BAYESIAN PROJECTIONS OF TOTAL FERTILITY RATE CONDITIONAL ON THE UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

By Daphne H. Liu[1] and Adrian E. Raftery[2]

[1]*Department of Statistics, University of Washington, dhliu@uw.edu*

[2]*Department of Statistics and Department of Sociology, University of Washington, raftery@uw.edu*

Women's educational attainment and contraceptive prevalence are two mechanisms identified as having an accelerating effect on fertility decline and that can be directly impacted by policy. Quantifying the potential effect of education and family planning policies on fertility decline in a probabilistic way is of interest to policymakers, particularly in high-fertility countries. We propose a conditional Bayesian hierarchical model for projecting fertility given education and family planning policy interventions. To illustrate the effect policy changes could have on future fertility, we create probabilistic projections of fertility that condition on scenarios such as achieving the Sustainable Development Goals (SDGs) for universal secondary education and universal access to family planning by 2030. Translating the conditional fertility projections into population projections, we find that meeting the SDGs in 2030 would lead to a reduction in projected world population in 2100 of 1.96 billion people with a 95% projection interval of (0.53, 3.75) if all unmet need for family planning is eliminated by 2030. Under the more realistic scenario that 75% of demand for family planning is satisfied by 2030, we project a reduction in world population in 2100 of 1.49 (0.09, 3.27) billion people.

1. Introduction. World population in the next century will be driven by high-fertility countries. The United Nations projects that more than half of the projected increase in world population from 7.8 billion people in 2020 to 10.9 billion people in 2100 will occur in high-fertility countries, primarily in sub-Saharan Africa (United Nations 2019a). Much of the rest of the population increase is projected to occur in countries with above-replacement fertility, mostly in Asia and Latin America.

Policymakers in these countries have an interest in slowing this population increase by accelerating fertility decline, as high fertility and rapid population growth are likely to have adverse economic, environmental, health, governmental, and political consequences (Bongaarts, 2013). Reductions in fertility can also benefit the economy through what is known as the demographic dividend, where declining fertility can lead to accelerated economic growth by reducing the dependency ratio, increasing women's participation in the paid labor force, and allowing increased investments in human and physical capital (Lee and Mason, 2006; Mason and Lee, 2006).

There is widespread agreement in the demographic literature that increasing education and increasing family planning are the two main factors that can be influenced by policy and may help accelerate fertility decline (Hirschman, 1994). Education is thought to accelerate fertility decline by increasing the opportunity cost of having children for women and by increasing the cost of raising children (Caldwell, 1982; Caldwell, Reddy and Caldwell, 1985; Easterlin and Crimmins, 1985; Axinn and Barber, 2001). These increased costs are evident in education differentials in fertility that have been observed across countries, with more highly educated women tending to have fewer children than less educated women (Martín, 1995; Bongaarts, 2003).

Keywords and phrases: Bayesian hierarchical model, fertility, Sustainable Development Goals.

Family planning is also thought to accelerate fertility decline, as family planning is needed to translate changes in fertility desires into changes in realized fertility. Contraceptive prevalence, in particular, is a proximate determinant of fertility that provides a venue for individuals to achieve their desired childbearing (Bongaarts, 1987). Liu and Raftery (2020) found significant accelerating effects of women's educational attainment and contraceptive prevalence on fertility decline in the high-fertility setting. Liu and Raftery found that the effect of education on fertility operates through increasing mother's education rather than through increasing children's enrollment, and that the attainment level with the largest effect size was lower secondary education or higher. Liu and Raftery also found that the effect of family planning on fertility operates primarily through increasing contraceptive prevalence of modern contraceptive methods rather than through decreasing unmet need for family planning.

Figure 1 shows the relationship between the Total Fertility Rate, the proportion of women attaining lower secondary education or higher, and the contraceptive prevalence rate of modern methods, plotted as time series covering the five-year time periods 1970-1975 to 2015-2020 for each country. We can see a negative association between educational attainment and fertility and between contraceptive prevalence and fertility across countries and across regions.

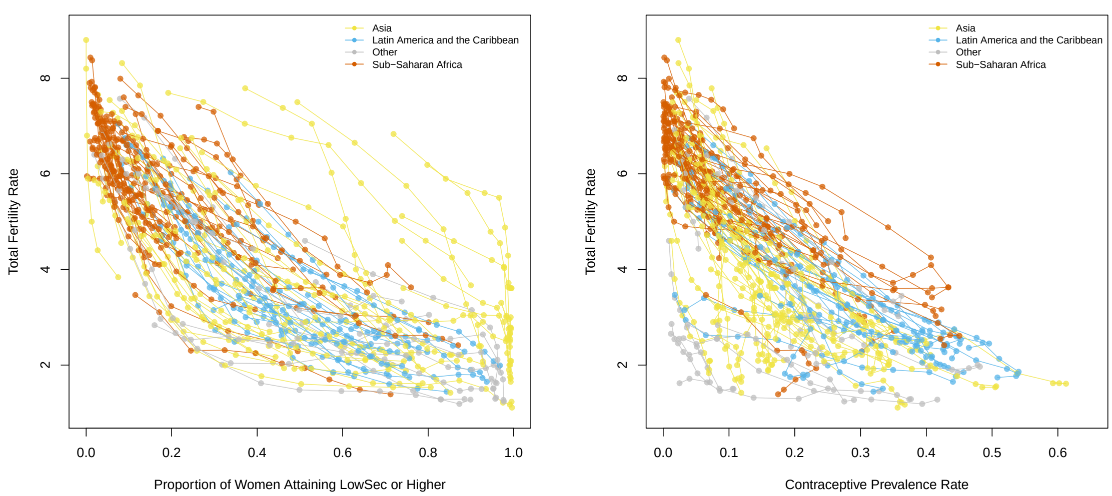

Fig 1: Relationship between Total Fertility Rate, the proportion of women attaining lower secondary (LowSec) education or higher, and the contraceptive prevalence rate of modern methods plotted as a time series covering five-year time periods from 1970-1975 to 2015-2020 for each country and color-coded by region. Only countries used to estimate the second stage of the conditional TFR projection model and only time periods corresponding to when the country was in Phase II of the fertility transition are plotted.

There is also evidence to suggest that interventions related to education and family planning may have a smaller impact on fertility in sub-Saharan Africa (SSA) than elsewhere. Most of the world's currently high-fertility countries are located in SSA, and the fertility transition being experienced in SSA is slower than the historical fertility transitions observed in Asia and Latin America (Bongaarts and Casterline, 2013), where the fertility transition refers to the decline from high to low fertility that occurs as a country develops.

The relationships between education, family planning, and fertility are different in SSA than in other regions, with higher fertility and lower contraceptive use for a given level of education compared to other regions (Bongaarts, Mensch and Blanc, 2017). Differences in ideal family size may diminish the effect of family planning policy interventions in SSA (Bongaarts, Frank and Lesthaeghe, 1984; Bongaarts and Casterline, 2013), while differences in school quality may diminish the effect of education policy interventions (Grant, 2015). Liu and Raftery (2020) found that the accelerating effect that increases in women's attainment and increases in contraceptive prevalence have on fertility decline were indeed smaller in SSA compared to other regions.

This raises the question of how the accelerating effects of women's educational attainment and contraceptive prevalence could impact future fertility and population size in high-fertility countries, particularly in the context of meeting policy goals for education and family planning. Two of the United Nations Sustainable Development Goals (SDGs) refer directly to increasing educational attainment and increasing access to family planning, and thus are likely to have an effect on future population.

The SDGs are a set of goals related to global development that were identified by the United Nations as a follow-up to the previous Millennium Development Goals. The SDGs were established in 2015 with a target date of completion in 2030. The SDG targets that relate directly to education and family planning are Targets 4.1 and 3.7. Target 4.1 relates to universal educational attainment goals, specifically, "By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes," while Target 3.7 includes goals related to family planning, specifically, 'By 2030, ensure universal access to sexual and reproductive health-care services, including for family planning, information and education, and the integration of reproductive health into national strategies and programmes" (United Nations, 2015).

The United Nations (UN) has produced estimates and projections of world population since 1951 and remains the premier producer of global demographic projections, with projections from the UN used by policymakers around the world. In particular, governments and agencies 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-based scenarios, although projection variants (low, medium, and high) based on different underlying demographic assumptions are available. For fertility projections, 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.

Two other major producers of global demographic projections, the Wittgenstein Centre for Demography and Global Human Capital and the Institute for Health Metrics and Evaluation (IHME), do produce scenario-based projections of fertility and population that include scenarios corresponding to attaining the SDGs in 2030 (Abel et al., 2016; Vollset et al., 2020). These existing population projections based on policy scenarios either do not fully incorporate uncertainty or do not fully incorporate field-specific demographic knowledge. There are also substantial differences between the reference scenario projections produced by the UN and the reference scenario projections produced by both the Wittgenstein Centre and IHME due to differences in methodology and underlying assumptions, so the policy-based projections from other sources cannot be directly compared with the UN reference scenario projections. Demographic projections based on policy scenarios using the UN methodology are thus of interest.

The UN projection model for TFR currently does not explicitly incorporate the effect of covariates, whereas the Wittgenstein Centre emphasizes the effect of education on fertility and IHME incorporates the effects of both education and family planning in their fertility model. Instead, the UN projection model implicitly captures the effect of covariates on fertility by modeling future TFR based on historical trends in TFR. However, for policy-making it may be important to incorporate these covariates explicitly into fertility projection models (Lutz, Butz and KC, 2014).

Here we develop a conditional probabilistic projection model for TFR that extends the probabilistic fertility projection model used by the UN. The conditional projection model explicitly accounts for women's educational attainment, contraceptive prevalence of modern methods, and GDP per capita and allows for the creation of projections of TFR that are conditional on policy-based intervention scenarios related to education and family planning. Using a Bayesian framework, we address the question of what the likely quantitative effect of meeting SDG Targets 3.7 and 4.1 would be on future fertility and population.

This paper is organized as follows. In Section 2, we describe the data and methods. In Section 3, we describe the out-of-sample validation results for the model. Section 4 presents the projection results for TFR and population size, using Nigeria as a case study. We also present regional aggregate results for sub-Saharan Africa and the world. In Section 5, we discuss and compare our results with related work. Finally, we summarize the findings of this paper in Section 6.

2. Methods.

2.1. *Data.* Estimates of TFR are obtained from the United Nations *World Population Prospects* (WPP) 2019 Revision (United Nations 2019a). 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 from WPP 2019 are available for 201 countries by five-year time periods, are comparable across countries and time periods, and 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 were obtained from the Wittgenstein Centre Data Explorer Version 2.0 (Wittgenstein Centre 2018; Lutz et al. 2018). The Wittgenstein Centre produces a harmonized dataset of the educational attainment distribution that is comparable across countries and times. The educational attainment distribution uses 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 cumulative attainment, specifically on the proportion of women attaining lower secondary education or higher, abbreviated as LowSec+. Liu and Raftery (2020) found this to be the summary measure of education most closely associated with fertility decline.

Probabilistic projections of educational attainment were created following the Wittgenstein Centre methodology using the "wicedproj" package[1] in R, which was released alongside Abel et al. (2016). Figure 2 illustrates estimates and projections of women's attainment of LowSec+ for Nigeria. Intervention-based probabilistic projections of educational attainment corresponding to achieving the SDGs were obtained using the methodology developed by Abel et al. (2016), with further details in the Supplementary Material.

Estimates and projections of contraceptive prevalence of modern methods for all women aged 15-49 are obtained following the methodology of Kantorová et al. (2020). Kantorová et al. created probabilistic estimates and projections of family planning indicators using a

[1] Available at `https://github.com/bifouba/wicedproj`, downloaded on June 17, 2020

Bayesian hierarchical model, which is implemented in the "FPEMglobal" package[2] in R. We used the median estimates of contraceptive prevalence of modern methods from a converged simulation of FPEMglobal as an input to our TFR projection model, where contraceptive prevalence is a proportion between 0 and 1 and is constructed for five-year time periods from 1970-1975 through 2015-2020. Probabilistic projections of contraceptive prevalence from 2020-2025 to 2095-2100 were similarly obtained using a converged simulation of FPEMglobal. Figure 2 illustrates estimates and projections of contraceptive prevalence for Nigeria. Intervention-based probabilistic projections of contraceptive prevalence corresponding to meeting the SDGs were created by modifying the non-intervention projections. Details of the SDG intervention projections of contraceptive prevalence can be found in Section 2.5 and in the Supplementary Material.

Estimates of GDP per capita were obtained from the Maddison Project (Maddison Project 2018) and projections of GDP were obtained using a Bayesian hierchical model developed by Raftery et al. (2017). As we are not interested in interventions targeting GDP, we considered only non-intervention projections of GDP for our conditional TFR projections.

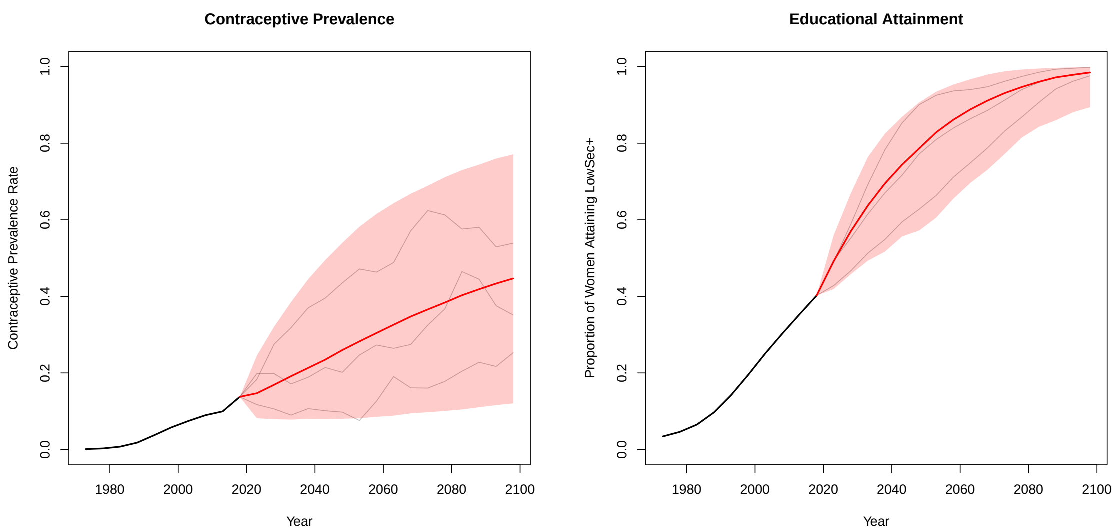

Fig 2: Estimates and non-intervention projections of contraceptive prevalence of modern methods for all women and proportion of women attaining lower secondary education or higher for Nigeria from 1970-1975 to 2095-2100. Estimates of the past are plotted in black, medians and 95% intervals for projections are plotted in red, and sample projection trajectories are plotted in grey.

2.2. *Model.* Our model builds upon the unconditional model for probabilistic fertility projections that is the basis for fertility projections produced by the UN (Alkema et al., 2011; Raftery, Alkema and Gerland, 2014; Fosdick and Raftery, 2014). The unconditional model is a Bayesian hierarchical model that has been implemented in the R package "bayesTFR"[3]

[2]Available at `https://github.com/FPcounts/FPEMglobal`, version 1.1.0 downloaded on June 17, 2020

[3]bayesTFR version 6.4.0 was used for this paper

(Ševčíková, Alkema and Raftery, 2011). The unconditional fertility projection model, referred to in this paper as the "bayesTFR" model, 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. Since all or almost all countries have already begun the fertility transition, Phase I is not needed for TFR projections and thus is not modeled. The bayesTFR Phase II and Phase III models, as well as our modifications to the Phase II model, are described in this section.

In the bayesTFR Phase II model, fertility decline is modeled as a random walk with drift, where the drift term represents the systematic decline. Let $f_{c,t}$ denote the TFR in country c and five-year time period t. Decrements in TFR are constructed as a measure of fertility decline, with the TFR decrement between five-year time periods t and $(t+1)$ defined as $\Delta f_{c,t+1} = f_{c,t+1} - f_{c,t}$. The unconditional Phase II model is written

$$\begin{aligned} \Delta f_{c,t+1} &= f_{c,t+1} - f_{c,t} \\ &= -g(f_{c,t}|\theta_c) + \varepsilon_{c,t}, \\ \theta_c &\sim h(\cdot|\phi), \\ \phi &\sim \pi(\cdot), \end{aligned}$$

where $g(f_{c,t}|\theta_c)$ is a five-parameter double logistic function that represents the expected TFR decrement from five-year time period t to five-year time period $(t+1)$. The double logistic function is defined as

$$\begin{aligned} g(f_{c,t}|\theta_c) = &\frac{-d_c}{1+\exp\left(-2\frac{\ln(9)}{\Delta_{c1}}\left(f_{c,t} - \sum_i \Delta_{ci} + 0.5\Delta_{c1}\right)\right)} \\ &+ \frac{d_c}{1+\exp\left(-2\frac{\ln(9)}{\Delta_{c3}}\left(f_{c,t} - \Delta_{c4} - 0.5\Delta_{c3}\right)\right)} \end{aligned}$$

and takes the current value of TFR ($f_{c,t}$) and a vector of country-specific parameters $\theta_c = (\Delta_{c1}, \Delta_{c2}, \Delta_{c3}, \Delta_{c4}, d_c)$ as inputs. The country-specific parameter vector specifies the shape of each country's individual decline curve and follows a world distribution $h(\cdot|\phi)$ with parameter ϕ, where the prior distribution of ϕ is $\pi(\cdot)$. Further details of the decline function can be found in the Supplementary Material.

The error term for each five-year time period t in the bayesTFR Phase II model is given by

$$\varepsilon_{c,t} \sim \begin{cases} N(m_t, s_t^2) & \text{for } t = \tau_c \\ N(0, \sigma(f_{c,t})^2) & \text{otherwise,} \end{cases}$$

where τ_c is the starting time period of Phase II, m_τ is the mean of the error in the start period, and s_τ is the standard deviation of the error in the start period. In time periods following the start of the fertility transition, the standard deviation depends on the current level of the TFR and is given by the function $\sigma(f_{c,t})$, with details given in the Supplementary Material.

Accounting for between-country correlation in TFR is important when constructing aggregates, such as regional or world TFR. The bayesTFR projection model accounts for between-country correlation in projections using a pairwise likelihood method developed by Fosdick and Raftery (2014), which models correlation between countries i and j as a function of whether countries i and j are contiguous, whether they had a common colonizer after 1945, and whether they belong to the same UN region. In estimation of the bayesTFR model, the error terms are assumed to be independent.

We create a conditional TFR projection model by extending the unconditional Phase II model to include a covariate term and to account for between-country correlation in estimation. Covariates were constructed as changes over time on the same scale as the TFR decrements $\Delta f_{c,t+1}$. For example, the change over time from t to $(t+1)$ for covariate X is denoted by $\Delta X_{c,t+1}$. The covariates added are the change over time in the proportion of women aged 20-39 who have attained at least lower secondary education, denoted by ΔLowSec+, the change over time in the contraceptive prevalence of modern methods for all women of reproductive age, denoted by ΔCP, and the percent change in GDP per capita, denoted by ΔGDP. We also consider interaction terms between all covariates and an indicator function SSA_c for whether country c is in sub-Saharan Africa.

The conditional TFR projection model is specified as

$$\begin{aligned}
\Delta f_{c,t+1} =& f_{c,t+1} - f_{c,t} \\
=& - g(f_{c,t}|\theta_c) + \mathbf{\Delta X}_{c,t}\beta + \varepsilon_{c,t},
\end{aligned}$$

$$\beta = \begin{bmatrix} \beta_E \\ \beta_F \\ \beta_G \\ \beta_{E,SSA} \\ \beta_{F,SSA} \\ \beta_{G,SSA} \end{bmatrix}, \quad \mathbf{\Delta X}^T_{c,t} = \begin{bmatrix} (\Delta\text{LowSec+})_{c,t} \\ (\Delta\text{CP})_{c,t} \\ (\Delta\text{GDP})_{c,t} \\ (\Delta\text{LowSec+})_{c,t} \times SSA_c \\ (\Delta\text{CP})_{c,t} \times SSA_c \\ (\Delta\text{GDP})_{c,t} \times SSA_c \end{bmatrix},$$

$$\beta_j \sim N\left(0, 0.25 \times \frac{Var(\Delta f_{c,t})}{Var(\Delta X_j)}\right) \quad \text{for } j \in (E; F, G; E, SSA; F, SSA; G, SSA).$$

The prior distributions of the coefficients β_j were chosen to be diffuse, where the prior variances are determined by the ratio of the sample variance of observed changes in $f_{c,t}$ to the sample variance of observed changes in X_j.

We account for between-country correlation in the estimation of the conditional model using clusters based on UN region membership. Each UN region consists of countries that are both 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 time period. Let $\tilde{\sigma}$ denote the vector of values of $\sigma(f_{c,t})$ ordered by UN Region and time period. The error term for the conditional TFR projection model is specified as:

$$\begin{aligned}
&\varepsilon \sim N(0, \Sigma), \\
&\Sigma = \text{diag}(\tilde{\sigma}) \cdot R \cdot \text{diag}(\tilde{\sigma}), \\
&R[i,j] = \begin{cases} 1 & \text{if } i = j \\ \rho^{[bc]} & \text{if } i,j \in \text{same UN region and same time point} \\ 0 & \text{otherwise} \end{cases}, \\
&\rho^{[bc]} \sim \text{Uniform}(0,1),
\end{aligned}$$

where 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 $\rho^{[bc]}$. Further details of the conditional TFR projection model can be found in the Supplementary Material.

To create fertility projections, we use the same unconditional post-transition Phase III model as does bayesTFR. The post-transition phase represents what happens to a country's TFR once it has completed the fertility transition in Phase II, where the end of Phase II is defined by the UN as the midpoint of the five-year time periods where two successive increases in TFR have been observed after TFR has fallen below 2 children per woman (United Nations 2019b). In Phase III, fertility is assumed to converge towards and fluctuate around country-specific long-term TFR levels. It is modeled as a first-order autoregressive (or AR(1)) time series model written as

$$f_{c,t+1} \sim N(\mu + \rho(f_{c,t} - \mu), s^2),$$

where μ is the world mean parameter for the country-specific asymptotes and is restricted to be no greater than replacement-level fertility, i.e. $\mu \leq 2.1$. The autoregressive parameter ρ is restricted to $|\rho| < 1$ and s is the standard devation of the random errors. The Phase III model is estimated using a Bayesian hierarchical model, with further details available in Alkema et al. (2011) and Raftery, Alkema and Gerland (2014).

2.3. *Causal Assumptions.* The primary goal of creating the conditional TFR projection model is to create intervention-based projections of TFR for interventions corresponding to policy outcomes, which is an inherently causal goal. The directed acyclic graph (DAG) in Figure 3 illustrates the causal assumptions underlying our analysis that are necessary for the causal interpretation of intervention-based projections of TFR from the conditional projection model.

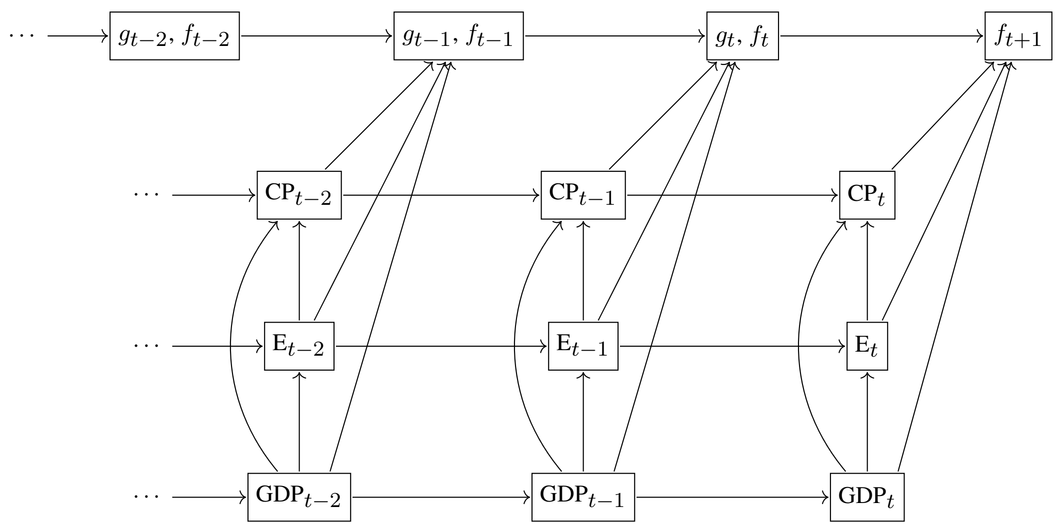

Fig 3: Directed acyclic graph (DAG) for TFR f, the double logistic expected TFR decrement term g, contraceptive prevalence CP, educational attainment E, and GDP per capita GDP

Each node in the DAG represents a time-varying variable. TFR at time t is represented by the node labeled f_t. The covariate nodes are labeled as CP_t for the contraceptive prevalence term, E_t for the educational attainment term, and GDP_t for the GDP per capita term. Each covariate node represents the main effect of the covariate and its interaction with the SSA indicator. For example, the E_t node represents the contribution of both $(\Delta\mathrm{LowSec}+)_t$ and $(\Delta\mathrm{LowSec}+)_t \times SSA$. The double logistic expected TFR decrement term $g(f_t|\theta)$ is denoted in the graph by "g_t." As the double logistic term is a function of f_t and the parameters of the double logistic term are estimated using only historical fertility data, the double logistic node coincides with the TFR node f_t in our DAG. Each arrow in the DAG represents an assumed causal relationship in the direction indicated by the arrow. These causal relationships are informed by demographic background knowledge, primarily the proximate determinants framework for fertility developed by John Bongaarts (Bongaarts, 1978; Bongaarts, Frank and Lesthaeghe, 1984; Bongaarts, 2010).

Child mortality and urbanization, two key variables associated with the fertility transition, are assumed to be mediated through variables included in the DAG. Liu and Raftery (2020) found that the effect of child mortality on fertility decline was mediated through the double logistic expected TFR decrement. Through path analysis, Liu and Raftery found an insignificant effect of child mortality decrement on TFR decrement after controlling for the double logistic expected TFR decrement term. Liu and Raftery also found that inclusion of the child mortality decrement did not improve model fit.

Urbanization is assumed to be mediated through the GDP term. Liu and Raftery (2020) found this to be the case via path analysis, where the effect of urbanization was insignificant after controlling for GDP. There is considerable debate about causal relationships underlying modernization variables, such as GDP and urbanization, and fertility decline (Hirschman, 1994; de Silva and Tenreyro, 2017). The potential for reverse causality between GDP and fertility decline, where past values of fertility decline cause future values of GDP, is omitted from our DAG, though studies such as Herzer, Strulik and Vollmer (2012) suggest this causal pathway may exist. We note that the inclusion of reverse causal paths like $f_{t-1} \rightarrow \text{GDP}_t$ in the DAG does not change the assumptions needed for a causal interpretation of interventions on education and family planning.

We follow the logic of the back-door criterion introduced by Pearl (1993) to identify the adjustment set W needed to estimate the causal effect that interventions on $X = \{\text{E}_t, \text{CP}_t\}$ have on $Y = \{f_{c,t+1}\}$. We find that the set $W = \{g_t, \text{GDP}_t\}$ satisfies the generalized back-door criterion developed by Maathuis and Colombo (2015). W does not contain descendants of X and, for every X_i in X, the set $W \cup X \backslash \{X_i\}$ blocks every back-door path from X_i to Y. Following Theorem 3.1 from Maathuis and Colombo (2015), W is then an appropriate adjustment set for estimating the causal effect of X on Y. In the conditional projection model, we include all elements of the adjustment set as covariates. Thus, under the assumptions underlying the DAG in Figure 3, our estimated effects can be interpreted as causal.

2.4. *Estimation.* The conditional projection model is estimated using a Markov chain Monte Carlo algorithm with Gibbs sampling, Metropolis-Hastings, and slice sampling steps. We estimated the conditional TFR projection model in two stages. In the first stage, the country-specific parameters θ_c for the double logistic expected TFR decrement function were estimated in the absence of the covariates. In the second stage, the β coefficients were estimated jointly, conditionally on the posterior distributions of the double logistic parameters from the first stage, where all the covariates were centered prior to estimation. Using two stages for estimation allows us to preserve the demographic interpretation of the double logistic parameters, while still explicitly accounting for the effect of covariates in the TFR projection model.

The first stage was estimated analogously to the UN projection model, using estimates of TFR for 201 countries spanning 1950-1955 through 2015-2020 from WPP 2019. This allowed us to use all the available data to estimate the double logistic expected TFR decrement term and ensured that our estimates of θ_c were comparable to the estimates used by the UN.

In the second stage, we were primarily interested in the impact of education and family planning policy interventions on future TFR in the high-fertility setting. We thus restricted the subset of data used for estimation of the second stage to consider only current and historical "high-fertility" transitions, defined for each country as the time periods where the country 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. This results in a subset of 114 countries with 1007 observations, where the earliest time period for which we have data is

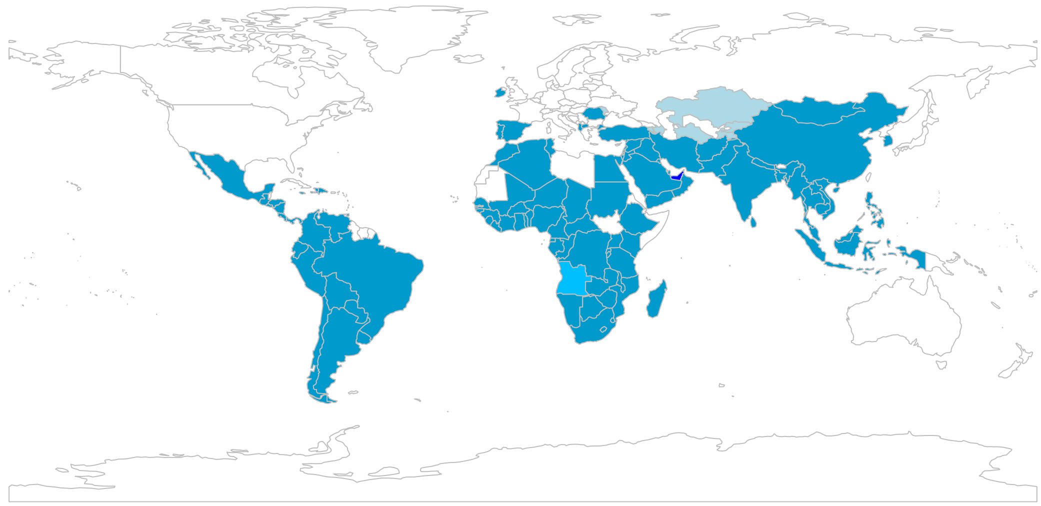

Fig 4: Number of observations for each country used for estimation of the conditional TFR projection model, where the total number of observations is 1007. Observations come from 114 countries and cover time periods 1970-1975 to 2015-2020.

1970-1975. Figure 4 shows the number of observations from each country included in the second stage of estimation.

Estimating the effect of education and family planning on TFR in a second stage conditional on the double logistic parameters also provides us with an interpretation of the coefficients that better lends itself to the intervention setting. For example, β_E becomes the effect of ΔLowSec+ on TFR decline *controlling for* the decline in TFR that we would already expect to occur based on historical trends in TFR (and thus, implicitly, based on historical trends in education and other covariates). The coefficient β_E can then be interpreted as the additional effect ΔLowSec+ has on TFR after we account for the pace of the fertility decline as estimated by the double logistic function, controlling for the other covariates. To create projections of TFR conditional on policy interventions for educational attainment, this is the relationship between education and TFR that we need to estimate.

2.5. *Projection.* Our focus is on creating intervention-based projections of TFR in the high-fertility setting. The relationships between education, family planning, and fertility decline estimated in the high-fertility context may not apply once fertility has declined to around replacement level. For example, there is evidence that the effect of educational attainment on fertility decline is weaker in the low-fertility setting than in the high-fertility setting (Asderá, 2017a; Sobotka, Beaujouan and Van Bavel, 2017). Due to these differing relationships, we created intervention-based projections only for countries with TFR greater than 2.1 in 2015-2020 that have available covariate data, which are highlighted in blue in Figure 5. TFR projections for countries with current TFR less than 2.1 and countries without available covariate data were created using the bayesTFR Phase II model. Note that for our purposes, TFR projections for low-fertility countries were primarily of interest to produce regional aggregates. For all countries, the post-transition phase was projected using the bayesTFR Phase III model.

As an input to the conditional TFR projections, we considered five scenarios for intervention-based projections of educational attainment and contraceptive prevalence. These

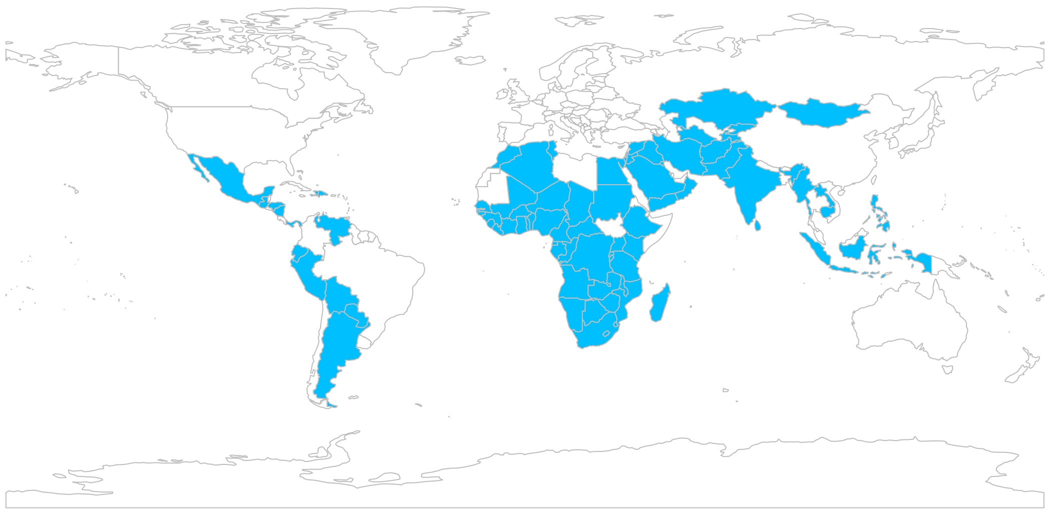

Fig 5: TFR projections are created using the conditional TFR projection model for countries highlighted in blue.

scenarios are summarized in Table 1 and further details of the methods used to construct the intervention-based covariate projections can be found in the Supplementary Material. First, we considered non-intervention projections of the covariates as our reference scenario. We note that TFR projections from the reference scenario are not expected to be identical to the projections produced by the UN for WPP 2019. However, the two sets of projections should be very similar, as the reference scenario was constructed to reflect the assumption of no additional policy intervention targeting education or family planning that is implicit in the WPP 2019 projections.

Next, we considered two scenarios corresponding to attaining SDG Targets 4.1 and 3.7 simultaneously in 2030. Both scenarios interpret achievement of Target 4.1 as attaining universal lower secondary education by 2030, following the implementation developed by Abel et al. (2016). Both scenarios also include the effect of achieving Target 4.1 on family planning, where increased educational attainment is assumed to increase demand for family planning. Where the two scenarios differ is in their implementations of Target 3.7. The first of these scenarios, labeled "Both SDGs (0% Unmet)," interprets Target 3.7 as meaning that unmet need for family planning will decline to zero in 2030. This scenario can be thought of as an upper bound on the possible effect the SDG intervention could have on TFR projections.

The second scenario, labeled "Both SDGs (75% DS)," interprets Target 3.7 as meaning that at least 75% of the demand for family planning in 2030 will be satisfied using modern methods. Demand satisfied using modern methods is defined as the ratio of contraceptive prevalence of modern methods to total demand, where total demand is the sum of total contraceptive prevalence and unmet need for family planning. This scenario follows the benchmark for achievement of Target 3.7 proposed by Fabic et al. (2015) and provides a more realistic interpretation of the effect that attaining the target might have on projections of contraceptive prevalence. The SDG intervention projections of contraceptive prevalence for this scenario were constructed following the accelerated transition method developed by Cahill, Weinberger and Alkema (2020) with some modifications.

We also considered a more realistic policy intervention of the SDGs being achieved in 2040, called "Both SDGs 2040 (75% DS)." This scenario follows the same implementation as the Both SDGs (75% DS) scenario, with the modification that the SDG targets are assumed to be met in 2040 instead of 2030. For many high-fertility countries, achieving the

SDG targets in 2030 is highly ambitious (Abel et al., 2016; Friedman et al., 2020), so considering a scenario where the same goals are met a decade later acts as a more realistic policy intervention.

Finally, we considered an "Education SDG Only" scenario where only SDG Target 4.1 is met in 2030 with no additional policy intervention for family planning. For the Education SDG Only scenario, the projection model was re-estimated to include only education, GDP, and their interactions with the SSA indicator as covariates. Education is a less proximate cause of fertility decline than family planning, as seen in Figure 3. Re-estimating the projection model without the family planning variable is necessary to ensure that the coefficient of education fully captures both the direct effect that education has on fertility and the indirect effect education has on fertility through the effect of education on family planning. By comparing results from the Education SDG Only scenario with results from the scenarios where both SDG targets are met, we are able to quantify the additional effect that meeting Target 3.7 would have on TFR projections.

For all intervention-based projection scenarios, we assume the policy efforts required to attain the SDGs in the target year (2030 or 2040) are sustained out to 2100.

TABLE 1
Summary of projection scenarios

Scenario	Target 4.1 Assumptions	Target 3.7 Assumptions
Reference	No intervention	No intervention
Both SDGs (0% Unmet)	Universal lower secondary education by 2030	Unmet need reaches 0% in 2030; all unmet need is assumed to be met with modern methods
Both SDGs (75% DS)	Universal lower secondary education by 2030	Demand satisfied by modern methods reaches 75% by 2030; all increases in contraceptive prevalence are assumed to be for modern methods
Both SDGs 2040 (75% DS)	Universal lower secondary education by 2040	Demand satisfied by modern methods reaches 75% by 2040; all increases in contraceptive prevalence are assumed to be for modern methods
Education SDG Only	Universal lower secondary education by 2030	No intervention

TFR projections from the conditional TFR projection model are translated into population projections using the cohort-component method as implemented in the "bayesPop" R package (Ševčíková, and Raftery, 2016), which is based on the demographic balancing equation,

$$\text{Population}_{t+1} = \text{Population}_t + \text{Births}_t - \text{Deaths}_t + \text{Immigrants}_t - \text{Emigrants}_t,$$

where the population size at time $(t+1)$ is equal to the population size at time t plus the number of births and number of immigrants occurring in time interval t to $(t+1)$ and minus the number of deaths and number of emigrants occuring in time interval t to $(t+1)$ (Preston, Heuveline and Guillot, 2001). The bayesPop package uses the cohort-component method of population projection, an age- and sex-specific version of the demographic balancing equation, to create age- and sex-specific population projections. Population projections were created using probabilistic projections of mortality and migration as inputs. Projections of mortality were created using the "bayesLifeHIV" R package[4] (Godwin and Raftery, 2017) and projections of migration were created following the method of Azose and Raftery (2015).

3. Validation. The conditional TFR projection model was assessed using out-of-sample validation. Out-of-sample validation is a method frequently used to validate probabilistic forecasts, and in particular was the method used to validate the original bayesTFR method (Alkema et al., 2011). Our goal in developing the conditional TFR projection model is not to improve the predictive performance of the existing bayesTFR projection method, but to expand the utility of the method to allow creation of policy-based intervention projections. To that end, the validation exercises conducted on our model are compared to analogous exercises for bayesTFR to ensure our model has similar predictive performance to bayesTFR.

For the first out-of-sample validation exercise, we created projections for the five-year time period 2015-2020 using the conditional projection model estimated using data spanning 1970-1975 through 2010-2015. Fertility observations came from WPP 2019 and were subject to the same "high-fertility" constraint as before, where only country-time pairs where the country was in Phase II and had TFR > 2.5 were included in estimation of the second stage. Covariate data were restricted to reflect the true data availability before 2015 as much as was possible for both estimation and projection. We used data from Version 1.0 of the Wittgenstein Centre Data Explorer to fit the educational attainment model to create out-of-sample estimates and projections of ΔLowSec+. For estimates and projections of contraceptive prevalence, the FPEMglobal model was re-estimated using only survey estimates that were available before 2015. The model for GDP was also re-estimated using only data that were available in the 1970-1975 through 2010-2015 estimation period. This first validation exercise checks the marginal predictive performance of our model, where we expect our model to perform similarly to bayesTFR.

For the second validation exercise, we considered out-of-sample validation conditional on knowing the true values of the covariates for 2015-2020. The projection model was estimated using the same method as the first out-of-sample exercise, where the model is estimated leaving out data for the 2015-2020 time period. Then, TFR for 2015-2020 is projected using the left-out 2015-2020 values of the covariates as inputs. This second validation exercise checks the conditional predictive performance of our model.

The results of the two validation exercises are summarized in Table 2, where the results for our model are compared with analogous results for bayesTFR. Results for both models are averaged over the 97 countries included in the out-of-sample estimation. The out-of-sample validation exercises are denoted "OOS" in the "Validation Type" column, while the conditional out-of-sample validation is denoted "Conditional OOS." The mean absolute error (MAE) is calculated as

$$\frac{1}{676}\sum_{c}\sum_{t}|\hat{f}_{c,t} - f_{c,t}|$$

where $\hat{f}_{c,t}$ denotes the median projection of TFR for country c and time t, $f_{c,t}$ is the observed value of TFR for country c and time t from WPP 2019, the sums are taken over all countries and five-year time periods included in the out-of-sample estimation, and 676 is the number of country-time period pairs included in the out-of-sample estimation. The MAE evaluates the performance of the point predictions. Our model performed similarly to bayesTFR, though both the out-of-sample and conditional out-of-sample exercises resulted in larger MAE values than bayesTFR.

[4] Available at `https://github.com/PPgp/bayesLifeHIV`, downloaded on March 30, 2021

The performance of the projection intervals was evaluated by computing the coverage of the 95% projection intervals with respect to the left-out observations, where coverage is averaged over all 97 countries and is calculated as the proportion of the intervals that contained the true 2015-2020 value of TFR from WPP 2019. Our model performed very similarly to bayesTFR, with both projection models having close to nominal coverage for the 95% intervals. The projection intervals were also evaluated by looking at the average interval width across all countries. The intervals from the conditional projection model were wider than the intervals from bayesTFR. This follows our expectations, as the conditional model incorporates uncertainty about covariate projections into projections of TFR. Based on these validation exercises and comparisons to bayesTFR, the conditional projection model performed similarly to bayesTFR.

TABLE 2

Out-of-sample validation results for one five-year time period (2015-2020) left out for our model and bayesTFR using WPP 2019, where results are averaged across all 97 countries included in estimation of the second stage.

Model	Validation Type	MAE	95% Cvg	95% Width
Conditional Projection Model	OOS	0.1334	0.9691	0.9017
Conditional Projection Model	Conditional OOS	0.1179	0.9691	0.8953
bayesTFR	OOS	0.0752	0.9691	0.8046

We also conducted a sensitivity analysis for the prior distributions of the β coefficients and found that the conditional projection model is not sensitive to changes in the prior distributions. Further details of this analysis and other validation exercises can be found in the Supplementary Material.

4. Results. Projections of TFR and population size from the conditional projection model are presented in this section for the five-year time periods from 2020-2025 to 2095-2100 using Nigeria as a case study. Projections of TFR and population size for sub-Saharan Africa and projections of population size for the world are also presented. Additional projection results are available in the Supplementary Material.

4.1. *Case Study: Nigeria.* We present projection results for TFR and population size using Nigeria as a case study. Nigeria is one of the most important countries for projections of future world population as it is a high-fertility country, with TFR in 2015-2020 of 5.42 children per woman, and is the most populous country in Africa, with population size in 2020 of 206 million people.

Median projections of TFR for Nigeria are plotted for all projection scenarios in Figure 6. We also plot 95% projection intervals (PIs) for the reference and Both SDGs (0% Unmet) scenarios. Population projections for Nigeria corresponding to the TFR projection scenarios are shown in Figure 7. Median projected values of TFR and population size for all scenarios are included in Tables 3 and 4, where differences in medians across different scenarios are also presented.

In 2030-2035, the time period directly following the SDG intervention, the Both SDGs (0% Unmet) scenario projects TFR to be 3.93 children per woman with a 95% PI of (2.74, 4.83), while the Both SDGs (75% DS) scenario projects TFR to be 4.00 (2.87, 4.88). This is a reduction of 0.49 and 0.42 of a child, respectively, from the reference scenario projection of 4.41 (3.31, 5.21). These differences translate into differences in population size projections of 9.1 and 7.4 million fewer people in 2035, respectively, compared to the reference scenario.

As expected, the most extreme interpretation of the SDGs, Both SDGs (0% Unmet), leads to the largest reduction in projected TFR and population size out of all intervention scenarios in 2030-2035, while the more conservative interpretations of meeting the SDGs lead to

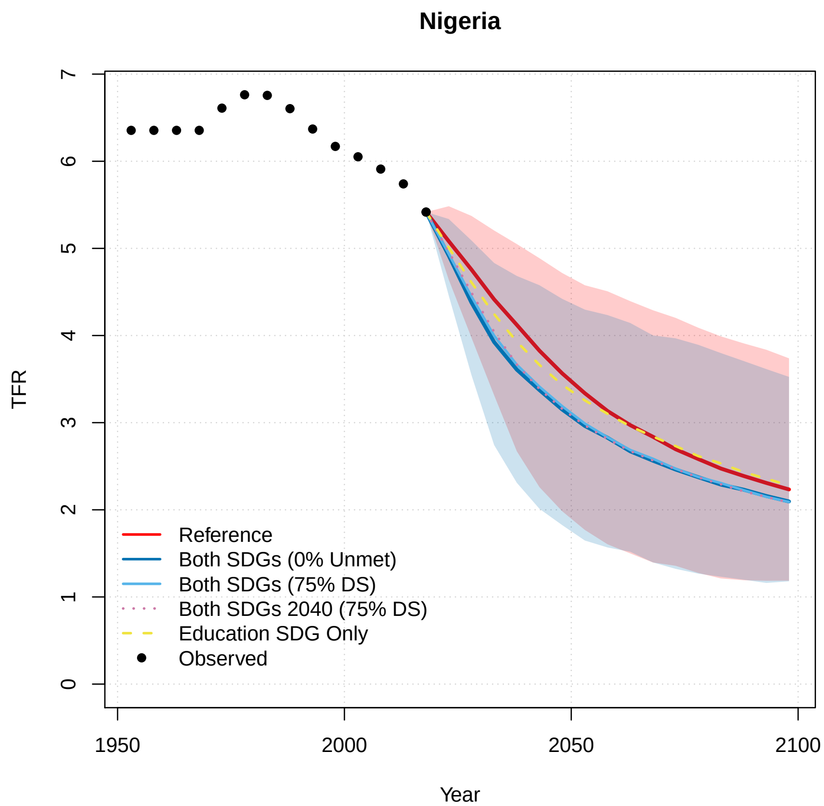

Fig 6: Comparison of median TFR projections for Nigeria from reference scenario in red, Both SDGs (0% Unmet) in dark blue, Both SDGs (75% DS) in light blue, Both SDGs 2040 (75% DS) in pink dotted, and Education SDG Only in yellow dashed. 95% projection intervals for the reference and Both SDGs (0% Unmet) scenarios are also plotted.

TABLE 3

Median TFR projections in 2030-2035, 2045-2050, and 2095-2100 for Nigeria for all projection scenarios and differences between projection scenarios in children per woman

	2030-2035	2045-2050	2095-2100
Reference	4.41	3.57	2.23
Both SDGs (0% Unmet)	3.93	3.15	2.10
Both SDGs (75% DS)	4.00	3.19	2.09
Both SDGs 2040 (75% DS)	4.04	3.16	2.08
Educ SDG Only	4.25	3.43	2.28
Reference − Both SDGs (0% Unmet)	0.49	0.41	0.14
Reference − Both SDGs (75% DS)	0.42	0.38	0.14
Reference − Both SDGS 2040 (75% DS)	0.37	0.41	0.15
Reference − Educ SDG Only	0.17	0.13	-0.05
Both SDGs (75% DS) − Both SDGs (0% Unmet)	0.07	0.04	-0.01
Both SDGs 2040 (75% DS) − Both SDGs (75% DS)	0.04	-0.03	-0.01
Educ SDG Only − Both SDGs (0% Unmet)	0.32	0.28	0.18
Educ SDG Only − Both SDGs (75% DS)	0.25	0.25	0.19

smaller reductions in projected TFR and population size. From the Education SDG Only scenario, we see that attaining Target 4.1 in 2030 in the absence of any policy intervention for

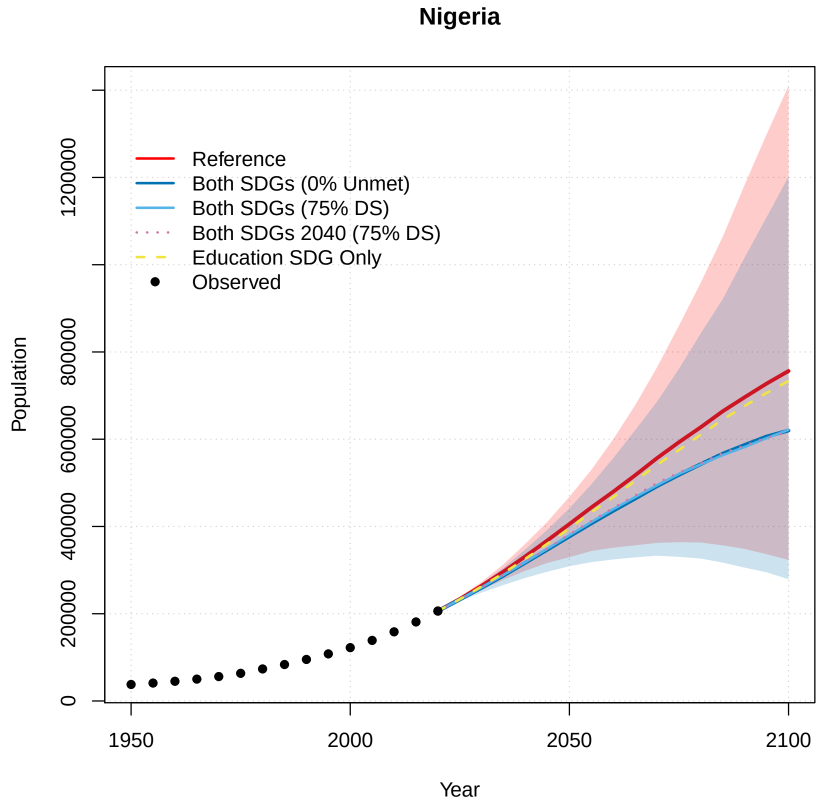

Fig 7: Comparison of median population projections for Nigeria from reference scenario in red, Both SDGs (0% Unmet) in dark blue, Both SDGs (75% DS) in light blue, Both SDGs 2040 (75% DS) in pink dotted, and Education SDG Only in yellow dashed. 95% projection intervals for the reference and Both SDGs (0% Unmet) scenarios are also plotted.

TABLE 4

Median population projections in 2035, 2050, and 2100 for Nigeria for all projection scenarios and differences between projection scenarios in millions of people

	2035	2050	2100
Reference	296.7	405.6	756.4
Both SDGs (0% Unmet)	287.7	377.2	620.0
Both SDGs (75% DS)	289.3	379.9	621.6
Both SDGs 2040 (75% DS)	289.9	382.1	617.0
Educ SDG Only	293.3	395.6	733.5
Reference − Both SDGs (0% Unmet)	9.1	28.4	136.4
Reference − Both SDGs (75% DS)	7.4	25.7	134.8
Reference − Both SDGS 2040 (75% DS)	6.9	23.5	139.4
Reference − Educ SDG Only	3.5	10.0	22.9
Both SDGs (75% DS) − Both SDGs (0% Unmet)	1.6	2.7	1.7
Both SDGs 2040 (75% DS) − Both SDGs (75% DS)	0.6	2.1	-4.6
Educ SDG Only − Both SDGs (0% Unmet)	5.6	18.3	113.5
Educ SDG Only − Both SDGs (75% DS)	4.0	15.6	111.8

family planning still leads to a reduction of 0.17 in median projected TFR for Nigeria compared to the reference scenario in 2030-2035. The additional effect of policy interventions for family planning result in additional reductions in median projected TFR of 0.32 or 0.25 for the different interpretations of Target 3.7.

In 2045-2050, TFR is projected to be 3.15 (1.82, 4.42) in the Both SDGs (0% Unmet) scenario and 3.19 (1.84, 4.49) in the Both SDGs (75% DS) scenario. Compared to the reference scenario projection of 3.57 (1.98, 4.72), this is a reduction of 0.41 and 0.38 of a child, respectively. These differences in TFR translate into differences in population size of 28.4 and 25.7 million fewer people, respectively, in 2050.

After mid-century, TFR projections for all scenarios begin to converge. TFR projections in 2095-2100 range from 2.23 (1.19, 3.74) in the reference scenario, 2.10 (1.18, 3.53) in Both SDGs (0% Unmet), 2.09 (1.13, 3.64) in Both SDGs (75% DS), 2.28 (1.20, 3.78) in Education SDG Only, and 2.08 (1.16, 3.56) in Both SDGs 2040 (75% DS). This convergence is due to the shared post-transition Phase III model, where once a country has entered Phase III, the country is projected to converge towards and fluctuate around a long-term mean TFR. As TFR projections across all scenarios eventually converge to the same country-specific mean, the most interesting comparisons of the projected effects of the SDG interventions occur before mid-century.

Despite the convergence in TFRs, population projections remain relatively distinct across the projection scenarios out to 2100 due to population momentum. In 2100, Nigeria's population is projected to reach 756 (323, 1410) million people under the reference scenario. In the Both SDGs (0% Unmet) scenario, population is projected to reach 620 (279, 1202) million, a reduction of 136 million people compared to the reference scenario. In the Both SDGs (75% DS) scenario, population is projected to reach 622 (290, 1273) million, a reduction of 135 million people compared to the reference scenario. In the Both SDGs 2040 (75% DS) scenario, population is projected to be 617 (291, 1247) million in 2100, which is a reduction of 139 million people compared to the reference scenario. We note that the predictive distributions of population in 2100 are very similar for the Both SDGs (0% Unmet), Both SDGs (75% DS), and Both SDGs 2040 (75% DS) scenarios, with substantial overlap between their 95% prediction intervals. This is unsurprising given the similarities of the TFR projections for the three scenarios and the convergence of TFR projections across all scenarios after mid-century.

For Nigeria, population projections from the Education SDG Only scenario overlap significantly with the reference scenario projections. In 2100, population is projected to reach 633 (320, 1359) million people under Education SDG Only, compared to the reference scenario's projected 756 (323, 1410) million people. This overlap suggests that policy interventions targeting educational attainment in the absence of interventions for family planning are not likely to have notable long-term impacts on population size in Nigeria.

4.2. *Sub-Saharan Africa.* Next, we present projection results for sub-Saharan Africa. World population in the next century will be driven by population growth in high-fertility countries, the majority of which are in SSA. As described in Section 2.5, TFR projections for countries with current TFR above replacement level follow the conditional TFR projection model, while countries that currently have low fertility are projected with the bayesTFR model. Countries without available covariate data are also projected using the bayesTFR model. Thus, our intervention-based projections of regional aggregates reflect only the impact of policy interventions in countries with TFR above replacement level that had available covariate data.

Figure 8 shows median projections of TFR for SSA for all projection scenarios alongside 95% PIs for the reference and Both SDGs (0% Unmet) scenarios. Median projected values of TFR for SSA for all scenarios and differences between scenarios are shown in Table 5 for 2035, 2050, and 2100. TFR results were aggregated for SSA as the average of the age-specific fertility rates for countries in SSA, weighted by the size of the female population for each country.[5] Figure 9 and Table 6 summarize the population projections corresponding to the TFR projection scenarios for SSA.

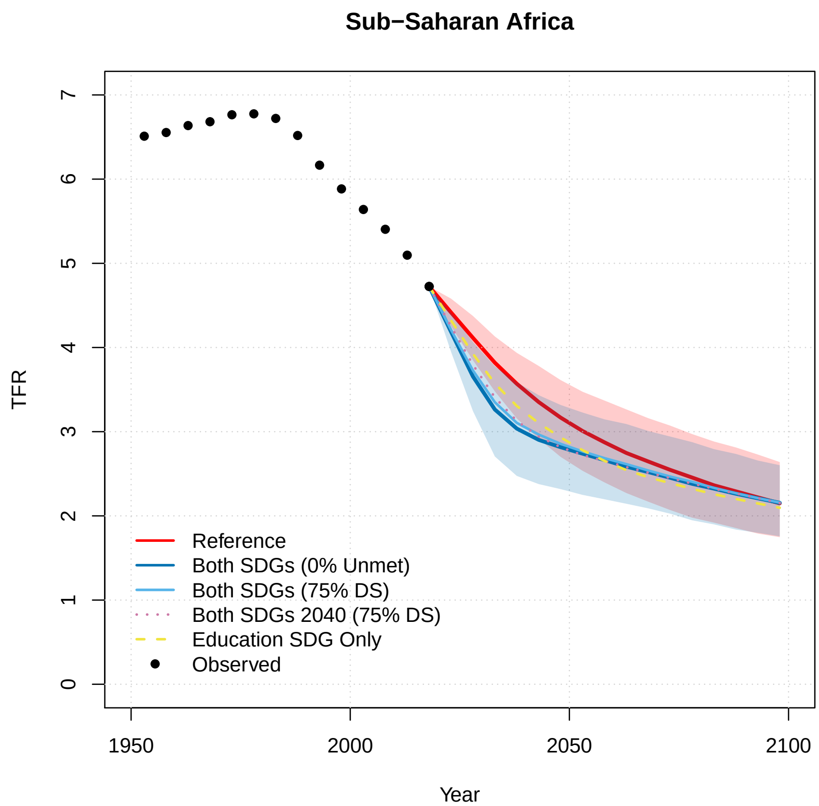

Fig 8: Comparison of median TFR projections for sub-Saharan Africa from reference scenario in red, Both SDGs (0% Unmet) in dark blue, Both SDGs (75% DS) in light blue, Both SDGs 2040 (75% DS) in pink dotted, and Education SDG Only in yellow dashed. 95% projection intervals for the reference and Both SDGs (0% Unmet) scenarios are also plotted.

In 2030-2035, the Both SDGs (0% Unmet) scenario projects TFR to be 3.26 (2.70, 3.77) children per woman in SSA while the Both SDGs (75% DS) scenario projects TFR to be 3.35 (2.87, 3.80) children per woman. This is a reduction of 0.56 and 0.47 of a child, respectively, from the reference scenario projection of 3.82 (3.48, 4.13) From the Education SDG Only scenario, attaining Target 4.1 in 2030 in the absence of any policy intervention for family planning leads to a reduction of 0.25 in median projected TFR compared to the reference scenario in 2030-2035. The additional effect of policy interventions for family planning leads to an additional reduction in median projected TFR of 0.31 or 0.22 for the different interpretations of Target 3.7. In the time period immediately following the intervention, we see the relative effect sizes of interventions for education and interventions for family planning on TFR are similar for SSA.

In 2045-2050, the TFR for SSA is projected to be 2.82 (2.32, 3.32) in the Both SDGs (0% Unmet) scenario and 2.86 (2.39, 3.32) in the Both SDGs (75% DS) scenario. Compared to

[5] Note that is not the exact TFR for SSA, but is likely to be a very close approximation.

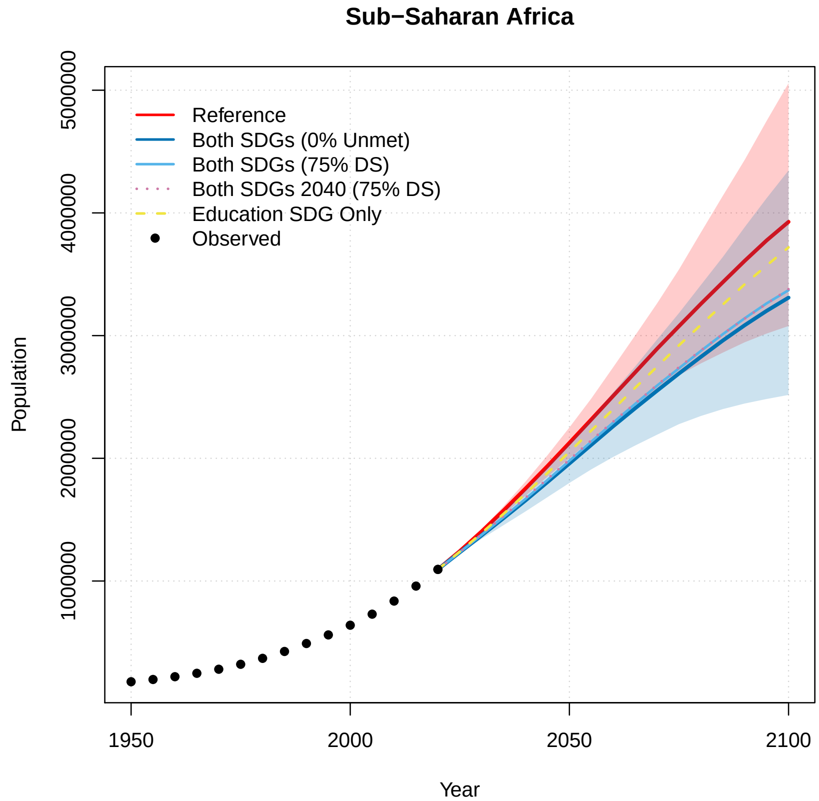

Fig 9: Comparison of median population projections for sub-Saharan Africa from reference scenario in red, Both SDGs (0% Unmet) in dark blue, Both SDGs (75% DS) in light blue, Both SDGs 2040 (75% DS) in pink dotted, and Education SDG Only in yellow dashed. 95% projection intervals for the reference and Both SDGs (0% Unmet) scenarios are also plotted.

TABLE 5

Median TFR projections in 2030-2035, 2045-2050, and 2095-2100 for sub-Saharan Africa for all projection scenarios and differences between projection scenarios in children per woman

	2030-2035	2045-2050	2095-2100
Reference	3.82	3.17	2.15
Both SDGs (0% Unmet)	3.26	2.82	2.16
Both SDGs (75% DS)	3.35	2.86	2.16
Both SDGs 2040 (75% DS)	3.41	2.82	2.15
Educ SDG Only	3.57	2.93	2.10
Reference − Both SDGs (0% Unmet)	0.56	0.35	-0.01
Reference − Both SDGs (75% DS)	0.47	0.31	-0.01
Reference − Both SDGS 2040 (75% DS)	0.41	0.35	-0.00
Reference − Educ SDG Only	0.25	0.24	0.05
Both SDGs (75% DS) − Both SDGs (0% Unmet)	0.09	0.04	0.00
Both SDGs 2040 (75% DS) − Both SDGs (75% DS)	0.06	-0.04	0.00
Educ SDG Only − Both SDGs (0% Unmet)	0.31	0.12	-0.06
Educ SDG Only − Both SDGs (75% DS)	0.22	0.08	-0.06

the reference scenario projection of 3.17 (2.70, 3.61), this is a reduction of 0.35 and 0.31 of a child, respectively. Attaining Target 3.1 in 2030 in the absence of any policy intervention for

TABLE 6
Median projections in 2035, 2050, and 2100 of population size for sub-Saharan Africa for all projection scenarios and differences between projection scenarios in millions of people

	2035	2050	2100
Reference	1,575.4	2,125.7	3,927.1
Both SDGs (0% Unmet)	1,512.9	1,957.8	3,309.5
Both SDGs (75% DS)	1,521.4	1,979.7	3,369.9
Both SDGs 2040 (75% DS)	1,529.5	1,988.7	3,379.3
Educ SDG Only	1,548.2	2,052.5	3,719.2
Reference − Both SDGs (0% Unmet)	62.5	167.9	617.5
Reference − Both SDGs (75% DS)	54.0	146.0	557.2
Reference − Both SDGs 2040 (75% DS)	45.9	136.9	547.8
Reference − Educ SDG Only	27.2	73.1	207.8
Both SDGs (75% DS) − Both SDGs (0% Unmet)	8.5	21.9	60.3
Both SDGs 2040 (75% DS) − Both SDGs (75% DS)	8.1	9.1	9.4
Educ SDG Only − Both SDGs (0% Unmet)	35.3	94.8	409.7
Educ SDG Only − Both SDGs (75% DS)	26.8	72.9	349.3

family planning leads to a reduction of 0.24 of a child, and the additional effect of attaining Target 3.7 leads to a reduction of 0.12 or 0.08 of a child.

After mid-century, we note the same convergence in TFR projections across projections scenarios that was observed in Nigeria. The convergence is more pronounced for the SSA aggregate than for Nigeria. The TFR of SSA is projected to approach replacement level in 2095-2100 in all projection scenarios. Population in 2100 in SSA is projected to reach 3.9 (3.1, 5.1) billion in the reference scenario, 3.3 (2.5, 4.3) billion in the Both SDGs (0% Unmet Need) scenario, 3.4 (2.7, 4.3) billion in the Both SDGs (75% Unmet Need) scenario, 3.4 (2.6, 4.4) billion in the Both SDGs 2040 (75% DS) scenario, and 3.7 (2.9, 4.9) billion in the Education SDG Only scenario.

Population in 2100 is projected to be 618 million lower in the Both SDGs (0% Unmet) scenario and 557 million lower in the Both SDGs (75% DS) scenario than the reference scenario. If the SDGs are instead met in 2040, this difference is 548 million. The projections for the Both SDGs (75% DS) and Both SDGs 2040 (75% DS) scenarios are very similar, indicating that achieving the SDG targets a decade later in countries that are not currently on track to meet the SDGs in 2030 could still have notable long-term demographic implications for SSA.

In 2100, if only the target of universal lower secondary education is attained with no intervention targeting family planning, population is projected to be 208 million lower than the reference scenario. The additional effect of attaining the SDG corresponding to family planning is a reduction of 410 million people in 2100 if Target 3.7 is interpreted as 0% Unmet Need and 349 million people if the target is interpreted as 75% Demand Satisfied.

4.3. *World.* Finally, we present population projection results for the world. Projections for all 201 countries included in WPP 2019 are aggregated to produce world projections. Figure 10 shows median projections of world population size for all projection scenarios alongside 95% PIs for the reference and Both SDGs (0% Unmet) scenarios. Median projected values of world population size for all scenarios and differences between scenarios are shown in Table 7 for 2035, 2050, and 2100.

In 2100, world population is projected to reach 11.0 (9.6, 12.8) billion in the reference scenario, 9.0 (7.8, 10.5) billion in the Both SDGs (0% Unmet Need) scenario, 9.5 (8.2, 10.9) billion in the Both SDGs (75% Unmet Need) scenario, 9.5 (8.2, 11.2) billion in the Both SDGs 2040 (75% DS) scenario, and 10.7 (9.3, 12.4) billion in the Education SDG Only scenario. The Both SDGs (0% Unmet) scenario projects population to be 1.96 billion lower than

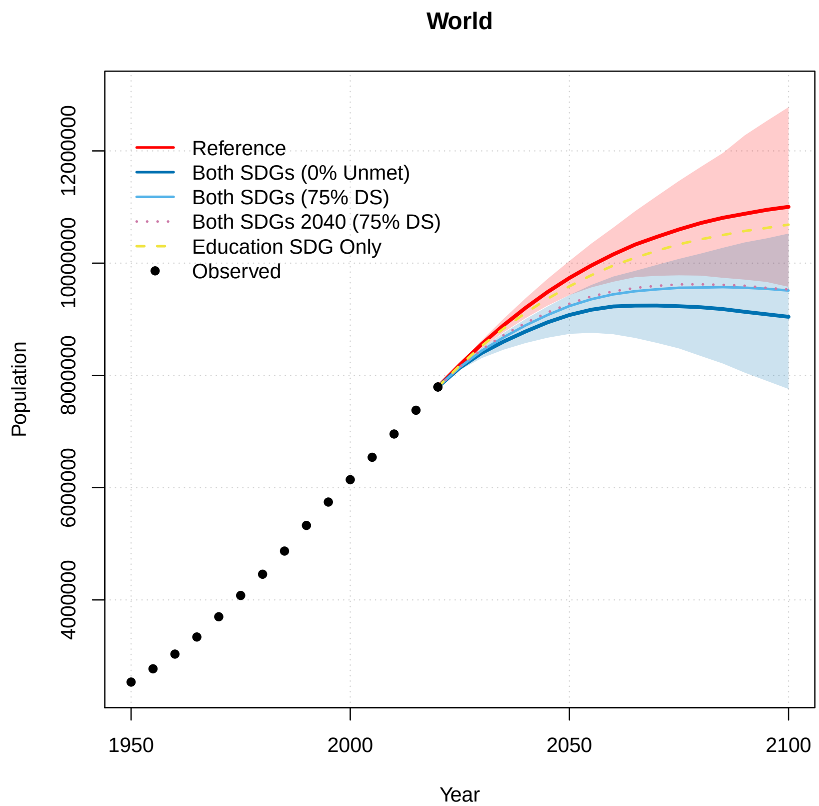

Fig 10: Comparison of median world population projections from reference scenario in red, Both SDGs (0% Unmet) in dark blue, Both SDGs (75% DS) in light blue, Both SDGs 2040 (75% DS) in pink dotted, and Education SDG Only in yellow dashed. 95% projection intervals for the reference and Both SDGs (0% Unmet) scenarios are also plotted.

TABLE 7
Median projections in 2035, 2050, and 2100 for world population size for all projection scenarios and differences between projection scenarios in millions of people

	2035	2050	2100
Reference	8,895	9,736	11,003
Both SDGs (0% Unmet)	8,603	9,076	9,044
Both SDGs (75% DS)	8,679	9,236	9,513
Both SDGs 2040 (75% DS)	8,718	9,278	9,531
Educ SDG Only	8,836	9,587	10,686
Reference − Both SDGs (0% Unmet)	292	660	1,959
Reference − Both SDGs (75% DS)	216	500	1,490
Reference − Both SDGs 2040 (75% DS)	177	458	1,472
Reference − Educ SDG Only	59	149	317
Both SDGs (75% DS) − Both SDGs (0% Unmet)	76	160	469
Both SDGs 2040 (75% DS) − Both SDGs (75% DS)	39	42	18
Educ SDG Only − Both SDGs (0% Unmet)	233	511	1,642
Educ SDG Only − Both SDGs (75% DS)	157	351	1,173

the reference scenario. If the SDGs correspond to attaining 75% Demand Satisfied instead, this difference is 1.49 billion. If the SDGs correspond to attaining 75% Demand Satisfied and were met in 2040 instead of 2030, this difference is 1.47 billion, indicating that policies focused on meeting the SDGs a decade later in countries that are not currently on track to meet the SDGs in 2030 could still have a substantial impact on world population.

If only the target of universal lower secondary education is attained with no additional intervention targeting family planning, population is projected to be 317 million lower than the reference scenario in 2100. The additional effect of attaining the SDG target corresponding to family planning is a reduction of 1.64 billion people in 2100 if Target 3.7 is interpreted as 0% Unmet Need. If the target is instead interpreted as 75% Demand Satisfied, the additional reduction is 1.17 billion.

5. Discussion. We created a conditional projection model for TFR that extends the unconditional model that is the basis of the fertility projections published by the UN. The conditional model enables the creation of probabilistic projections of TFR conditional on policy interventions that target educational attainment and contraceptive prevalence, such as meeting the SDG targets for education and family planning.

Previous work has explored potential ways to quantify the possible impact of the SDGs on fertility and population size. We compare our results with those of Abel et al. (2016) and Vollset et al. (2020). Abel et al. (2016) created population projections based on attaining the SDGs by building upon the population projection model developed by the Wittgenstein Centre. The Wittgenstein Centre projections are based on global population scenarios corresponding to the Shared Socioeconomic Pathways (SSPs) used by the Intergovernmental Panel on Climate Change (Lutz, Butz and KC, 2014). In lieu of reporting population projections with corresponding measures of uncertainty, the Wittgenstein Centre produces population projections following a number of different SSP scenarios corresponding to different levels of socioeconomic development.

Abel et al. (2016) extends this work to consider different SDG scenarios based on varying interpretations of the SDG targets. In particular, Target 4.1 is interpreted as either universal lower secondary education or universal upper secondary education and Target 3.7 is interpreted as meaning that education-specific fertility rates will either be 20% lower or 10% lower due to reductions in unmet need for family planning. These different SDG scenarios lead to a range of possible world population size projections. However, the individual SDG scenario projections do not come with measures of uncertainty.

Vollset et al. (2020) created probabilistic population projections for the Global Burden of Disease (GBD) project at IHME. The GBD model incorporates measures of education and family planning as covariates in the fertility projection model and incorporates uncertainty in projections. The GBD model projects completed cohort fertility at age 50 as a function of educational attainment (measured as years of education) and contraceptive met need. Vollset et al. consider scenarios for population projections based on different rates of change in educational attainment and contraceptive met need, including a scenario corresponding to meeting the SDGs.

Unlike the Abel et al. (2016) projections, the GBD projections do come with measures of uncertainty. However, the GBD projections have been criticized in the demographic community for questionable model assumptions and demographically implausible projection results (Gietel-Basten et al., 2020; Gietel-Basten and Sobotka, 2020). The interpretation of their intervention-based projections as causal has also been questioned by Alkema (2020), who highlighted a key flaw in the causal assumptions underlying the GBD model. By using met need for contraception as the measure of family planning, the GBD model does not distinguish between the effect of increased demand for family planning and the effect of improved access among those with a need for family planning in their SDG intervention scenario.

We avoided this issue in our model by focusing on the relationship between contraceptive prevalence and fertility. In our model, increases in contraceptive prevalence that result from the SDG intervention correspond both to fertility reductions that are due to increases in demand for family planning and fertility reductions that are due to improved access. These two pathways leading to fertility reductions are also reflected in our implementation of the SDG intervention projections for CP.

There are notable differences between our results and the two existing sets of intervention-based projections. Table 8 summarizes a comparison of median world population size projections under reference and SDG intervention scenarios from our model, the Abel et al. model, and the Vollset et al. model. SDG intervention results from our model are presented for the Both SDGs (0% Unmet) and Both SDGs (75% DS) projection scenarios in Table 8, where Both SDGs (0% Unmet) aligns most closely with the SDG assumptions used by Abel et al. and Vollset et al. Results from Both SDGs (75% DS) are included in the comparison to illustrate a more realistic interpretation of meeting the SDGs. We note there are large differences between our reference scenario projections and those from the Wittgenstein Centre and IHME. These differences are largely due to underlying differences in the fertility projection assumptions in the low-fertility setting when TFR has reached below 2.5 children per woman. As our analysis is primarily conducted in the high-fertility setting, these differences are out of the scope of this paper, but have been discussed by Wilmoth (2019), Vollset et al. (2020), and Kaneda, Falk and Patierno (2021), among others. Instead, we focus our comparisons on the projected differences between the reference scenario and the SDG intervention scenario from each set of projections.

TABLE 8

Comparison of median world population projections in 2050 and 2100 under the reference model, the intervention scenario assuming both SDG targets are met in 2030, and the difference between the two scenarios from our conditional projection model, Abel et al. (2016), and Vollset et al. (2020) in billions of people. The SDG results from our model follow the Both SDGs (0% Unmet) and Both SDGs (75% DS) scenarios. The SDG results from the Abel et al. model follow the SDG2 scenario.

Year	Scenario	Our Model (0% Unmet)	Our Model (75% DS)	Abel et al. (2016)	Vollset et al. (2020)
2050	Reference	9.74	9.74	9.14	9.55
	SDG	9.08	9.24	8.87	8.77
	Difference	0.66	0.50	0.27	0.78
2100	Reference	11.00	11.00	8.95	8.79
	SDG	9.04	9.51	8.43	6.29
	Difference	1.96	1.49	0.51	2.50

The scenario "SDG2" from Abel et al. (2016) aligns most closely with our Both SDGs (0% Unmet) scenario. We project larger reductions in population size in both 2050 and 2100 due to attaining both SDGs in 2030 compared to Abel et al. Under SDG2, Abel et al. project world population size to be 8.43 billion in 2100, which is a reduction of 514 million compared to their reference scenario projection of 8.95 billion in 2100. In contrast, we project a difference of 1.96 billion people between our reference and Both SDGs (0% Unmet) scenarios, which is more than three times the difference projected by Abel et al. These differences in projection results are also seen in 2050, with our Both SDGs (0% Unmet) scenario projecting a reduction of 660 million people from meeting the SDGs and the Abel et al. model projecting a reduction of 274 million people. The projected differences in population size from our more realistic Both SDGs (75% DS) scenario aligns more closely with the Abel et al. results compared to the Both SDGs (0% Unmet) scenario. However, our more realistic scenario still projects about three times the projected reduction in population size from the Abel et al. SDG2 scenario in 2100. A large part of the differences in the projected effect of the SDGs after mid-century is due to the underlying differences between the fertility projection models used by the UN and the Wittgenstein Centre. Abel et al. projected population to peak by mid-century in both the reference and SDG intervention scenarios, whereas our projections continue to increase to 2100 in all scenarios.

The SDG intervention projection scenario from Vollset et al. (2020) also aligns most closely with our Both SDGs (0% Unmet) scenario. Vollset et al. found that meeting the SDG targets for education and contraceptive met need would result in world population in 2100 of 6.29 billion with 95% PI (4.82, 8.73). Compared to their reference scenario, which projects world population will be 8.79 billion (6.83, 11.80) in 2100, they project the effect of meeting the SDGs will lead to a global reduction of 2.50 billion people in 2100. In comparison, we project a reduction of 1.96 billion people in 2100 from our Both SDGs (0% Unmet) scenario. Similar differences between the GBD projections and our projections occur in earlier time periods. In 2050, Vollset et al. projected that world population would be 9.55 billion (9.05, 10.16) in the reference scenario and 8.77 billion (8.33, 9.35) in the SDG intervention scenario, which is a difference of 780 million. Using the Both SDGs (0% Unmet) scenario, we project a difference of 660 million.

We note that the uncertainty intervals reported by Vollset et al. are wider than those from our model. In the reference scenario projections at 2100, the 95% PI from the GBD model is 4.97 billion people wide, whereas our reference scenario 95% PI width is 3.20 billion people. Part of the differences between our projections and the GBD projections are again due to underlying differences in fertility model assumptions. Vollset et al. project world population to peak around or slightly after mid-century in both reference and SDG scenarios, whereas our projections continue to increase to 2100. A comparison of the reference scenario projections from the GBD model, the Wittgenstein Centre model, and the UN model was conducted in Vollset et al. (2020). They found that the GBD model aligns more closely with the Wittgenstein Centre model for both fertility and population projections than with the UN model. However, despite these similarities in reference scenario projections, it is notable that Vollset et al. project the effect of meeting the SDGs to be nearly three times the effect projected by Abel et al. in 2050 and nearly five times the effect in 2100.

Our method improves upon the existing intervention-based projections of TFR and population. First, unlike the Abel et al. model, our model fully incorporates uncertainty about covariate projections into projections of TFR and provides probabilistic projections of TFR and population size. Second, unlike the Vollset et al. model, our model incorporates demographic background knowledge to ensure that results are demographically plausible and to inform the causal framework underlying our model.

Our projections also reflect only the impact of policy interventions in the high-fertility setting. While the accelerating effect of education and family planning expansion on fertility decline is well established in the high-fertility context, the effect is less clear in the low-fertility context, in particular for education. Although there is some evidence that the effect of education on fertility persists over the course of the fertility transition (Lutz, Butz and KC, 2014), there is also evidence that the effect of education may be different in countries where a majority of women have attained tertiary education (Asderá, 2017b). For example, there is evidence to suggest that the relationship between education and fertility may in fact be reversed in the low-fertility setting, where higher educated women have greater resources to attain their desired childbearing and thus have higher fertility compared to lower educated women (Sobotka, Beaujouan and Van Bavel, 2017). This uncertainty about the long-run relationship between education and fertility decline once a country reaches low fertility levels is not reflected in either the Abel et al. or Vollset et al. projections.

Unlike the existing projection models, our model also accounts for the fact that the associations between the covariates and fertility decline have been observed to be weaker in SSA compared to other regions of the world. This difference is especially important in the context of intervention-based projections, where, for example, the effect of eliminating unmet need for family planning is likely to have a weaker effect on fertility decline in SSA compared to other regions of the world due to high ideal family sizes (Bongaarts and Casterline, 2013).

Despite these improvements on the existing SDG intervention-based projections, our results have several limitations. First, the policy intervention scenarios rely on statistical extrapolation for projections of educational attainment and contraceptive prevalence. The SDG projections of the covariates are extreme scenarios, where the amount of acceleration in educational attainment and contraceptive prevalence encoded in the SDG intervention projections has not been observed historically. The intervention scenarios also assume that the historical relationships between education, family planning, and fertility will hold in the extrapolation, which may not be the case. This limitation is shared with all existing SDG intervention projections, and indeed is acknowledged by both Abel et al. (2016) and Vollset et al. (2020).

Our projections are also limited in terms of interpretation as causal effects due to the simplifying assumptions needed to model the complex causal relationship between education, family planning, and fertility. The assumptions used in our model are are outlined in Section 2.3 and are based on demographic background knowledge. However, this does not preclude the possibility that our model omits confounders or overly simplifies the underlying causal structure. The accuracy of our projections is further limited by the accuracy of the estimates and projections of the covariates. We used the best data available for globally and historically comparable estimates and projections of the covariates, but these still have limitations. For example, the estimates of contraceptive prevalence used in our model do not take the effectiveness of different contraceptive methods into account, which Bongaarts (2017) identifies as a key aspect of analyzing the relationship between contraceptive prevalence and TFR.

Finally, our population projection results assume that the SDG intervention scenarios affect population size only through the impact of the interventions on fertility. All population projections are created using non-intervention projections of mortality and migration. The potential impacts of universal secondary education and universal access to family planning on mortality and migration are not known to be substantial, and seem likely to be much smaller than the effects on fertility.

6. Conclusion. We have developed a conditional Bayesian hierarchical model for projections of TFR that incorporates the effect of educational attainment, contraceptive prevalence, and GDP per capita. This model creates probabilistic projections of TFR conditional on projections of the covariates, where the covariate projections can correspond to policy intervention outcomes. These conditional TFR projections can be used to answer questions about the likely effect of education and family planning policies on future fertility and can provide an informative tool for policymakers in high-fertility countries.

As an illustrative policy intervention, we focused on attaining the SDG Targets 3.7 and 4.1, which target universal access to family planning and universal secondary education, respectively. We created projections of TFR for five-year time periods covering 2020-2025 to 2095-2100 conditional on several policy-based intervention scenarios for differing rates of increase in educational attainment and contraceptive prevalence corresponding to different translations of the SDG targets. Using the intervention-based projections of TFR, we created corresponding probabilistic projections of population size. We found that meeting SDG Targets 3.7 and 4.1 in 2030 is projected to lead to a reduction in world population size in 2100 of 1.96 billion people compared to the reference scenario if Target 3.7 is interpreted as completely eliminating unmet need for family planning by 2030. If Target 3.7 is instead interpreted as meeting 75% of demand for family planning by 2030, the reduction in population size is projected to be 1.49 billion people. We found that even in the more conservative intervention scenario of attaining the SDGs in 2040, world population size in 2100 is still projected to be 1.47 billion people lower compared to the reference scenario. Our findings suggest that attainment of SDG Targets 3.7 and 4.1 are likely to have significant long-term effects on population growth in the high-fertility setting, even if the targets are met a decade later than the target achievement date of 2030.

Funding. This work was supported by NICHD grant R01 HD070936.

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** 14294-14299. https://doi.org/10.1073/pnas.1611386113.

ALKEMA, L. (2020). The Global Burden of Disease fertility forecasts: Summary of the approach used and associated statistical concerns. OSF Preprints. https://doi.org/10.31219/osf.io/3m6va.

ALKEMA, L., RAFTERY, A. E., GERLAND, P., CLARK, S. J., PELLETIER, F., BUETTNER, T. and HEILIG, G. K. (2011). Probabilistic Projections of the Total Fertility Rate for All Countries. *Demography* **48** 815-839. https://doi.org/10.1007/s13524-011-0040-5.

ASDERÁ, A. (2017a). Education and Fertility in the Context of Rising Inequality. *Vienna Yearbook of Population Research* **15** 63-92. https://doi.org/10.1553/populationyearbook2017s063.

ASDERÁ, A. (2017b). The future fertility of highly educated women: the role of educational composition shifts and labor market barriers. *Vienna Yearbook of Population Research* **15** 19-25. https://doi.org/10.1553/populationyearbook2017s019.

AXINN, W. G. and BARBER, J. S. (2001). Mass Education and Fertility Transition. *American Sociological Review* **66** 481-505. https://doi.org/10.2307/3088919.

AZOSE, J. J. and RAFTERY, A. E. (2015). Bayesian Probabilistic Projection of International Migration Rates. *Demography* **52** 1627-1650. https://doi.org/10.1007/s13524-015-0415-0.

BONGAARTS, J. (1978). A Framework for Analyzing the Proximate Determinants of Fertility. *Population and Development Review* **4** 105-132. https://doi.org/10.2307/1972149.

BONGAARTS, J. (1987). The Proximate Determinants of Exceptionally High Fertility. *Population and Development Review* **13** 133-139. https://doi.org/10.2307/1972125.

BONGAARTS, J. (2003). Completing the fertility transition in the developing world: The role of educational differences and fertility preferences. *Population Studies* **57** 321-335. https://doi.org/10.1080/0032472032000137835.

BONGAARTS, J. (2010). The Causes of Educational Differences in Fertility in Sub-Saharan Africa. Poverty, Gender, and Youth Working Paper no. 20. New York: Population Council. https://doi.org/10.31899/pgy3.1023.

BONGAARTS, J. (2013). Demographic Trends and Implications for Development. IUSSP 2013 Meeting, Busan. http://www.iussp.org/en/event/17/programme/session/1011.

BONGAARTS, J. (2017). The Effect of Contraception on Fertility: Is Sub-Saharan Africa Different? *Demographic Research* **37** 129-146. https://doi.org/10.4054/DemRes.2017.37.6.

BONGAARTS, J. and CASTERLINE, J. (2013). Fertility Transition: Is Sub-Saharan Africa Different? *Population and Development Review* **38** 153-168. https://doi.org/10.1111/j.1728-4457.2013.00557.x.

BONGAARTS, J., FRANK, O. and LESTHAEGHE, R. (1984). The Proximate Determinants of Fertility in Sub-Saharan Africa. *Population and Development Review* **10** 511-537. https://doi.org/10.2307/1973518.

BONGAARTS, J., MENSCH, B. S. and BLANC, A. K. (2017). Trends in the Age at Reproductive Transitions in the Developing World: The Role of Education. *Population Studies* **71** 139-154. https://doi.org/10.1080/00324728.2017.1291986.

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**. https://doi.org/10.12688/gatesopenres.13125.1.

CALDWELL, J. C. (1982). *Theory of Fertility Decline*. Academic Press, New York.

CALDWELL, J. C., REDDY, P. H. and CALDWELL, P. (1985). Educational Transition in Rural South India. *Population and Development Review* **11** 29-51. https://doi.org/0.2307/1973377.

DE SILVA, T. and TENREYRO, S. (2017). Population Control Policies and Fertility Convergence. *Journal of Economic Perspectives* **31** 205-228. https://doi.org/10.1257/jep.31.4.205.

EASTERLIN, R. A. and CRIMMINS, E. M. (1985). *The Fertility Revolution: A Supply-Demand Analysis*. University of Chicago Press, Chicago.

FABIC, M. S., CHOI, Y., BONGAARTS, J., DARROCH, J. E., ROSS, J. A., STOVER, J., TSUI, A. O., UPADHYAY, J. and STARBIRD, E. (2015). Meeting demand for family planning within a generation: the post-2015 agenda. *Lancet* **385** 1928-1931. https://doi.org/10.1016/S0140-6736(14)61055-2.

FOSDICK, B. K. and RAFTERY, A. E. (2014). Regional Probabilistic Fertility Forecasting by Modeling Between-Country Correlations. *Demographic Research* **30** 1011-1034. https://doi.org/10.4054/DemRes.2014.30.35.

FRIEDMAN, J., YORK, H., GRAETZ, N., WOYCZYNSKI, L., WHISNANT, J., HAY, S. I. and GAKIDOU, E. (2020). Measuring and Forecasting Progress towards the Education-Related SDG Targets. *Nature* **580** 636-639. https://doi.org/10.1038/s41586-020-2198-8.

GIETEL-BASTEN, S. and SOBOTKA, T. (2020). Uncertain Population Futures: Critical Reflections on the IHME Scenarios of Future Fertility, Mortality, Migration and Population Trends from 2017 to 2100. *SocArXiv*. https://doi.org/10.31235/osf.io/5syef.

GIETEL-BASTEN, S., SOBOTKA, T. et al. (2020). Letter on 'Fertility, Mortality, Migration, and Population Scenarios for 195 Countries and Territories from 2017 to 2100: A Forecasting Analysis for the Global Burden of Disease Study' by S. E. Vollset et al. (published Online 14 July 2020; https://doi.org/10.1016/). https://osf.io/ytf6m/?view_only=5389a004f7e94917b30b5a4d4ea7a154.

GODWIN, J. and RAFTERY, A. E. (2017). Bayesian Projection of Life Expectancy Accounting for the HIV/AIDS Epidemic. *Demographic Research* **37** 1549-1610. https://doi.org/10.4054/DemRes.2017.37.48.

GRANT, M. J. (2015). The Demographic Promise of Expanded Female Education: Trends in the Age at First Birth in Malawi. *Population and Development Review* **41** 409-438. https://doi.org/10.1111/j.1728-4457.2015.00066.x.

HERZER, D., STRULIK, H. and VOLLMER, S. (2012). The Long-Run Determinants of Fertility: One Century of Demographic Change 1900âĂŞ1999. *Journal of Economic Growth* **17** 357-385. https://doi.org/10.1007/s10887-012-9085-6.

HIRSCHMAN, C. (1994). Why Fertility Changes. *Annual Review of Sociology* **20** 203-233. https://doi.org/10.1146/annurev.so.20.080194.001223.

KANEDA, T., FALK, M. and PATIERNO, K. (2021). Understanding and Comparing Population Projections in sub-Saharan Africa. https://www.prb.org/resources/understanding-and-comparing-population-projections-in-sub-saharan-africa/. Accessed: 2021-07-23.

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.

LEE, R. and MASON, A. (2006). What Is the Demographic Dividend? *Finance and Development* **43** 16-24.

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

LUTZ, W., BUTZ, W. P. and KC, S., eds. (2014). *World Population and Human Capital in the Twenty-First Century*. Oxford University Press, Oxford.

LUTZ, W., GOUJON, A., KC, S., STONAWSKI, M. and STILIANAKIS, N., eds. (2018). *Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries*. Publications Office of the European Union, Luxembourg.

MAATHUIS, M. H. and COLOMBO, D. (2015). A Generalized Back-Door Criterion. *The Annals of Statistics* **43** 1060-1088. https://doi.org/10.1214/14-AOS1295.

MADDISON PROJECT DATABASE, VERSION 2018. BOLT, JUTTA AND INKLAAR, ROBERT AND DE JONG, HERMAN AND VAN ZANDEN, JAN LUITEN (2018). Rebasing 'Maddison': new income comparisons and the shape of long-run economic development, Maddison Project Working paper 10.

MARTÍN, T. C. (1995). Women's Education and Fertility: Results from 26 Demographic and Health Surveys. *Studies in Family Planning* **26** 187-202. https://doi.org/10.2307/2137845.

MASON, A. and LEE, R. (2006). Reform and Support Systems for the Elderly in Developing Countries: Capturing the Second Demographic Dividend. *Genus* **LXII** 11-35. https://doi.org/10.2307/29789308.

PEARL, J. (1993). Comment: Graphical models, causality and intervention. *Statist. Sci.* **8** 266-269. https://doi.org/10.1214/ss/1177010894.

PRESTON, S. H., HEUVELINE, P. and GUILLOT, M., eds. (2001). *Demography: Measuring and Modeling Population Processes*. Blackwell Publishers, Oxford.

RAFTERY, A. E., ALKEMA, L. and GERLAND, P. (2014). Bayesian Population Projections for the United Nations. *Statistical Science* **29** 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.

ŠEVČÍKOVÁ, H., and RAFTERY, A. E. (2016). bayesPop: Probabilistic Population Projections. *Journal of Statistical Software* **75** 1–29. https://doi.org/10.18637/jss.v075.i05.

ŠEVČÍKOVÁ, H., ALKEMA, L. and RAFTERY, A. E. (2011). bayesTFR: An R Package for Probabilistic Projections of the Total Fertility Rate. *Journal of Statistical Software* **43** 1–29. https://www.jstatsoft.org/v43/i01/.

SOBOTKA, T., BEAUJOUAN, E. and VAN BAVEL, J. (2017). Introduction: education and fertility in low-fertility settings. *Vienna Yearbook of Population Research* **15** 1-16. https://doi.org/10.1553/populationyearbook2017s001.

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 (2019a). World Population Prospects: The 2019 Revision. Online edition.

UNITED NATIONS, DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, POPULATION DIVISION (2019b). World Population Prospects 2019: Methodology of the United Nations population estimates and projections.

VOLLSET, S. E., GOREN, E., YUAN, C.-W., CAO, J., SMITH, A. E., HSIAO, T., BISIGNANO, C., AZHAR, G. S., CASTRO, E., CHALEK, J., DOLGERT, A. J., FRANK, T., FUKUTAKI, K., HAY, S. I., LOZANA, R., MOKDAD, A. H., NANDAKUMAR, V., PIERCE, M., PLETCHER, M., ROBALIK, T., STEUBEN, K. M., WUNROW, H. Y., ZLAVOG, B. S. and MURRAY, C. J. L. (2020). Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *Lancet* **396** 1285-1306. https://doi.org/10.1016/S0140-6736(20)30677-2.

WILMOTH, J. (2019). Global population projections: A critical comparison of key methods and assumptions. https://www.un.org/en/development/desa/population/about/director/pdf/Wilmoth_APC_Nov2019_Script.pdf.

WITTGENSTEIN CENTRE FOR DEMOGRAPHY AND GLOBAL HUMAN CAPITAL (2018). Wittgenstein Centre Data Explorer Version 2.0. Available at: http://www.wittgensteincentre.org/dataexplorer.