Conditional Probabilistic Projections of Fertility Given Policy Intervention Scenarios

Daphne H. Liu[1], Patrick Gerland[2], Vladimíra Kantorová[2], Mark C. Wheldon[2]

[1]U.S. Census Bureau [2]United Nations Population Division

Abstract

The United Nations Sustainable Development Goals (SDGs) include targets for universal secondary education and universal access to sexual and reproductive health-care services, including family planning. Due to the accelerating effect of women's educational attainment and contraceptive prevalence on fertility decline in high-fertility settings, achievement of these SDG targets is likely to have an impact on future fertility and population size for countries that are currently undergoing the fertility transition. Policymakers in high-fertility countries may therefore be interested in quantifying the potential effect of different policy interventions related to education and family planning on the future fertility and population of their countries. We propose a conditional Bayesian hierarchical model for projections of fertility that incorporates women's educational attainment, contraceptive prevalence, and GDP per capita as covariates and create annual probabilistic projections of fertility given a range of policy intervention scenarios targeting expansion of education and access to family planning.

1 Introduction

The United Nations (UN) has produced estimates and projections of world population by country since 1951 and remains the premier producer of global demographic projections. Policymakers in countries that do not have robust vital registration systems of their own often rely on the UN estimates and projections to inform planning and policy decisions. However, the UN does not currently produce projections for policy intervention scenarios, although projection variants (low, medium, and high) based on different underlying demographic assumptions are available. For fertility, the low and high projection variants correspond to assuming the Total Fertility Rate (TFR) will be, respectively, half a child below or half a child above the medium variant TFR. While these variants can provide some guidance to policymakers, they have the drawback of being deterministic. The variants are also in terms of the TFR, rather than in terms of variables that can be more directly influenced by policy.

Two such variables that can be directly influenced by policy and that have been found to have significant accelerating effects on fertility decline in the high-fertility setting are women's educational attainment and contraceptive prevalence. Liu and Raftery (2020a) found that faster increases in women's educational attainment and contraceptive prevalence, for example due to policy interventions, were associated with faster increases in the pace of fertility decline beyond what we would expect the fertility decline to look like assuming no policy intervention. Two of the UN Sustainable Development Goals (SDGs) relate directly to increasing educational attainment and access to family planning. Target 4.1 aims to reach universal primary and secondary education, while target 3.7 includes goals related to universal access to sexual and reproductive health-care services, including for family planning

(United Nations, 2015). Due to the accelerating effect of education and family planning on fertility decline, achievement of these SDG targets is likely to have an impact on future fertility and population size. Quantifying the potential impact of policies aimed to expand education and access to family planning on future fertility and population size using the UN methodology, particularly in the context of meeting the SDG targets, could therefore be of interest for policymakers to help plan for the future infrastructure needs of their constituencies and guide decisions regarding resource allocation.

We extend previous work from Liu and Raftery (2024) to develop a conditional Bayesian hierarchical model based on the current UN fertility projection model that allows for the creation of conditional probabilistic projections depicting the potential impact of changes in contraceptive use and women's educational attainment on future fertility and population dynamics. Unlike Liu and Raftery (2024), this work uses a one-year instead of a five-year time scale, enables the creation of conditional projections for a larger number of countries, and incorporates uncertainty about past values of TFR in projections. We update all results to use the most recent (2024) revision of the UN *World Population Prospects* (WPP), which provides updated TFR estimates based on more data compared to previous revisions. We also update the hypothetical policy intervention scenarios considered for the conditional projections. Liu and Raftery (2024) created conditional projections of TFR given intervention scenarios related to achieving SDG targets 4.1 and 3.7. In this work, we explore a wider and more realistic array of projection scenarios, including scenarios for changes in contraceptive use that are based on ambitious yet achievable targets for improving access to family planning as discussed in Kantorová et al. (2017) and Biddlecom et al. (2023).

2 Methods

2.1 Fertility Projection Model

The fertility projection model used by the UN divides the fertility transition into three phases as defined by Alkema et al. (2011): phase I is the high-fertility pre-transition phase, phase II is the transition phase where fertility falls from high to low, and phase III is the low-fertility post-transition phase. Liu and Raftery (2024) extended the unconditional phase II model that was used by the UN for the 2019 revision of WPP (Alkema et al., 2011; Raftery et al., 2014; Fosdick and Raftery, 2014; United Nations, 2019) to incorporate changes over time in women's education attainment, contraceptive prevalence, and GDP per capita as covariates. Using this model, conditional projections of fertility for five-year time periods were created given policy intervention scenarios related to SDG targets 4.1 and 3.7.

Starting with the 2022 revision of WPP, the fertility projection model used by the UN was updated to account for uncertainty in past values of TFR and to produce annual projections (Liu and Raftery, 2020b; Liu, Ševčíková, and Raftery, 2023). We extend the conditional TFR projection model from Liu and Raftery (2024) to incorporate these two methodological updates. The extended conditional TFR projection model is a four-level Bayesian hierarchical model, where Levels 1 and 3 of the hierarchical model are identical to the specification in Liu, Ševčíková, and Raftery (2023). In Level 2, the conditional TFR projection model modifies the model for phase II of the fertility transition, but uses the same models for phase

I and phase III as Liu, Ševčíková, and Raftery (2023). Additional prior distributions for the added phase II parameters are specified on Level 4 of the model. All other prior distributions on Level 4 are specified as in Liu, Ševčíková, and Raftery (2023).

Let $f_{c,t}$ denote the true (unknown) value of TFR for country c and year t. Estimates of the TFR from data source s for country c and year t are denoted $y_{c,t,s}$. For country c and year t, the change over time in the proportion of women aged 20-39 who have attained at least lower secondary education is denoted $(\Delta\text{LowSec+})_{c,t}$, the change over time in the contraceptive prevalence for all women of reproductive age is denoted $(\Delta\text{CP})_{c,t}$, and the percent change in GDP per capita is denoted $(\Delta\text{GDP})_{c,t}$. The change over time in each covariate Z from time $(t-1)$ to time t is denoted as $\Delta Z_{c,t}$. Finally, let SSA_c be an indicator for whether country c is in sub-Saharan Africa.

The conditional TFR projection model is

Level 1:

$$\begin{aligned} y_{c,t,s}|f_{c,t} \sim& N(f_{c,t} + \delta_{c,s}, \rho^2_{c,s}) \\ E[\delta_{c,s}] =& \boldsymbol{x}_{c,s}\boldsymbol{\beta} \\ E[\rho_{c,s}] =& \boldsymbol{x}_{c,s}\boldsymbol{\gamma} \end{aligned}$$

Level 2: Phase I:

$$\begin{aligned} f_{c,t+1} =& f_{c,t} + \varepsilon_{c,t} \\ \varepsilon_{c,t} \sim& N(0, s_t^2) \end{aligned}$$

Phase II:

$$\begin{aligned} f_{c,t+1} =& f_{c,t} - d_{c,t} + \boldsymbol{\Delta}\mathbf{Z}_{c,t}\boldsymbol{B} \\ d_{c,t} =& g(f_{c,t}|\boldsymbol{\theta}_c) + \varepsilon_{c,t} \\ d_{c,t+1} - g(\boldsymbol{\theta}_c, f_{c,t+1}) =& \phi(d_{c,t} - g(\boldsymbol{\theta}_c, f_{c,t})) + \varepsilon_{c,t} \end{aligned}$$

$$\boldsymbol{B} = \begin{bmatrix} B_E \\ B_F \\ B_G \\ B_{E,SSA} \\ B_{F,SSA} \\ B_{G,SSA} \end{bmatrix}, \quad \boldsymbol{\Delta}\mathbf{Z}^T_{c,t} = \begin{bmatrix} (\Delta\text{LowSec+})_{c,t} \\ (\Delta\text{CP})_{c,t} \\ (\Delta\text{GDP})_{c,t} \\ (\Delta\text{LowSec+})_{c,t} \times SSA_c \\ (\Delta\text{CP})_{c,t} \times SSA_c \\ (\Delta\text{GDP})_{c,t} \times SSA_c \end{bmatrix}$$

$$\boldsymbol{\varepsilon} \sim N(\boldsymbol{m}, \Sigma)$$

Phase III:

$$\begin{aligned} f_{c,t+1} =& \mu_c + \rho_c(f_{c,t} - \mu_c) + \varepsilon_{c,t} \\ \varepsilon_{c,t} \sim& N(0, s^2) \end{aligned}$$

Level 3:

$$\begin{aligned} \boldsymbol{\theta}_c \sim& h(\cdot|\psi) \\ \mu_c \sim& N(\bar{\mu}, \sigma^2_\mu) \\ \rho_c \sim& N(\bar{\rho}, \sigma^2_\rho) \end{aligned}$$

Level 4:

$$\begin{aligned} B_j \sim& N\left(0, 0.25 \times \frac{Var(\Delta f_{c,t})}{Var(Z_j)}\right) \quad \text{for } B_j \in \boldsymbol{B} \\ \rho^{[bc]} \sim& \text{Uniform}(0,1) \\ \phi \sim& \text{Uniform}(0,1) \\ m_t, s_t^2, \psi, \bar{\mu}, \sigma^2_\mu, \bar{\rho}, \sigma^2_\rho, s^2 \sim& \pi(\cdot) \end{aligned}$$

In level 1 of the Bayesian hierarchical model, the observed TFR estimates are modeled using country- and source-specific data quality indicators, denoted $\boldsymbol{x}_{c,s}$, which are used to estimate the bias $\delta_{c,s}$ and measurement error variance $\rho^2_{c,s}$.

In level 2, the three phases of the fertility transition are modeled. Phase I is modeled using a random walk with random distortions $\varepsilon_{c,t}$. In phase II, changes over time in the true (unknown) value of TFR are modeled as a random walk with drift using a double logistic function and a covariate term. The double logistic function is defined as in Alkema et al.

(2011) as

$$g(f_{c,t}|\boldsymbol{\theta}_c) = \frac{-d_c}{1+\exp\left(-2\frac{\ln(9)}{\Delta_{c1}}\left(f_{c,t}-\sum_i \Delta_{ci}+0.5\Delta_{c1}\right)\right)} + \frac{d_c}{1+\exp\left(-2\frac{\ln(9)}{\Delta_{c3}}\left(f_{c,t}-\Delta_{c4}-0.5\Delta_{c3}\right)\right)}$$

and takes in the current value of TFR $f_{c,t}$ and a vector of country-specific parameters $\boldsymbol{\theta}_c = (\Delta_{c1}, \Delta_{c2}, \Delta_{c3}, \Delta_{c4}, d_c)$. The covariate matrix $\Delta \boldsymbol{Z}_{c,t}$ with vector of coefficients $\boldsymbol{B}$ includes the main effects of all covariates and interaction terms with an indicator function for whether a country is in sub-Saharan Africa. Between-country correlation $\rho^{[bc]}$ is accounted for in estimation of $\boldsymbol{B}$ using clusters based on UN region membership, with further details in the appendix.

Phase III is modeled using a first-order autoregressive (AR(1)) time series model, where fertility is assumed to converge towards and fluctuate around country-specific long-term TFR levels. The country-specific means μ_c are assumed to be drawn from a world distribution with mean μ, which itself has a prior distribution restricting it to be no greater than replacement-level fertility (i.e., $\mu \leq 2.1$). The country-specific autoregressive parameter ρ_c is restricted to $0 < \rho_c < 1$, and s is the standard devation of the random errors.

Level 3 specifies the distributions for the country-specific parameters from the phase II and phase III models, while level 4 specifies the prior distributions for all global parameters and hyperparameters. The prior distributions for the coefficients $\boldsymbol{B}$ were chosen to be diffuse, where the prior variances are determined by the ratio of the sample variance of changes in f to the sample variance of changes in Z_j. The prior distribution for $\rho^{[bc]}$ was chosen to reflect the prior belief that between-country correlation is positive (Fosdick and Raftery, 2014).

Further details of the model specification can be found in the appendix.

2.2 Data

Estimates of TFR for 237 countries for years 1950-2023 are obtained from the United Nations *World Population Prospects* (WPP) 2024 Revision (United Nations, 2024b,c). TFR is a period measure of fertility that measures the expected number of children a woman would bear in her lifetime if she were to experience the period-specific fertility rates at each age and if she lived through the reproductive age range, here defined as ages 15–49. The estimates of TFR from WPP 2024 are based on vital registers, censuses, and surveys such as the Demographic and Health Surveys (DHS) and the Multi-Indicator Cluster Surveys (MICS).

Estimates of educational attainment for women in the broad age group 20–39 are obtained from the Wittgenstein Centre Data Explorer version 2.0 (Wittgenstein Centre, 2018; Lutz et al., 2018). The Wittgenstein Centre produces estimates for six levels of attainment based on the International Standard Classification of Education: No Education, Incomplete Primary, Primary, Lower Secondary, Upper Secondary, and Post Secondary. We focus on the proportion of women who have attainment Lower Secondary, Upper Secondary, or Post Secondary education. This cumulative attainment is a abbreviated as "LowSec+". Probabilistic projections of educational attainment are created using a modification of the Bayesian hierarchical model implemented in the *wicedproj* package in R (Barakat, 2016). Projections for hypothetical policy intervention scenarios corresponding to meeting the SDG targets are created by adapting the methodology of Abel et al. (2016). Projections for additional policy intervention scenarios that are not directly tied to the SDG targets are created using a similar methodology as Biddlecom et al. (2023). Further details of the projections for hypothetical policy intervention scenarios can be found in Section 2.4 and in the appendix. As the Wittgenstein Centre's estimates of educational attainment and the *wicedproj* model are only available on the five-year time scale, we linearly interpolate the five-year estimates and projections of the change over time in the proportion of women aged 20–39 who have attained lower secondary education or higher to obtain estimates and projections on the annual scale.

Estimates of contraceptive prevalence for married women aged 15–49 are obtained from the UN *Estimates and Projections of Family Planning Indicators* (United Nations, 2024a). Probabilistic projections of contraceptive prevalence are created using the Bayesian hierarchical model for projections of family planning indicators developed by Kantorová et al. (2020) and implemented in the *FPEMglobal* package in R (Wheldon et al., 2022). Projections of family planning indicators for hypothetical policy intervention scenarios corresponding to meeting the SDG targets are created following an adapted version of the accelerated transition method of Cahill et al. (2020), where each trajectory of the reference scenario projections is modified to meet the SDG target in a specified year. Projections for additional policy intervention scenarios that are not directly tied to the SDG targets are created following the methodology of Biddlecom et al. (2023). Further details of the projections for hypothetical policy intervention scenarios can be found in Section 2.4 and in the appendix.

Estimates of GDP per capita in terms of purchasing power parity (PPP) are obtained by harmonizing data from the Penn World Table version 10.01 (Feenstra et al., 2015), the Maddison Project Database 2020 (Maddison Project Database, 2020), and the World Bank World Development Indicators (World Bank, 2023). An ad-hoc approach was used to determine which source of data to use for each country-year, where the country-specific estimates from the Penn World Table are prioritized when data is available. When possible, country-years with no data from the Penn World Table are filled in using country-specific estimates from the Maddison Project. The remaining countries are proxied using regional averages calculated from the country-specific Penn World Table and World Bank WDI estimates. Further details of the data harmonization for GDP per capita can be found in the appendix. Probabilistic projections of GDP per capita are created using a Bayesian hierarchical model developed by Raftery et al. (2017). As we are not interested in hypothetical policy interventions targeting GDP, we only consider reference scenario projections of GDP per capita for the conditional TFR projections.

2.3 Estimation

The conditional TFR projection model is estimated using an MCMC algorithm with Gibbs sampling, Metropolis-Hastings, and slice sampling steps. The majority of estimation proceeds as in Liu, Ševčíková, and Raftery (2023), but estimation of the Phase II model for the conditional TFR projection model occurs in two stages. In the first stage, the country-specific parameters $\boldsymbol{\theta}_c$ for the double logistic expected TFR decrement function and the autoregressive parameter ϕ are estimated in the absence of the covariates. In the second stage, the $\boldsymbol{\beta}$ coefficients are estimated conditional on the posterior distributions of the parameters estimated in the first stage.

The first stage is estimated analogously to the UN projection model used for WPP 2024, using estimates of TFR for 237 countries spanning years 1950-2023. The first stage of estimation enables the use of available data to estimate the double logistic expected TFR decrement term and ensures that our estimates of $\boldsymbol{\theta}_c$ are comparable to the estimates used by the UN.

In the second stage, estimation of the effect of the covariates is restricted to current and historical "high-fertility" transitions, defined as the years for each country where the country was in phase II (i.e., had begun the fertility transition) and had TFR greater than 2.5. Countries without available covariate data are excluded from analyses in the second stage, resulting in a subset of 138 countries with 4,389 observations in years 1970-2019. The top panel of Figure 1 shows the number of observations from each country included in the second stage of estimation.

The model for uncertainty in past TFR (Level 1 of the conditional bayesTFR model) and the models for phase I and phase III (in Level 2 of the conditional bayesTFR model) are estimated using the same data and methodology as was used for WPP 2024 (United Nations, 2024c).

2.4 Projection Scenarios

For all covariates, we consider reference scenario projections that assume no additional policy intervention targeting education or family planning takes place. The conditional TFR projections under the reference scenario are not expected to be identical to the unconditional projections produced by the UN for WPP 2024, but the two sets of projections should be very similar.

For the education and family planning covariates, we consider a range of hypothetical policy intervention scenarios related to increasing women's educational attainment and access to family planning. These scenarios are summarized in Table 1. Two of these scenarios are based on achieving SDG targets 4.1 and 3.7. The "SDG 2030" scenario assumes the SDG targets for universal lower secondary education and universal access to family planning are met by 2030. The education SDG target is interpreted in a similar fashion as Abel et al. (2016), where we assume the proportion of women aged 15-19 that have attained lower secondary education reaches 97-99% by the target year. The family planning SDG target is interpreted as the proportion of the demand for family planning that is satisfied by modern methods reaches 87-92% by the target year. The "SDG 2050" scenario assumes these same targets are met by 2050 instead.

We also consider an "ambitious yet achievable" scenario that assumes each country experiences accelerated progress towards education and family planning targets based on the country's reference scenario projections. Unlike the SDG 2030 and SDG 2050 scenarios, the ambitious yet achievable scenario uses country-specific targets. Targets for development indicators, such as educational attainment and contraceptive prevalence, have previously been set by looking at a subset of "best-performing" countries over a defined time period, or simply by picking the maximum value on the scale (e.g., 100%). While aspirational, universal

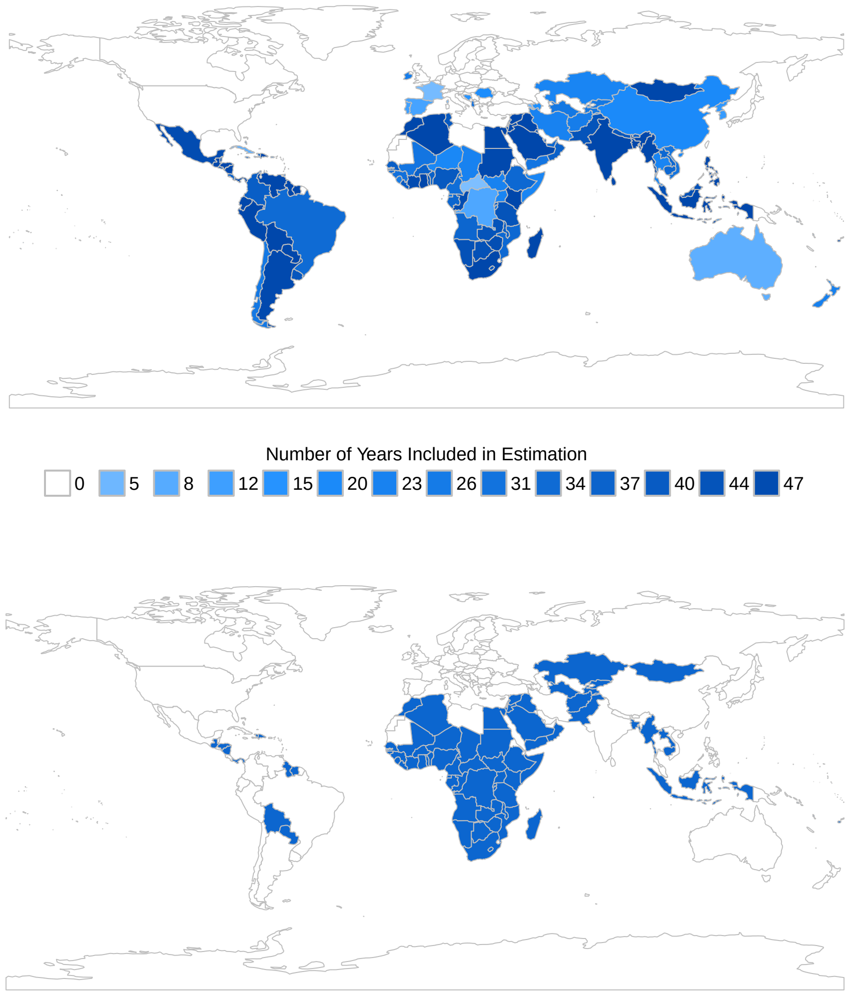

Figure 1: Top panel: Number of observations for each country used for estimation of the conditional TFR projection model. Bottom panel: conditional TFR projections are created for the 85 countries shaded in blue.

targets for all countries may be inappropriate and unachievable because they ignore the wide variation in country contexts, such as varying starting points and varying historic rates of change. Rather than set fixed, aspirational targets that are the same for all countries, the ambitious yet achievable targets are derived from model-based country-specific projections. They are data-informed, country-specific, and ensure that, by the target date, there is a small but non-negligible probability of achieving the target level. As such, they are more useful as a basis for in-country policy planning and budgeting. For education, projections under this scenario are created by resampling from 85th-95th percentiles of the reference scenario trajectories in 2100. For family planning, projections under this scenario are created following the methodology of Biddlecom et al. (2023) by resampling from the 85th-95th percentiles of the projected changes between 2019 and 2040 in the demand for family planning satisfied by modern methods from reference scenario trajectories.

All covariate projections are centered at their expected values assuming no policy intervention. After centering, the covariate projections measure acceleration in trends beyond what we would expect if no policy intervention occurred. For example, the reference scenario projections of educational attainment reflect the increases in educational attainment that are expected to occur assuming no explicit policy intervention. The centered reference scenario projections of ΔLowSec+ are therefore close to 0. In the hypothetical policy intervention scenarios, educational attainment is projected to increase at faster rates than would occur assuming no intervention. Correspondingly, the centered projections of ΔLowSec+ under the policy intervention scenarios are larger than 0.

Table 1: Summary of projection scenarios

Scenario	Education Assumptions	Family Planning Assumptions
Reference	No intervention	No intervention
SDG 2030	Proportion of women aged 15-19 attaining lower secondary education reaches 97-99% by 2030	Proportion of married women with demand for family planning satisfied by modern methods reaches 87-92% by 2030; all increases in contraceptive prevalence are assumed to be for modern method
SDG 2050	Proportion of women aged 15-19 attaining lower secondary education reaches 97-99% by 2050	Proportion of married women with demand for family planning satisfied by modern methods reaches 87-92% by 2050; all increases in contraceptive prevalence are assumed to be for modern methods
Ambitious yet Achievable	Proportion of women aged 20-39 attaining LowSec+ reaches 85th-95th percentiles of reference scenario	Proportion of married women with demand for family planning satisfied by modern methods reaches 85th-95th percentiles of projected changes between 2019 and 2040 from reference scenario

2.5 Projection

Conditional projections of TFR for years 2024-2100 are created conditional on the projected distributions of the covariates. Uncertainty about the future values of the covariates is propagated into the conditional projections of TFR by randomly drawing from the projected distributions of the covariates when constructing each trajectory of projected TFR: for each projected trajectory of TFR for country c, we use one trajectory from the projected distribution of ΔLowSec+ for country c, one trajectory from the projected distribution of ΔCP for country c, and one trajectory from the projected distribution of ΔGDP for country c.

Projections of TFR given policy intervention scenarios were created for the 85 countries with TFR ≥ 2.1 in 2023 that have available covariate data, which are shaded in blue in the bottom panel of Figure 1.

3 Results

Conditional projections of TFR are presented in this section for 2024-2100 using Nigeria and Ethiopia as case studies. Additional projection results are available in the appendix.

3.1 Case Study: Nigeria

Nigeria is the most populous country in Africa, with estimated population size in 2023 of 230 million people. Nigeria is also a high-fertility country as defined for the conditional TFR projection model, with a TFR in 2023 of 4.48 children per woman. As of 2020, the estimated proportion of women aged 20-39 who have attained at least lower secondary education is 0.488. Among married women, the estimated proportion of demand for family planning satisfied by modern contraceptive methods is 0.505 in 2023.

The projection results for the proportion of women aged 20-39 who have attained lower secondary education or higher, the demand for family planning satisfied by modern contraceptive methods for married women, and the TFR are shown in Figure 2 for Nigeria under different projection scenarios. The median projections are shown as lines for all projection scenarios, while 95% projection intervals are shown as shaded regions for the reference and ambitious yet achievable scenarios in red and grey, respectively. The conditional TFR projections additionally show estimates of past TFR with 95% uncertainty intervals in purple. While probabilistic projections of education and family planning are used as inputs for the conditional TFR projections, the conditional projection model does not account for uncertainty in past values of the covariates. The figures for the education and family planning indicators therefore only show deterministic estimates of the past corresponding to the median from the reference scenario.

Table 2 summarizes the conditional TFR projection results for Nigeria, where medians and 95% projection intervals are reported for all scenarios for the years directly following the SDG intervention scenario target years (2031 and 2051) and for the end of the projection time period (2100). Differences in median projected values across the different projection scenarios are also reported for ease of comparison.

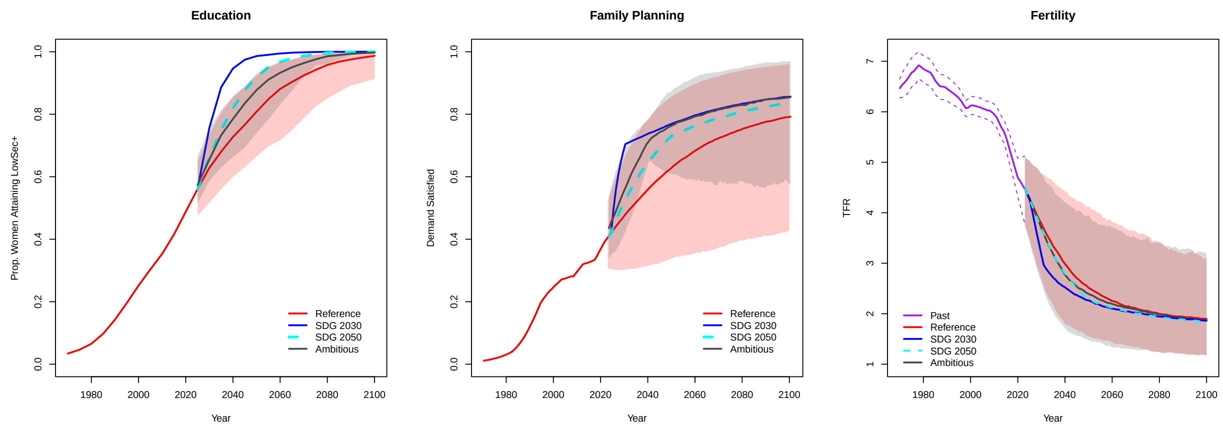

Figure 2: Comparison of median projections for educational attainment, family planning indicators, and TFR for Nigeria for a range of projection scenarios. 95% projection intervals for the reference and ambitious yet achievable scenarios are shown as shaded regions in red and grey, respectively.

Table 2: Median TFR projections in 2031, 2051, and 2100 for Nigeria in children per woman for all projection scenarios with 95% projection intervals. Rows indicating differences between projection scenarios show differences between median projected TFR.

	2031	2051	2100
Reference	3.69 (2.56, 4.76)	2.49 (1.54, 4.07)	1.90 (1.16, 3.10)
SDG 2030	2.97 (1.83, 4.32)	2.24 (1.37, 3.74)	1.86 (1.16, 3.06)
SDG 2050	3.59 (2.45, 4.75)	2.25 (1.41, 3.82)	1.84 (1.16, 3.14)
Ambitious	3.58 (2.46, 4.69)	2.37 (1.46, 3.88)	1.87 (1.18, 3.20)
Reference − SDG 2030	0.72	0.24	0.04
Reference − SDG 2050	0.10	0.23	0.06
Reference − Ambitious	0.11	0.11	0.03
SDG 2050 − SDG 2030	0.62	0.01	−0.02
Ambitious − SDG 2030	0.61	0.13	0.00
Ambitious − SDG 2050	−0.01	0.12	0.03

In 2031, the SDG 2030 scenario projects TFR to be 2.97 children per woman with a 95% prediction interval of (1.83, 4.32). This is a reduction of 0.72 of a child from the reference scenario projection of 3.69 (2.56, 4.76) children per woman, which is the largest difference in median projected TFR found for Nigeria across all projection scenarios and all projection years. The SDG 2050 and ambitious yet achievable projection scenarios reflect less extreme hypothetical policy interventions, and correspondingly have less extreme impacts on projected TFR. Attaining both SDG targets in 2050 leads to a reduction in median projected TFR of 0.10 compared to the reference scenario projection, while attaining the ambitious yet achievable target leads to a reduction in median projected TFR of 0.11.

By 2051, the differences between the SDG 2030 and SDG 2050 scenarios are less pronounced. The SDG 2030 scenario projects TFR to be 2.24 (1.37, 3.74) while the SDG 2050 scenario projects TFR to be 2.25 (1.41, 3.82), corresponding to reductions in median projected TFR of 0.24 and 0.23, respectively, compared to the reference scenario projection. In comparison, the more realistic ambitious yet achievable scenario projects TFR to be 2.37 (1.46, 3.88), which is a reduction in median projected TFR of 0.11 compared to the reference scenario projection.

After 2051, the TFR projections for all scenarios begin to converge due to the shared post-transition phase III model. Once a country has entered phase III, TFR is projected to converge toward and fluctuate around a long-term, country-specific mean TFR. As the TFR projections across all scenarios eventually converge to the same country-specific mean, the majority of the differences in the conditional TFR projections occur before mid-century.

3.2 Case Study: Ethiopia

Like Nigeria, Ethiopia is a high-fertility country with an estimated TFR in 2023 of 3.99 children per woman. Ethiopia is less populous than Nigeria, with estimated population size in 2023 of 130 million people. The estimated proportion of women aged 20-39 who have attained at least lower secondary education is 0.125 in 2020, and the estimated proportion of demand for family planning satisfied by modern contraceptive methods among married women is 0.710 in 2023.

Figure 3 illustrates the projection results for Ethiopia under different projection scenarios. The conditional TFR projections for Ethiopia are further summarized in Table 3.

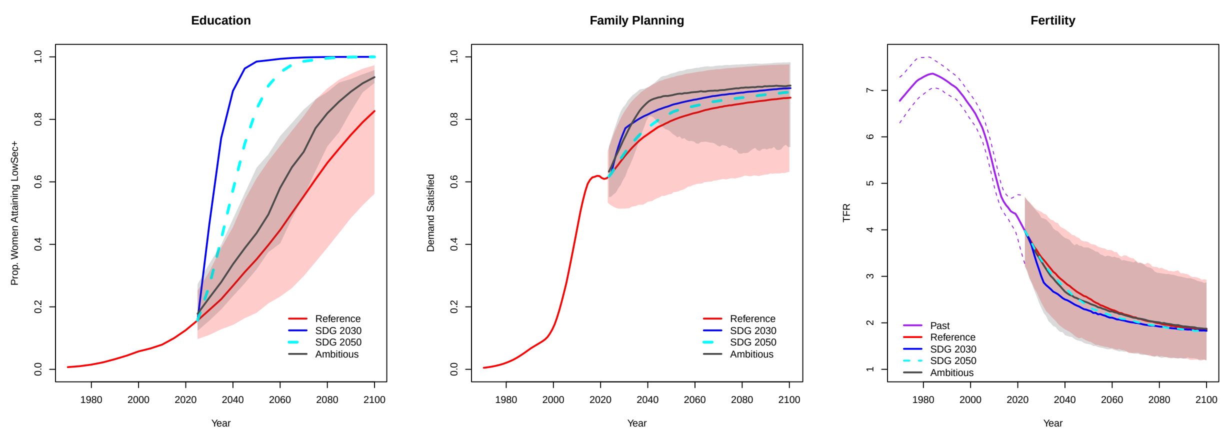

Figure 3: Comparison of median projections for educational attainment, family planning indicators, and TFR for Ethiopia for a range of projection scenarios. 95% projection intervals for the reference and ambitious yet achievable scenarios are shown as shaded regions in red and grey, respectively.

Across all intervention scenarios, the largest difference in median projected TFR for Ethiopia occurs in 2031, where the scenario assuming both SDG targets are met by 2030 results in a median projected TFR that is 0.49 lower than the reference scenario projection. The less extreme intervention scenarios, SDG 2050 and ambitious yet achievable, lead to reductions in median projected TFR of 0.07 and 0.12, respectively, compared to the reference scenario projection.

Table 3: Median TFR projections in 2031, 2051, and 2100 for Ethiopia in children per woman for all projection scenarios with 95% projection intervals. Rows indicating differences between projection scenarios show differences between median projected TFR.

	2031	2051	2100
Reference	3.35 (2.34, 4.35)	2.50 (1.59, 3.69)	1.86 (1.19, 2.93)
SDG 2030	2.87 (1.81, 3.99)	2.25 (1.09, 3.88)	1.83 (1.07, 2.78)
SDG 2050	3.28 (2.29, 4.30)	2.32 (1.32, 3.77)	1.82 (1.13, 2.78)
Ambitious	3.24 (2.21, 4.24)	2.40 (1.53, 3.59)	1.87 (1.20, 2.87)
Reference − SDG 2030	0.49	0.26	0.03
Reference − SDG 2050	0.07	0.18	0.04
Reference − Ambitious	0.12	0.10	−0.02
SDG 2050 − SDG 2030	0.41	0.07	−0.01
Ambitious − SDG 2030	0.37	0.15	0.05
Ambitious − SDG 2050	−0.04	0.08	0.06

Unlike in Nigeria, we still find notable differences in 2051 between the SDG 2030 and SDG 2050 scenarios for Ethiopia. The SDG 2030 scenario projects TFR to be 2.25 (1.09, 3.88) while the SDG 2050 scenario projects TFR to be 2.32 (1.32, 3.77), corresponding to reductions in median projected TFR of 0.26 and 0.18, respectively, compared to the reference scenario projection. The more realistic ambitious yet achievable scenario projects TFR to be 2.40 (1.53, 3.59) in 2051, which is a reduction in median projected TFR of 0.10 compared to the reference scenario projection.

After mid-century, the TFR projections for all scenarios begin to converge due to the shared post-transition phase III model.

4 Discussion

We developed a conditional probabilistic projection model for TFR that extends the unconditional Bayesian hierarchical model that is the basis of the fertility projections published by the UN. The conditional projection model incorporates the effect of women's educational attainment, contraceptive prevalence, and GDP per capita as covariates and enables the creation of annual, probabilistic projections of TFR conditional on hypothetical policy interventions that target education and family planning. These conditional projections can be used to answer questions about the likely effect of education and family planning policies on future fertility and population size, and could be an informative tool for policymakers in high-fertility countries. Compared to previous work in Liu and Raftery (2024), the conditional projection model presented here incorporates two methodological updates: accounting for uncertainty in past estimates of TFR (Liu and Raftery, 2020b) and producing projections on the annual time scale (Liu, Ševčíková, and Raftery, 2023). We also consider a more nuanced range hypothetical policy intervention scenarios compared to Liu and Raftery (2024), where targets for education and family planning are country-specific and data-informed.

Despite these improvements on the previous conditional TFR projection model, our results have several limitations. First, hypothetical policy intervention scenarios based on meeting the SDG targets are extreme scenarios that rely on extrapolation, where the assumed rate of increase in educational attainment and contraceptive prevalence under these scenarios has not been observed historically. These intervention scenarios also assume that the historical dynamics between education, family planning, and fertility remain the same in the extrapolation, which may not be the case. Second, we are limited by the availability of estimates of educational attainment and GDP per capita that are comparable across countries and times. Estimates of historical educational attainment from the Wittgenstein Centre are only available in five-year increments and the *wicedproj* projection model was developed under the assumption of five-year increments. We linearly interpolated the five-year estimates and projections to enable the creation of annual conditional projections of TFR, but ideally annual estimates and projections of educational attainment should be used. Estimates of GDP per capita suffered from a large amounts of missing data for the country-years of interest for this work. We performed an ad-hoc harmonization to combine estimates from across three data sources to improve coverage, but ideally an expert-based harmonized data set that covers more country-years should be used. Additionally, the reference scenario projections of GDP per capita are constrained by the difficulty of projecting GDP out to 2100, and should be interpreted solely as an assumed scenario. Finally, while the conditional TFR projection model accounts for uncertainty in past TFR and propagates uncertainty surrounding projected values of the covariates into projections of TFR, the model does not currently account for uncertainty in past estimates of the covariates.

We illustrated the conditional projection model by creating projections of TFR for 2024-2100 conditional on a range of hypothetical policy intervention scenarios based on accelerated progress towards meeting sustainable development targets for women's education attainment and access to family planning. In our case studies, we found that meeting any of the hypothetical policy intervention targets could lead to notable changes in future TFR and population size.

Acknowledgements

Any opinions and conclusions expressed herein are those of the authors and do not reflect the views of the U.S. Census Bureau or the United Nations. This work was supported, in whole or in part, by NICHD grant R01 HD070936 and by the Bill & Melinda Gates Foundation INV-033016 and INV-009900.

References

Abel, G. J., Barakat, B., KC, S., and Lutz, W. (2016). Meeting the Sustainable Development Goals leads to lower world population growth. *Proceedings of the National Academy of Sciences* **113(50)** 14294–14299. https://doi.org/10.1073/pnas.1611386113

Alkema, L., Raftery, A. E., Gerland, P., Clark, S. J., Pelletier, F., Buettner, T., and Heilig, G. K. (2016). Probabilistic Projections of the Total Fertility Rate for All Countries. *Demography* **48(3)** 815–839. https://doi.org/10.1007/s13524-011-0040-5

Barakat, B. (2016). wicedproj - Wittgenstein Centre Education Projections. *GitHub repository*. https://github.com/bifouba/wicedproj

Biddlecom, A., Sully, E. A., Kantorová, V., Wheldon, M. C., Lince-Deroche, N., and Riley, T. (2023). Setting Health Targets Using Information from Probabilistic Projections: A Research Brief on an Application to Contraceptive Coverage. *Population Research and Policy Review* **42(13)**. https://doi.org/10.1007/s11113-023-09766-2

Cahill, N., Weinberger, M. W., and Alkema, L. (2020). What increase in modern contraceptive use is needed in FP2020 countries to reach 75% demand satisfied by 2030? An assessment using the Accelerated Transition Method and Family Planning Estimation Model. *Gates Open Research* **4(113)**. https://doi.org/10.12688/gatesopenres.13125.1

Feenstra, R. C., Inklaar, R. and Timmer, M. P. (2015). The Next Generation of the Penn World Table. *American Economic Review* **105(10)** 3150–3182. Available for download at www.ggdc.net/pwt.

Fosdick, B. K., and Raftery, A. E. (2014). Regional probabilistic fertility forecasting by modeling between-country correlations. *Demographic Research* **30(35)** 1011–1034. https://doi.org/10.4054/DemRes.2014.30.35

Kantorová, V., Rou, J., Biddlecom, A., and Alkema, L. (2017). Setting ambitious yet achievable targets using probabilistic projections: Meeting demand for family planning. *Studies in Family Planning* **48(3)** 223–233. https://doi.org/10.1111/sifp.12025

Kantorová, V., Wheldon, M. C., Ueffing, P., and Dasgupta, A. N. Z. (2020). Estimating progress towards meeting women's contraceptive needs in 185 countries: A Bayesian hierarchical modelling study *PLoS Med* **17(2): e1003026**. https://doi.org/10.1371/journal.pmed.1003026

Liu, D. H. and Raftery, A. E. (2020a). How Do Education and Family Planning Accelerate Fertility Decline? *Population and Development Review* **46(3)** 409–441. https://doi.org/10.1111/padr.12347

Liu, D. H. and Raftery, A. E. (2024). Bayesian projections of total fertility rate conditional on the United Nations Sustainable Development Goals. *The Annals of Applied Statistics.* **18(1)** 375–403. https://doi.org/10.1214/23-AOAS1793

Liu, P. and Raftery, A. E. (2020b). Accounting for uncertainty about past values in probabilistic projections of the total fertility rate for most countries. *The Annals of Applied Statistics* **14(2)** 685–705. https://doi.org/10.1214/19-AOAS1294

Liu, P., Ševčíková, H., and Raftery, A. E. (2023). Probabilistic Estimation and Projection of the Annual Total Fertility Rate Accounting for Past Uncertainty: A Major Update of the bayesTFR R Package. *Journal of Statistical Software* **106(8)** 1–36. https://doi.org/10.18637/jss.v106.i08

Lutz, W., Goujon, A., KC, S., Stonawski, M., and Stilianakis, N. (2018). *Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries*. Publications Office of the European Union.

Maddison Project Database, version 2020. Bolt, J. and van Zanden, J. L. (2020). Maddison style estimates of the evolution of the world economy. A new 2020 update. https://www.rug.nl/ggdc/historicaldevelopment/maddison/publications/wp15.pdf

Raftery, A. E., Alkema, L., and Gerland, P. (2014). Bayesian Population Projections for the United Nations. *Statistical Science* **29(1)** 58–68. https://doi.org/10.1214/13-STS419

Raftery, A. E., Zimmer, A., Frierson, D. M. W., Startz, R., and Liu, P. (2017). Less than 2 C warming by 2100 unlikely. *Nature Climate Change* **7** 637–641. https://doi.org/10.1038/nclimate3352

United Nations (2015). Transforming our world: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019. https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0

United Nations, Department of Economic and Social Affairs, Population Division (2024a). Estimates and Projections of Family Planning Indicators 2024. https://www.un.org/development/desa/pd/data/family-planning-indicators

United Nations, Department of Economic and Social Affairs, Population Division (2024b). World Population Prospects 2024. https://population.un.org/wpp/

United Nations, Department of Economic and Social Affairs, Population Division (2024c). World Population Prospects 2024: Methodology of the United Nations population estimates and projections. UN DESA/POP/2024/DC/NO. 10, July 2024 [Advance unedited version].

Wheldon, M. C., New, J. R., Cahill, N., Gu, G., Tait, A., Hertog, S., and Alkema, L. (2022). FPEMglobal (Version 1.3.0). *GitHub repository.* https://github.com/FPcounts/FPEMglobal

Wittgenstein Centre for Demography and Global Human Capital (2018). Wittgenstein Centre Data Explorer Version 2.0. http://dataexplorer.wittgensteincentre.org/wcde-v2/

World Bank (2023). World Development Indicators. http://data.worldbank.org/data-catalog/world-development-indicators/

A Additional Model Specification Details

For country c, let τ_c denote the start year of phase II and λ_c denote the start year of phase III. τ_c is defined as

$$\tau_c = \begin{cases} \max\{t : (M_c - L_{c,t}) < 0.5\} & \text{if } L_{c,t} > 5.5, \\ \text{first estimation year} & \text{otherwise} \end{cases}$$

where M_c denotes the maximum observed TFR in country c in the estimation period for the first stage (1950 to 2023) and $L_{c,t}$ denote local maxima. The end of phase II is determined using five-year averages for TFR, where λ_c is the midpoint of the five-year time periods where two successive increases in TFR have been observed for country c after TFR has fallen below 2 children per woman.

The random distortions for the phase II model in level 2 of the Bayesian hierarchical model are given by

$$\varepsilon_{c,t} \sim \begin{cases} N(m_t, s_t^2) & \text{for } t \le \tau_c, \\ N(0, \sigma(f_{c,t})^2) & \text{otherwise,} \end{cases}$$
$$\sigma(f_{c,t}) = c_{1975}(t)\left(\sigma_0 + (f_{c,t} - S)\left(-aI_{[S,\infty)}(f_{c,t}) + bI_{[0,S)}(f_{c,t})\right)\right).$$

The maximum standard deviation of the distortions is denoted σ_0, which is attained at TFR level S. a and b are multipliers of the standard deviation used to model the linear decrease for larger and smaller outcomes of TFR, and $c_{1975}(t)$ is a constant that is added to model the higher error variance of the distortions before 1975. The $\varepsilon_{c,t}$ are modeled jointly as $\boldsymbol{\varepsilon}$ to account for between-country correlation using clusters based on UN region and year. Each UN region is composed of countries that are spatially contiguous and relatively culturally homogeneous, so we expect similar between-country correlation for all countries in the same UN region and at the same year. $\boldsymbol{\varepsilon}$ is modeled as

$$\boldsymbol{\varepsilon} \sim N(\boldsymbol{m}, \Sigma)$$
$$\Sigma = \text{diag}(\sigma(f_{c,t})) \cdot R \cdot \text{diag}(\sigma(f_{c,t})),$$
$$R[i,j] = \begin{cases} 1 & \text{if } i = j \\ \rho^{[bc]} & \text{if } i,j \in \text{same cluster}, \\ 0 & \text{otherwise} \end{cases}$$

where $\text{diag}(\sigma(f_{c,t}))$ is a diagonal matrix where the entries $\sigma(f_{c,t})$ are ordered by year. Within year, the $\sigma(f_{c,t})$ are further ordered by UN region membership so that observations in the same cluster appear sequentially. The (i,j)th term of the correlation matrix R represents the correlation between country-time pair i and country-time pair j. If observations i and j are from the same time period and refer to countries within the same UN region, the between-country correlation is $\rho^{[bc]}$.

B Data Harmonization for GDP

We use the RGDPe indicator from the Penn World Table version 10.01, which measures expenditure-side real GDP at chained PPPs in 2017 US dollars. The Penn World Table contains estimates for 183 countries and in years 1950-2019. For the country-years not included in the Penn World Table, we use a direct country proxy for two countries and use country-specific estimates from the Maddison Project Database 2020 for 11 countries. The two countries using a direct country proxy are Eritrea and South Sudan, which are proxied using the Penn World Table estimates for Ethiopia and Sudan, respectively.

For the remaining 13 countries, the country-specific estimates for GDP per capita are proxied using regional averages based on UN region membership. Countries without country-specific estimates in Eastern Africa, South-Eastern Asia, and the Caribbean are proxied using regional averages calculated from the Penn World Table estimates. Due to limited data in the Penn World Table, countries without country-specific estimates in Melanesia are instead proxied using regional averages calculated using per capita estimates of GDP PPP in constant 2017 international dollars from the World Bank World Development Indicators.

C Implementation of Policy Intervention Scenarios

C.1 Women's Educational Attainment

Probabilistic projections of educational attainment for the SDG 2030 and SDG 2050 scenarios are created using a similar methodology as (Abel et al., 2016). Abel et al. uses a modification of the Bayesian hierarchical model used to create the Wittgenstein Centre's estimates and projections of educational attainment, where the modified model treats the SDG target levels of educational attainment as future observations in the likelihood and allows for the projected trend in attainment to increase at whatever rate is necessary to reach the target educational attainment level in the year of the policy intervention. As the model projects educational attainment for five-year age groups and five-year time steps, the target educational attainment levels and the years at which the targets are met are age-group-specific.

We use the same Bayesian hierarchical model as Abel et al. to create the reference scenario projections of educational attainment. The target value for "universal lower secondary attainment" is interpreted as women aged 15-19 reach 97-99% lower secondary attainment by the intervention year, women aged 20-24 reach 97-99% lower secondary attainment by the intervention year + 5, women aged 25-29 reach 97-99% lower secondary attainment by the intervention year + 10, and women aged 30-24 reach 97-99% lower secondary attainment by the intervention year + 15. The SDG 2030 and SDG 2050 scenarios use intervention years of 2030 and 2050, respectively, and are created by modifying each trajectory of the reference scenario projections as follows. Let $loS_{i,a,t}$ denote the proportion of women in trajectory i, age group a, and time t that have attained lower secondary education or higher. Let T_a denote the target year for age group a and let t_1 denote the first projection year. For each trajectory i,

1. Sample the target value of educational attainment $\text{target}^{(i)} \sim \text{Uniform}(0.97, 0.99)$. This is the value of loS that is considered "universal lower secondary attainment" for this trajectory.

2. For each age group a,

(a) If $loS_{i,a,T_a} \geq 97\%$, the trajectory is not modified.

(b) Otherwise,

i. Set $loS_{i,a,T_a} = \text{target}^{(i)}$.

ii. Interpolate on the probit scale between loS_{i,a,t_1} and loS_{i,a,T_a} to get the SDG intervention trajectory for $(t_1, T_a]$.

iii. Interpolate on the probit scale between loS_{i,a,T_a} and $loS_{i,a,2100} = 100\%$ to get the SDG intervention trajectory for $(T_a, 2100]$.

C.2 Contraceptive Prevalence

To create projections of contraceptive prevalence under hypothetical policy intervention scenarios, we modified the reference scenario trajectories from a converged simulation of the FPEMglobal model (Kantorová et al., 2020; Wheldon et al., 2022) for married women.

FPEMglobal jointly models family planning indicators as the compositional vector $\boldsymbol{p}_{c,t} = (p_{c,t,1}, p_{c,t,2}, p_{c,t,3}, p_{c,t,4})$, where $p_{c,t,m}$ is the proportion of women in country c and year t who use traditional contraceptive methods ($m = 1$), use modern contraceptive methods ($m = 2$), have an unmet need for contraceptive methods ($m = 3$), or do not use and do not need contraceptive methods ($m = 4$). The family planning covariate used in the conditional TFR projection model, contraceptive prevalence of modern methods, is $p_{c,t,2}$. However, the hypothetical policy intervention scenarios are created in terms of the proportion of demand for family planning that is satisfied by modern methods, which is

$$DS_{c,t} = \frac{p_{c,t,2}}{p_{c,t,1} + p_{c,t,2} + p_{c,t,3}}.$$

Increases to $DS_{c,t}$ that are encoded in the policy intervention scenarios are translated into projections of $p_{c,t,2}$ using the compositional structure of $\boldsymbol{p}_{c,t}$.

The SDG 2030 and SDG 2050 scenarios were created using a modified version of the accelerated transition method of Cahill et al. (2020), where the target years are 2030 and 2050, respectively. Let T denote the target year and t_1 denote the first projection year. For each trajectory i,

1. Sample the target value $\text{target}^{(i)} \sim \text{Uniform}(0.87, 0.92)$. This is the value of DS that is considered "universal access to family planning" for this trajectory.

2. For each country c,

(a) Identify the year t^* when the country is projected to have DS reach $\text{target}^{(i)}$. If DS is not projected to reach the target value before 2100, set $t^* = 2100$.

(b) Set $p_{c,T,2} = p_{c,t^*,2}$.

(c) Linearly interpolate between $p_{c,t_1,2}$ and $p_{c,T,2}$ to get the SDG intervention trajectory for $(t_1, T]$.

(d) Set $p_{c,t,2} = p_{c,T,2}$ for all t in $(T, 2100]$ to get the SDG intervention trajectory for $(T, 2100]$.

The ambitious yet achievable scenario was created following Biddlecom et al. (2023) by resampling $\boldsymbol{p}_{c,t}$ from the trajectories that correspond to the 85th-95th percentiles of the projected changes in $DS_{c,2040} - DS_{c,2019}$ from the reference scenario. From each of the resampled trajectories of $\boldsymbol{p}_{c,t}$, we retain the component $p_{c,t,2}$ to create the ambitious yet achievable projection trajectories for contraceptive prevalence.

D Results for All Countries

Figures summarizing the projection results for all countries are available in the file all_countries_figures.pdf.