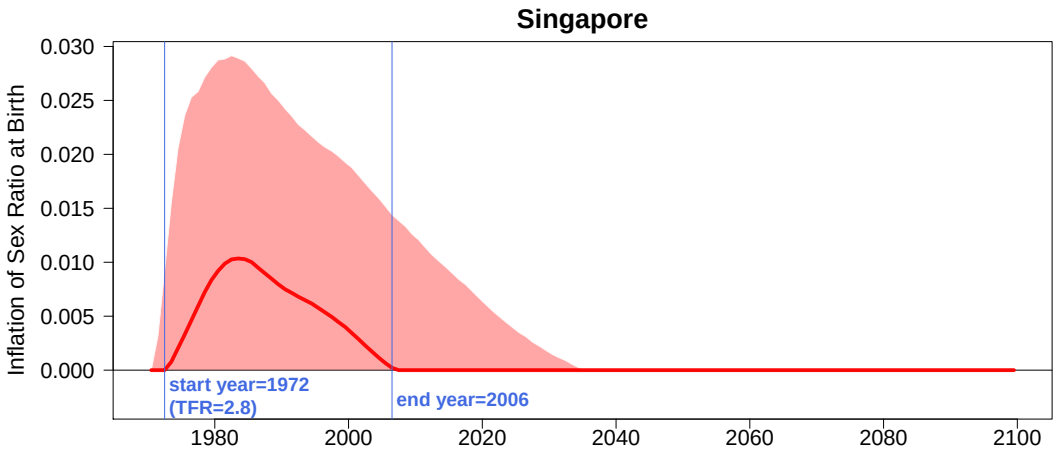

Fig. 6.1 **SRB inflation for Singapore.** The curve refers to the median estimates. Shaded area around the curve indicates 90% uncertainty interval. The start and end years of SRB inflation period are identified with blue vertical lines.

In 2016, the under-5 mortality rate (U5MR) of Singapore is 2.8 deaths per 1000 livebirths, among the ten lowest in the world [152]. When breaking down the national-level U5MR of Singapore by sex as described in Chapter 4, the U5MR for males and females in 2012 were 3.1 [2.6; 3.7] deaths per 1000 livebirths and 2.6 [2.2; 3.1] deaths per 1000 livebirths respectively. The sex ratio of male to female U5MR in 2016 is 1.19 [1.13; 1.26], the same level as the expected sex ratio given the national-level U5MR of Singapore in 2012 at 2.9 deaths per 1000 livebirths. As illustrated in Figure 6.2, the estimated sex ratio of U5MR for Singapore was around the same level as the expected sex ratio during 1990-2012. Similarly, the sex ratio for the infant mortality rate (IMR) and child mortality rate (CMR) all fluctuated around the expected sex ratio for the entire observation period. Hence, the results do not suggest unusually high or low rates of sex-specific mortality.

6.2 Main findings and contributions

In Chapter 2, we implemented a Bayesian hierarchical time series model to assess the extent of misclassification of maternal deaths in VR data. The uncertainty of

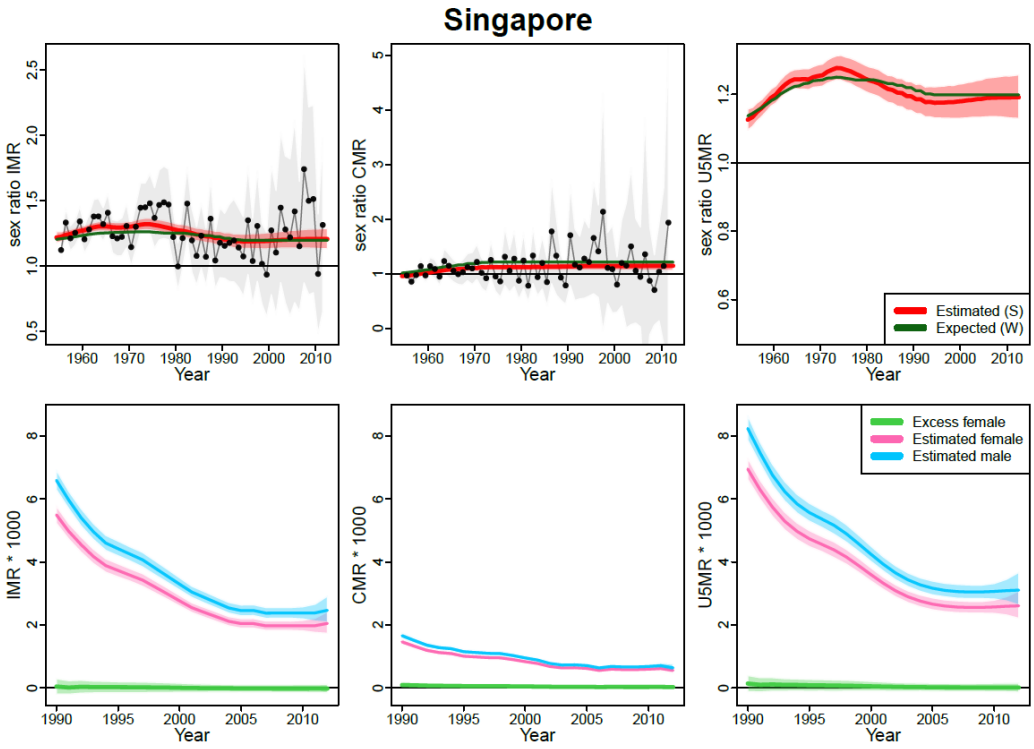

Fig. 6.2 **Sex-specific mortality results for Singapore.** The curves refer to the median estimates. Shaded areas around the curves indicate 90% uncertainty interval. Dots with connection lines indicate data series. Shaded areas around the data series are the corresponding sampling/stochastic errors. Three columns refer to results relating to IMR, CMR, and U5MR.

the outcome for countries without external data on misreporting is also analyzed. This method is meant to overcome the limitations of the current WHO adjustment method, which uses the same expert distribution on VR adjustment parameters for countries without external information and adjustment data with inconsistent observation period were used to inform the entire estimation period of MMR for countries with external information. Based on the method we developed, the time trends, where partial observation periods are covered by data, are well captured for each country we studied. Our model produced a distribution for the misclassification error that is more comparable to the observed data. The uncertainty intervals associated with the MMR are wider than those implemented by WHO. We have verified that the Bayesian VR adjustment model would provide more plausible adjustment estimates than the WHO model for countries with external information on VR quality, if the information available in those countries would not be used to construct the estimates. Hence, Bayesian modeling approaches that we developed can be used to provide more objective and data-driven insights into MMR estimates and data adjustment parameters.

In Chapter 3, we developed model-based estimates and probabilistic projections for the SRB for all countries from 1950 to 2100. We compiled a comprehensive database on national-level SRB with data from VR, censuses, international and national surveys. We developed Bayesian hierarchical models to estimate and project SRBs differently in country-years that are not affected by sex-selective abortion, and those that may be affected by sex-selective abortion that leads to unnatural SRB inflation. To quantify the effect of SRB imbalance due to sex-selective abortion, we computed the number of female births that should have been born on an annual basis and over time if no sex-selective abortion has been or will be practicing. We found that the regional biological norms are significantly different from the conventional SRB value 1.05 for the majority of regions, ranging from 1.03 [1.02; 1.03] in Sub-Saharan Africa to 1.07 [1.06; 1.08] in Eastern Asia and Oceania. The model results suggest that, the majority of missing female births since 1970 until

2015 were concentrated in Eastern Asia at 9.3 [5.7; 13.7] million and Southern Asia at 11.2 [7.2; 15.7] million, made up 44.3% [31.0;58.4] and 53.3% [39.2; 66.7] respectively of the global total number during the period. The majority of the missing female births will most likely remain in the two regions up to the 2060s. Until then, the main burden of missing female births may shift to Sub-Saharan Africa later this century, assuming that all countries at risk of future SRB inflation will follow the similar patterns of past experiences in Southern Asia and Eastern Asia. Our study is the first systematic analysis of the SRB for all countries that produces annual estimates and scenario-based projections with uncertainty assessment from 1950 to 2100 using reproducible methods. The results in this study can be used to update the global health indicators that make use of SRB and produce more accurate results.

In Chapter 4, we constructed estimates of sex ratios of IMR, CMR, and U5MR using a Bayesian model, accounting for differences between observations with respect to sampling and non-sampling error variance and the presence of outlying observations and countries with outlying sex ratios. Our findings provide new information about sex ratios worldwide and the relation between sex ratios and total mortality levels, and identify countries with outlying levels or trends in sex ratios. They confirmed findings from previous studies that chances of survival up to the age of 5 years tend to improve more rapidly for girls compared with boys as total mortality decreases, with a reversal of this trend at very low infant mortality, and quantified this relation between sex ratios and total mortality based on data for all countries since 1950. The study provided national and regional estimates of sex ratios. Additionally, we identified regions and countries with unexpectedly high or low sex ratios compared with their level of total mortality. This study provides a response to the call for disaggregation of under-5 mortality rates by sex from international monitoring initiatives [150, 151]. The country-specific annual estimates and projections of sex ratios, the assessment of excess female mortality and deaths, as well as the degree of uncertainty around them, provide the global health and development community a new platform for monitoring sex equity and evidence-

based policy making and programming.

In Chapter 5, we estimated U5MR by household economic status for all low- and middle-income countries (excluding China) from 1990 to 2015. To our knowledge, this work covers the widest range of countries among all disparity-related studies of the U5MR by household economic groups. In contrast to most other studies where the number of household members in each quintile is the same, we constructed wealth quintiles with equal numbers of births, to increase the sample size of births in the richest quintile. We are also the first study to model the relation between the ratio of the poorest to the richest U5MR and the national-level U5MR, and to estimate the U5MR for all wealth quintile groups. Based on the estimated relationship, increases in relative disparity are projected to coincide with mortality reductions in high-mortality countries. Our study showed that for all low- and middle-income countries (excluding China) combined, the difference of U5MR between the poorest and the richest households decreased significantly by 35.2 [29.6; 40.9] deaths per 1000 livebirths between 1990 and 2015. On the relative scale, however, there was no significant change during the period. In 2015, there were still 2.07 [1.93; 2.21] under-5 deaths among the poorest for every one under-5 death among the richest. While the poorest subpopulations in low- and middle-income countries (excluding China) have been making substantial progress in reducing under-5 mortality rate, even more so than their richest counterparts in terms of absolute reductions, the poorest are not catching up on a relative scale and remain at a disadvantage for the great majority of low- and middle-income countries. Information on disparities in child survival at the country level should form the basis of targeted interventions to reduce the higher mortality burden in the poorest subpopulations.

6.3 Future works

For Chapter 2, although we have provided a more plausible modeling approach to assess the misclassification error in the maternal mortality VR data, the limited amount of high quality data is still causing large uncertainty in the maternal mor-

tality estimation. The prime task for future work on the topic should focus on more data collection and research to measure maternal mortality and assess data quality.

For Chapter 3, future work should assess subnational divisions in countries where the SRB may be imbalanced at the sub-national level. The sub-national study on SRB for countries with outlying SRB on the country-level can help to better identify where female births are most discriminated against in the prenatal period in a certain country. Consequently, policies and planning can be better targeted to subnational population where the SRB is more imbalanced than other parts of the country. To countries where the national SRB fluctuates around the biological norms, breaking down the SRB into sub-national groups can be useful to check if the prenatal sex discrimination have been masked by the national-level results. Figure 6.3 illustrates state-level SRB data from India 2005-06 DHS. The SRB values shown in Figure 6.3 have been re-calculated using the Jackknife method to take account of the multiple-stage cluster sampling structure of the survey [58]. From left to right, the plot shows the change of SRB during 1995-2005. Based on the survey data, the SRB in the majority of the states is becoming more masculine/higher over time. However, great variations for state-level SRBs exist throughout the whole period. The SRB of Madhya Predesh (which is a large state in central India) is becoming more and more feminine/lower even though it is surrounded by states with increasingly masculine SRB during the same period.

In Chapter 4, we only focused on the sex imbalance of the post-natal period for the under-5 population. For a complete assessment of skewed under-5 population sex ratios in countries where sex discrimination might be present, sex-selective distortions of sex ratios at birth need to be taken into account as well [43]. Further analysis, focusing on a comprehensive assessment of under-5 sex ratios in the population by simultaneously modeling the SRB and sex-specific U5MR as described in Chapter 3 and Chapter 4 respectively could provide more insights into such issues.

In Chapter 5, the wealth quintile-specific U5MR data we used are from DHS and MICS, and the household economic status was approximated by information on

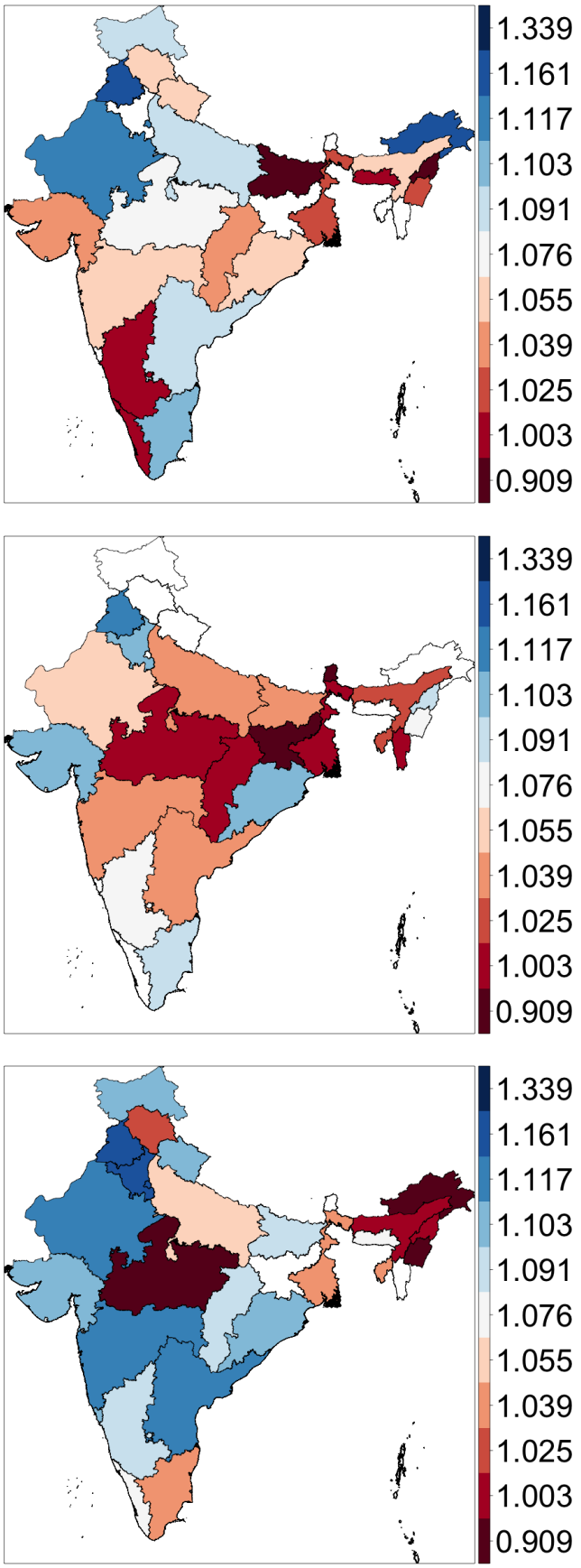

Fig. 6.3 **State-level SRB data from India 2005-06 DHS over time.** The average SRB during 1990–1995 (top), 1995–2000 (middle), and 2000–2005 (bottom). White area indicates missing data.

household assets. More studies on assessing whether the wealth index based on information on assets and amenities can correctly reflect the household economic status are needed. Although we have compiled a database on wealth quintile-specific U5MR from a large number of countries, we did not have data for 41 out of the 136 low- and middle-income countries (not considering China). Hence, more efforts are needed to collect reliable, disaggregated, and timely data to better understand trends in mortality disparities.

6.4 Conclusion

In conclusion, the chapters in this thesis provide a set of important analyses and fill the previous research void on global health indicators related to child and maternal mortality. These studies provide reproducible Bayesian modeling approaches. The methods implemented in this thesis take account of the data quality that varies across different sources as well as infer the levels and trends of indicators in countries and periods with limited data by data-rich country-years. The resulting estimates provide new insights into child and maternal mortality and the sex ratio at birth globally. The methods and results can be used by international agencies for policy making to move forward with the SDGs.

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Appendix

Chapter 3 additional files can be found at: https://www.dropbox.com/s/hf3fnboth6a0ed4/SRB_appendix_table9.pdf?dl=0.

Chapter 4 additional files can be found at: http://www.sciencedirect.com/sdfe/arp/media/1-s2.0-S2214109X14702803-mmc1.pdf.

Chapter 5 additional files can be found at: https://www.dropbox.com/s/z9pzuqk8i3fh8b2/appendix_CM_Wealth_table9.pdf?dl=0.