Long-term benefits of curbing human population growth

Melinda A. Judge[1,2,*], Chitra Maharani Saraswati[1], Lewis J.Z. Weeda[3], Quique Bassat[4,5,6,7,8], Ndola Prata[9], Peter N. Le Souëf[1,3], Corey J. A. Bradshaw[10,11]

[1]Telethon Kids Institute, Perth, Western Australia
[2]School of Mathematics and Statistics, University of Western Australia, Western Australia
[3]School of Medicine, University of Western Australia, Western Australia
[4]ISGlobal, Hospital Clínic - Universitat de Barcelona, Barcelona, Spain
[5]Centro de Investigação em Saúde de Manhiça (CISM), Maputo, Mozambique
[6]ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain.
[7]Pediatrics Department, Hospital Sant Joan de Déu, Universitat de Barcelona, Esplugues, Barcelona, Spain
[8]CIBER de Epidemiología y Salud Pública, Instituto de Salud Carlos III
[9]The Bixby Center for Population, Health and Sustainability, School of Public Health, University of California, Berkeley, Berkeley, California, USA
[10]Global Ecology | *Partuyarta Ngadluku Wardli Kuu*, College of Science and Engineering, Flinders University, Adelaide, South Australia
[11]Australian Research Council Centre of Excellence for Australian Biodiversity and Heritage, EpicAustralia.org.au

[*]Corresponding author: MA Judge (e-mail: melindaajudge@gmail.com)

Abstract

The human population's continuing growth, coupled with the dual effects of demographic transition, living longer, and increasing individual consumption, are placing unbearable strain on Earth's finite resources. Rapid population growth and its consumption has had devastating consequences for biodiversity and natural ecosystems. Despite concern in high-income countries surrounding declining fertility rates, in reality, the world's population has steadily risen by around 80 million people per year, every year, since 1975. High-income countries also have vastly higher consumption and disproportionately contribute to poor environmental outcomes compared to low- and middle-income countries. But the rate of consumption increases with economic development, so it would be remiss to ignore high population growth in developing countries and its future impacts. While fertility rates are declining globally, nations in sub-Saharan Africa are currently growing the fastest and this region's fertility rate is reducing at a much slower pace, likely associated with slower declining rates of infant mortality. We provide an assessment of the realism of current world population projections from three global sources. Based on our analysis of projected national infant mortality and fertility rates, the most-plausible end-of-century population range lies between 9.3 billion and 14.8 billion. Smaller populations and lower growth rates are needed to reduce pressures on the planet and its ecosystems, as well as human health and standards of living that depend on a functioning biosphere. In particular, global ecological damage already created by developed countries is most harming those in developing countries, which will be magnified by continued rapid population growth in those regions, but can be minimised through a concerted focus on reducing child mortality.

Introduction

The current global growth of the human population is a historical anomaly, akin to the 'plague phase' of a boom-bust population cycle. Growth continues despite overall declines in total fertility, mostly due to population momentum and continued rapid growth in certain parts of the globe. We provide an overview of the past trends in fertility and population size, assess the realism of the most well-known population models and their assumptions used to project future growth, and provide evidence regarding the most feasible, efficient, and ethically responsible means to promote strategies that lower population growth and size over the coming century. We discuss the relative contributions of lowering infant mortality, population density, and access to quality and voluntary family planning as the most beneficial and acceptable methods for achieving stable populations. We also discuss the corollary benefits to human society of achieving stable populations over the coming century.

Benefits of lower populations

Since Thomas Robert Malthus first discussed the implications of rapid human population growth in 1798[1], there has been much controversy on the topic[2,3]. Malthus discussed the limitations of the natural world to support an expanding human population, and was an advocate of population reduction, largely through abstinence and late marriage. The *neo-Malthusian movement* was coined in 1877 by Samuel Van Houten, which followed Malthus' framework, but advocated the use of contraception. His advocacy did not pass without controversy. Despite the simple mathematical and ecological ideas embedded within these concepts, some nefarious advocates have attempted to use them to promote discriminatory policies[4].

The continuing growth of the human population, along with demographic transition leading to longer lifespans, plus increasing individual consumption of the Earth's finite resources[5], have together devastated biodiversity and the ecosystem services it provides[6]. As human population size increases, so too does total consumption. Consumption in high-income nations is disproportionately higher than in lower- and middle-income nations, and increasing development inevitably increases consumption in high-population countries[7-9]. Consumption rather than overpopulation is often touted as the main driver of ecological damage; however, an analysis of ecological-footprint data instead demonstrates that population growth is the larger contributor [10].

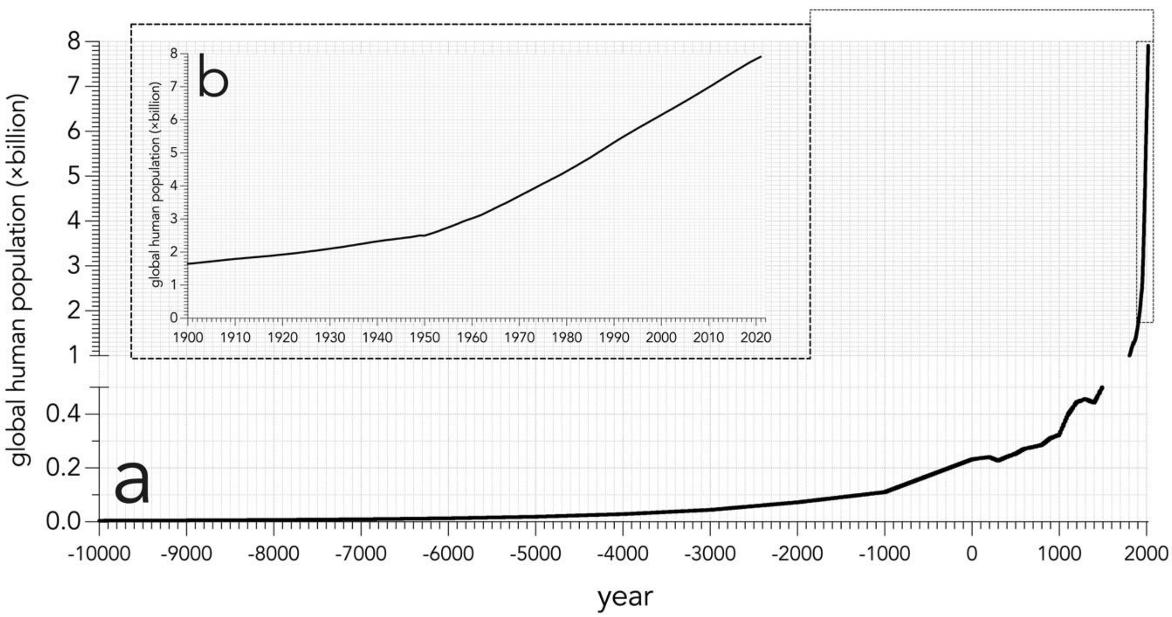
Newer economic theories propose that instead of accepting the existing economic model of never-ending, unchecked growth that would inevitably bring about environmental collapse, societies should consider growth and consumption within 'planetary boundaries' where development occurs in tandem with respecting the planet, ensuring a "safe and just space for all"[9,11,12]. Smaller populations and lower growth rates are generally beneficial to human health and standards of living [13]. Rapid population growth increases the rate of urbanisation and the associated negative living conditions[14-17]. High-density societies have lower access to water when scarce[18], and larger populations contribute more emissions that exacerbates the rate of climate disruption [10]. Given the choice, many people elect to have smaller families for many different reasons, including greater allocation of resources per person [19]. As stated in the 1969 United Nations General Assembly Resolution 2542(XXIV), "Parents have the exclusive right to determine freely and responsibly the number and spacing of their children"[20].

Rapid numerical dominance of *Homo sapiens*

As of 15 November 2022, the global human population was estimated at eight billion. It took almost 12,000 years for the world's population to increase from 4 million to 600 million people, but in only 320 years the total population has skyrocketed from 600 million to 8 billion. Since 1975, the global population has increased by a billion approximately every 12 years[21]. To put this in context, the world's population in 1950 was around 2.6 billion, grew to 5 billion by 1987, 6 billion by 1999, 7 billion by 2011, and reached 8 billion in 2022.

Despite reassurances from the United Nations that the rate of increase of the human population is slowing, this is only true if one standardises it as a per-capita value of the existing population. In fact, the annual increase in the number of additional humans on Earth has remained largely unchanged at around 83 million for the last five decades[22] (Fig. 1).

Figure 1: (a) Trajectory of the global population from 12,000 years ago to 2022 [22]. Inset (b) shows the same trajectory from 1900 to 2022.



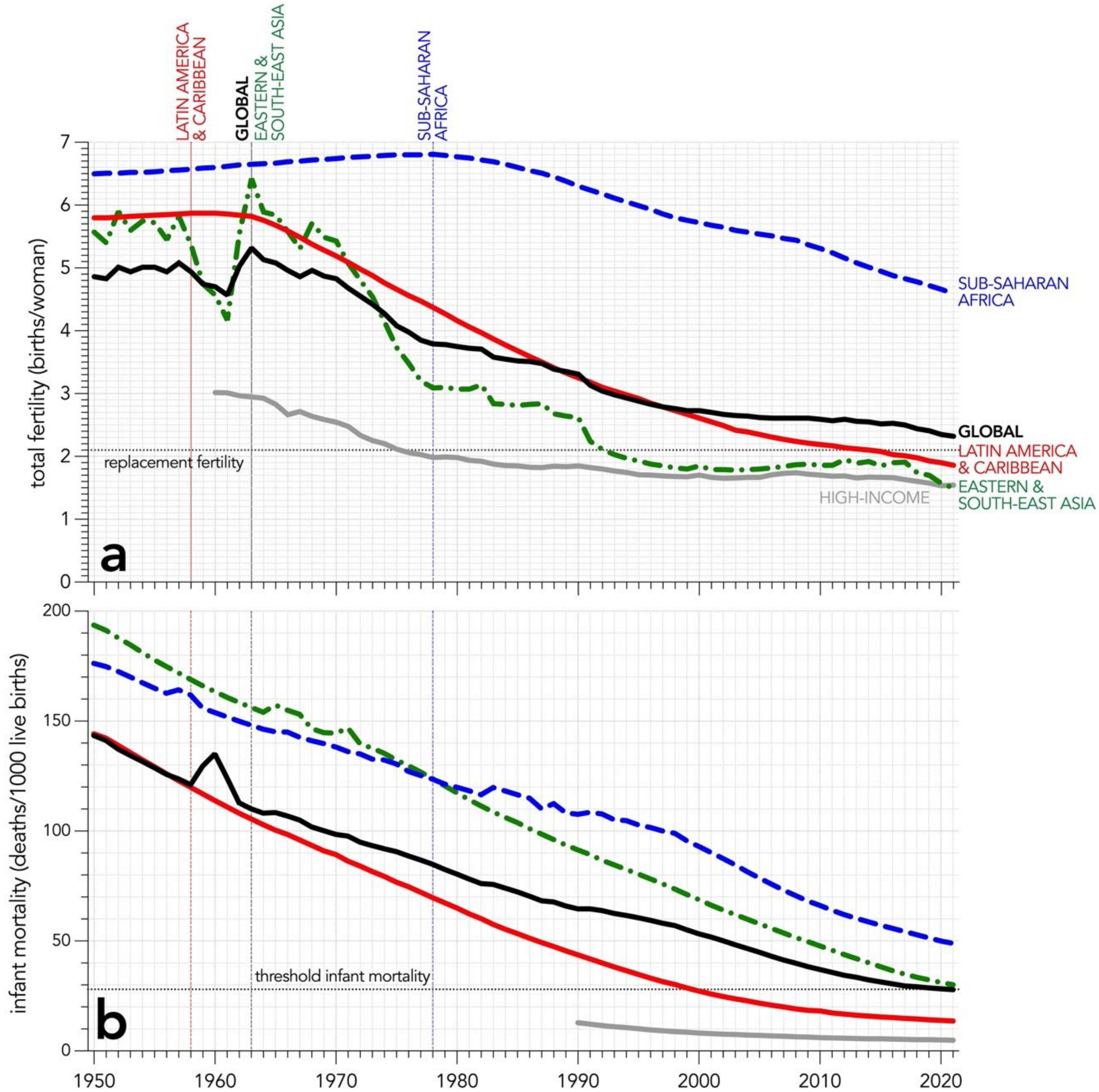
Sub-Saharan Africa currently has the fastest growing population globally. In 2017, only one African country (Nigeria) was among the ten most-populous countries in the world (ranked seventh). However, Nigeria is projected to have the second-largest population in the world by 2100, with other African nations such as Democratic Republic of Congo likely moving from 18th to the sixth position, Ethiopia from 13th to ninth, and Tanzania from 24th to tenth[22,23]. Similarly, in 2023 only two cities (Lagos and Kinshasa) in sub-Saharan Africa rank among the top 20 most populous cities (13th and 14th, respectively), while by 2100 it is projected that 12 of the most populous cities will reside in the region (Lagos: first, Kinshasa: second, Dar es Salaam: third, Khartoum: sixth, Niamey: seventh, Nairobi 12th, Lilongwe 13th, Blantyre 14th, Kampala 16th, Lusaka 18th, Mogadishu 19th, Addis Ababa 20th)[24]. Not only is the human population rising at the country scale, rapid population expansion in cities can have many negative consequences for human health[14-16].

Although fertility rates in developed countries are generally near the replacement value of 2.1 children per woman[25] (Fig. 2), population growth continues due to immigration. Among the 20 countries with the highest Human Development Index in 2023[26], 16 continued to show positive growth in 2021 despite the effects of the COVID-19 pandemic[27]. The low fertility rates in developed countries are often cited as positive indicators of the influence of climate change[28], but this can only contribute to reducing consumption if populations in these countries are allowed to decline.

Fertility trajectories

While total fertility globally has been declining from 5.32 births per woman in 1963 to 2.32 in 2021 (Fig. 2), regional differences in the trajectory are striking, and highly correlated with child mortality (more so than with either access to contraception, access to quality family planning services, or female education)[29]. The highest fertilities are in sub-Saharan Africa, having peaked in 1978 from a high of 6.81 births per woman and then declining slowly to 4.59 by 2021 (Fig. 2). The slow fertility decline in sub-Saharan Africa differs markedly from the declines observed in other parts of the developing world — fertility declined in southern and South-East Asia from a high of 6.42 births per woman in 1963 to a low of 1.50 in 2021 (Fig. 2). Similarly, fertility declined in Latin America and the Caribbean from a high of 5.87 in 1958 to 1.86 in 2021 (Fig. 2). Global fertility is predicted to decline to 2.1 by 2050[30].

Figure 2. Global and regional trends in (a) total fertility rate and (b) infant mortality rate (deaths per 1000 live births)[31]. Blue dashed line: sub-Saharan Africa; green dashed-dotted line: southern and South-East Asia; red line: Latin America and the Caribbean; black line: global. Vertical lines indicate peak fertility years for each region (both global and eastern/South-East Asia peaked in 1963). Horizontal dotted line in (a) indicates the generally accepted definition of 'replacement fertility' of 2.1 children per woman (fertility below which population declines)[25], and horizontal dotted line in (b) indicates threshold infant mortality below which human fertility declines precipitously[29].



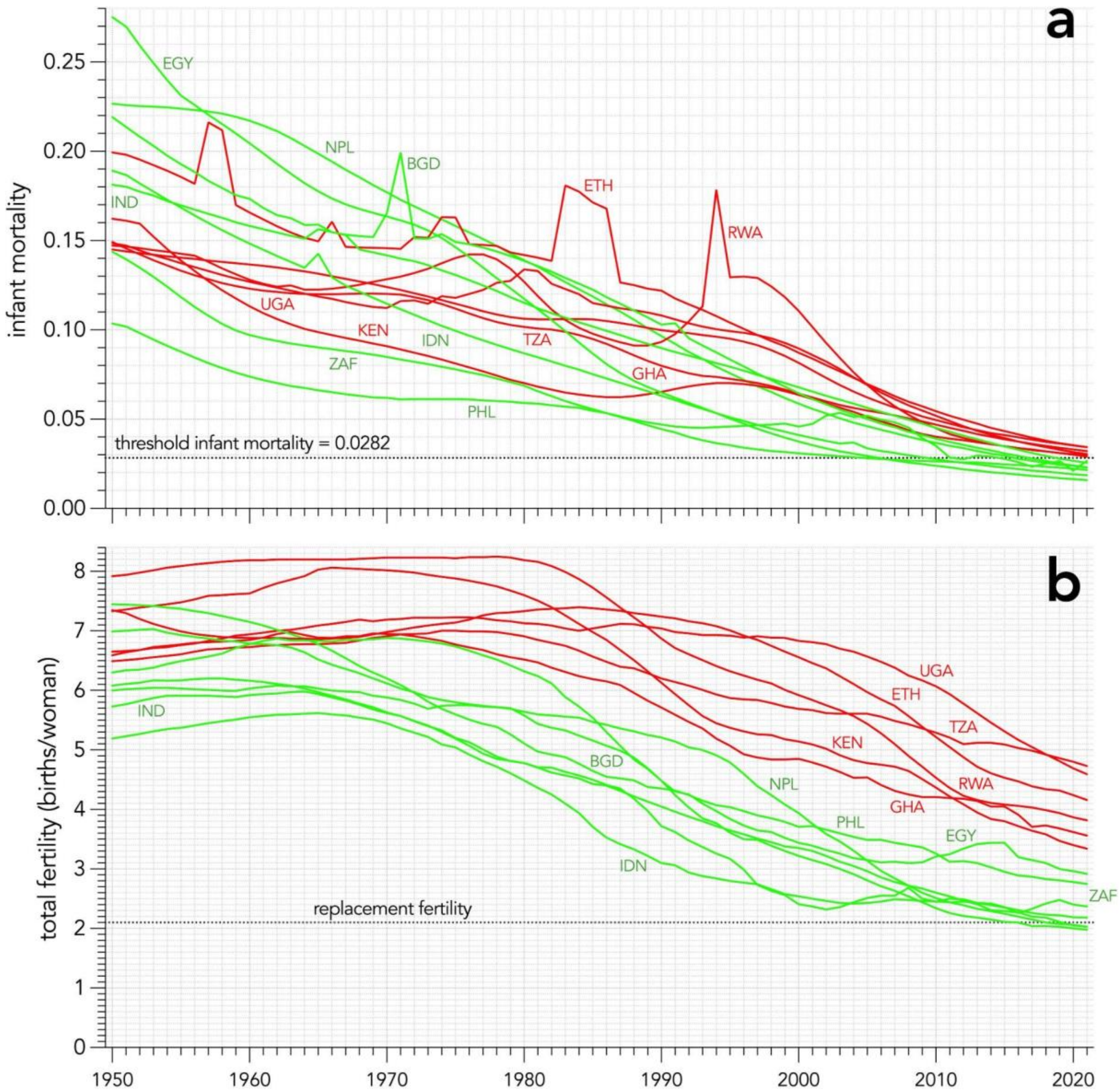
Despite these downward trends in fertility, the 2021 estimates by the United Nations Population Division predict continued global population growth to 2100, reaching 10.88 billion people and no definitive peak this century[31]. However, the latest data predict a world population likely to peak at 10.43 billion in 2086, with a slight decline to 10.36 by 2100[30].

Unsurprisingly given its high total fertility today, the largest population growth is occurring in sub-Saharan Africa, with a projected doubling of the total population of 1.138 billion today to 2.264 billion by 2050. In contrast, the populations of 61 countries predominantly in Europe are projected to decrease by 2050[30]. Some of the main reasons why the global population size is anticipated to rise this century despite reductions in fertility include the decline in child mortality in developing nations coupled with increases in life expectancy. International migration is the smallest contributor to a country's population size (but in many high-income nations, international immigration is the main driver of population growth)[32]; however, there are some countries where immigration and emigration as a result of economic strife and warfare have abruptly altered population trajectories (e.g., Ireland, Rwanda, Ethiopia)[33,34].

Plausibility of achieving additional fertility reduction

To assess the feasibility of fertility continuing to decline within the next few decades, we first examined the trajectory of total fertility and infant mortality from 1950 to the present for a sample of representative countries. To derive this sample of countries, we first examined the countries clustered around the threshold of infant mortality (28.2/1000 live births = 0.0282) below which total fertility drops precipitously[29] (Supplementary Information Fig. A1). Of those countries, we chose the most populous countries either side of the infant mortality threshold: seven countries with current infant mortality < 0.0282 (India, Indonesia, Bangladesh, Philippines, Egypt, South Africa, Nepal), and six countries with current infant mortality > 0.0282 (Ethiopia, Tanzania, Kenya, Uganda, Rwanda, Ghana) (Fig. 3). These countries today have a combined population of 2.5 billion people (~ one-third of the global population).

Figure 3. Trajectories of (a) total fertility and (b) infant mortality for seven countries with current infant mortality < 0.0282 (in green: IND = India, IDN = Indonesia, BGD = Bangladesh, PHL = Philippines, EGY = Egypt, ZAF = South Africa, NPL = Nepal) and six countries with current infant mortality > 0.0282 (in red: ETH = Ethiopia, TZA = Tanzania, KEN = Kenya, UGA = Uganda, RWA = Rwanda, GHA = Ghana). Threshold infant mortality of 0.0282 derived from [29]: point above which total fertility rises precipitously (increases by 1.5 times on average). Replacement fertility (2.1 births/woman) generally considered the fertility below which human populations decline[25].



Examining the trajectories of infant mortality in those countries already with child mortality < 0.0282, compared to those still > 0.0282, we determined that the latter would require an additional 13 ± 7 years to cross the threshold, assuming they behave in a similar manner on average to those in the < 0.0282 infant-mortality category (see also Supplementary Information Fig. A2). If we then assume that upon achieving this threshold that the six countries in the > 0.0282 category will experience reductions in fertility of approximately 32% (1 - 1/1.5), their average fertility would still be 2.75 (± 0.4) births per woman, compared to the current average fertility in the seven below-threshold countries (2.32 ± 0.4).

Extending this logic to the remainder of the world's countries contributing to global population growth, an optimistic view is that we are several decades or more away from achieving fertilities approaching population stability. Of note, however, is the slower rate of fertility decline in sub-Saharan Africa (Fig. 2) compared to other developing regions, and that all six countries in the > 0.0282 infant mortality category are in this region. Even the relationship between fertility and infant mortality differs between the two categories of countries — while the slopes are similar, there is a much higher fertility per unit infant mortality in the six African nations currently above the 0.0282 threshold (Supplementary Information Fig. A1). This further extends the plausible timeline of fertility reduction in most of sub-Saharan Africa, equating to a total African population of 3.9–5.4 billion by 2100 predicted for the United Nations medium- to high-fertility scenarios (see next section).

Uncertainty and realism of population projections

Accurate population projections are necessary for national planning policies that shape human societies, including the provision of healthcare, housing, infrastructure, childcare, and schooling. There are obvious difficulties in developing population projections given the range of required assumptions, but many different analytical approaches have been developed to deal with these uncertainties. There are also many different approaches to modelling population trajectories, hence the diversity of existing predictions. However, none of these models includes any negative feedbacks arising from environmental degradation.

The main projection models are those produced by the United Nations Population Division[31], the International Institute for Applied Systems Analysis and the European Commission's Joint Research Centre (IIASA-JRC)[35,36], and the Institute for Health Metrics and Evaluation (IHME)[28,37]. Fundamentally, all three approaches calculate the current population and model the following three main components dictating population change over time: (*i*) *fertility*, (*ii*) *mortality*, and (*iii*) *international migration*. The differences among models are mainly in the assumptions regarding how these three components themselves might change in response to expected economic development and the demographic changes these could precipitate (see below and Supplementary Information Tables 1 and 2).

United Nations Population Division

The projections from the United Nations Population Division are based on a cohort-component method, where existing population dynamics for each country are constructed and projected independently to provide an aggregate estimate to 2101[38]. Ten projection variants are generated based on different assumptions of future fertility, mortality, and migration, resulting in population projections by 2101 ranging from 7.1 billion to 12.4 billion people[30].

The 2022 revision of the Population Division's methodology[38] aimed to refine the estimates by moving from five-year age groups and projection intervals to single-year groups and intervals. They also implemented several additional enhancements to improve compilation of country-level demographic data as well as a range of techniques to refine aspects of the underlying demographic model[38]. Overall, the approach appears to be justified in terms of the probabilistic models used to account for missing data and under-sampled regions, 'crisis' mortality events, and the impacts of HIV/AIDS and COVID.

While the mechanics of the model appear robust, the assumptions underlying the variant projections must be judged in terms of both historical data and the likelihood of certain socio-economic and political futures. Fertility projections are country-specific and are assumed to follow the predictions arising from demographic transition theory where countries are categorised according to their position within one of three phases: *phase I*: high fertility prior to a decline; *phase II*: rapid decline in fertility; and *phase III*: low fertility. While theoretically attractive, the clear categorisation of a country into any particular phase is complicated by high variance in historical trajectories of fertility change among countries (see Fig. 3 for examples), and markedly different patterns among broad-scale regions (Fig. 2). Additional model modifications include projected patterns in the distribution of age-specific fertilities.

There are five fertility scenarios based on deviation from the (*i*) medium-fertility scenario within the main model; the four other scenarios assume (*ii*) high fertility (0.5 births/woman above the fertility in the medium scenario over the entire projection period except for the initial years), (*iii*) low fertility (fertility remains 0.5 births/woman below the fertility in the medium scenario over most of the projection interval), (*iv*) constant fertility (2022 fertility per country without change thereafter), and (*v*) instant replacement (fertility set to replacement level per country as of 2022). Complementing these five fertility scenarios are another five where mortality and migration assumptions are modified relative to the medium scenario: (*vi*) constant mortality, (*vii*) zero migration (no net international migration), (*viii*) instant replacement zero migration (replacement fertility and no net international migration), (*ix*) momentum (different treatment of mortality assumptions compared to scenario *xiii*), and (*x*) no change (constant fertility and mortality).

Many of the projection variants are only intended to compare the effect of parameter variation or isolation relative to the medium scenario (i.e., akin to a parameter sensitivity analysis), and so can be discarded as unrealistic projections — these include all instant-replacement, constant-fertility, constant-mortality, and zero-migration scenarios (scenarios 4–10). The three remaining scenarios (1–3) can be ranked relative to the analysis in the previous section. Given the likelihood that several decades will pass prior to many high-fertility countries passing the infant-mortality threshold where fertility drops precipitously, and the anomalous fertility trajectory in sub-Saharan Africa relative to Asia and Latin America, we can also discard the low-fertility scenario because it has little support historically and with respect to probable near-future trends in fertility. The medium and high-fertility scenarios are therefore the most realistic (predicting 10.4 to 14.8 billion by 2100, respectively).

International Institute for Applied Systems Analysis-European Commission Joint Research Centre (IIASA-JRC)

The IIASA-JRC projections take into account educational attainment, in addition to age and sex structures, to project populations in three scenarios based on shared socioeconomic pathways derived from both expert opinion and statistical modelling[36,39,40]. The *Medium* scenario forecasts a medium pathway for fertility and mortality rates, generally viewed as the most likely from today's perspective[41]. The *Rapid Social Development* scenario assumes rapid increases in life expectancy, a faster decline of fertility rates in currently high-fertility countries than data otherwise suggest, and a fulfilment of the education goals in the United Nations' Sustainable Development Goals. The *Stalled Social Development* scenario assumes a stall in education attainment within developing countries and continued high fertility and mortality. The 2018 *Medium* projection predicts a global population of 9.8 billion achieved between 2070 and 2080 before slowly declining to 9.3 billion people by 2100. In the *Rapid Social Development* scenario, a peak population of 8.9 billion is projected for 2055–2060 before declining to 7.8 billion by 2100. Assuming the *Stalled Social Development* conditions, the world population is forecasted to be 10 billion people in 2045, with a continued growth to 13.6 billion by 2100.

The available fertility trajectories described above suggest that the *Rapid Social Development* scenario is unrealistic. That scenario also depends entirely on the prospect of meeting Sustainable Development Goals, when in fact, there is evidence to suggest that the world is making limited progress on achieving them by 2030 or even beyond given the current set of policy priorities[42]. Many of the barriers to achieving the relevant goals are structural development challenges like poor governance and conflict, making attainment of better child health, survival, nutrition, and fertility outcomes difficult[42]. Furthermore, increasing populations will only exacerbate these existing barriers. Without major policy interventions currently not in effect, many Sustainable Development Goals will not be achieved[42].

Institute for Health Metrics and Evaluation (IHME)

These projections rely on a method known as ‘completed cohort fertility at age 50’, which is defined as the average number of children born to a woman if she lives to the end of her reproductive life[28]. Using this approach has been criticised for producing large variation among models due to assumptions of future fertility, education, age structure, and other development indicators[42]. The reference scenario using this method projected a peak population of 9.73 billion by 2064, and a decline to 8.79 billion by 2100[28]. Alternate scenarios assuming Sustainable Development Goals targets for education and contraceptive needs are met, project a median population of 6.29 billion by 2100, or a reduction of 1.79 billion people compared to today.

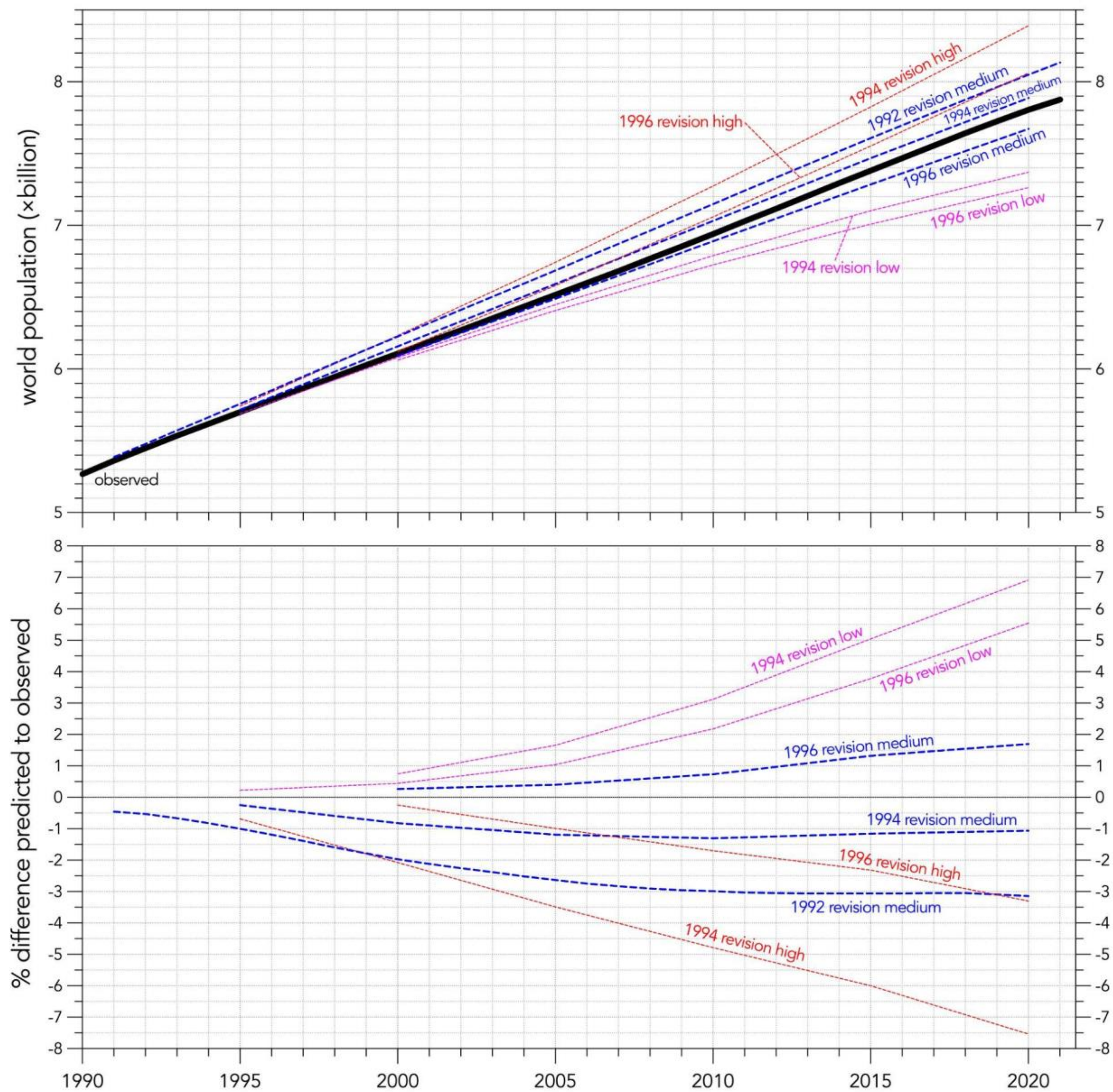
Of the three main projection sources described, the IHME’s projections appear the most out-of-step with the Population Division’s and IIASA-JRC’s projections, and the approach has been heavily critiqued for unrealistic assumptions[43]. This anomaly appears to stem from strong assumptions regarding the potential effects of income, family planning, and education on reductions in female fertility[28], as well as the plausibility of meeting United Nations’ Sustainable Development Goals. However, as we outline below, female education attainment and quality of family planning have some of the weakest influences on among-country variation in female fertility. Factors with the largest influences on fertility including infant mortality, household size and access to contraception[29] are not clearly defined by the IHME assumptions. Further, the probability of achieving relevant Sustainable Development Goals in the timeframes assumed in these models is low[43]. Large gaps remain in addressing the unmet need for family planning[44], with studies suggesting that more investments are needed to achieve the Sustainable

Development Goals[45,46]. A 2021 review of countries' attempts to improve education concludes that these government-led initiatives "show promise" but ultimately still have a long way to go[47].

Comparing past projections to observed population size

As an additional test to assess the plausibility of different future projections of the global human population, we accessed the United Nations revisions of population projections for 1992, 1994, and 1996, and compared the predictions to the observed global population sizes that eventuated (Fig. 4a). Here, the 1994 medium, 1996 medium, and the 1996 high projections best matched the observed global population size in terms of lowest absolute percentage differences (Fig. 4b). We also present additional data from earlier population projections in Supplementary Information Fig. A3.

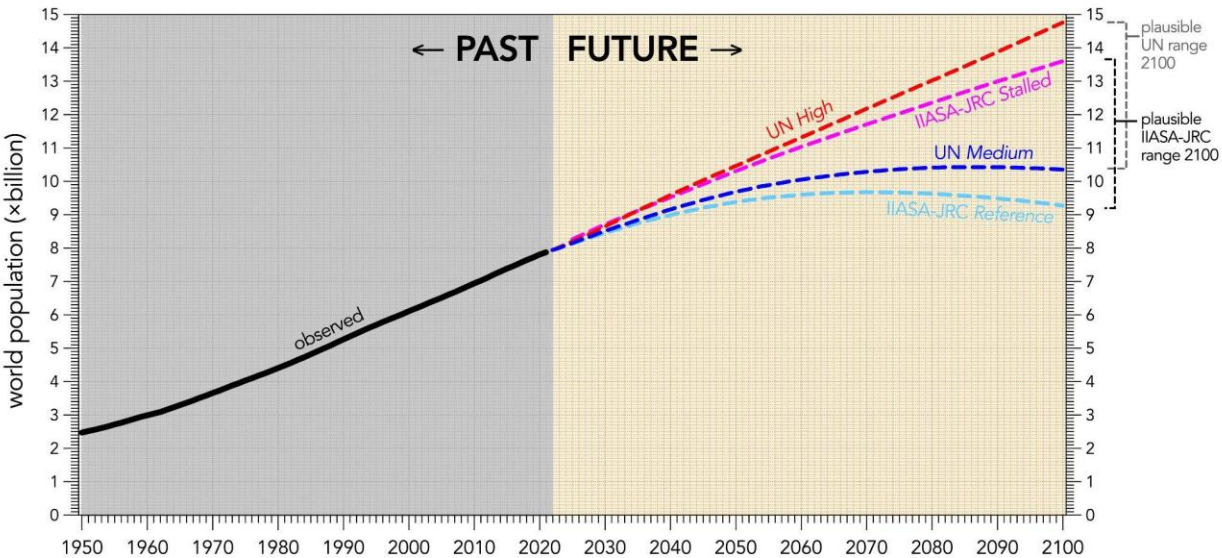
Figure 4. Top panel: comparison of the revisions of the 1992, 1994, and 1996 United Nations global population projections (medium, low, and high) to the observed trajectory. Lower panel: percentage difference between each historical projection and the observed global population[48-51].



Likeliest estimated population estimates for 2100

Based on our evaluations of fertility and infant-mortality trajectories, the most-plausible end-of-century population range lies between 9.3 billion and 14.8 billion (Fig. 5), which is the range bounded by the IIASA-JRC *Reference* projection, and the United Nations *High* projections (Fig. 5). This range ignores the implausible IHME projections, and is partially predicated on the observation that the historical United Nations projections best matched the Medium and High projections (Fig. 4).

Figure 5. Past trajectory and future projections of the global human population from the most-plausible models of the United Nations (UN) and IIASA-JRC. Shown are the *Medium* and *High* scenarios from the UN, and the *Reference* and *Stalled* scenarios from the IIASA-JRC (see scenario descriptions in the main text)[31,36].



Ranking approaches to achieve lower populations

There are many potential policy measures and actions available to 'bend down' projected population growth and limit damage to the biosphere. These include (*i*) increasing the access and availability to quality voluntary family-planning services, (*ii*) improving access to healthcare, and (*iii*) female education and empowerment. However, these actions are not all equal. While there is evidence that female education and reproductive health might lower fertility and hence reduce world population growth[52], our 2023 among-country analysis instead demonstrates that the strongest correlate of national-scale fertility is in fact infant mortality[29], with lower infant mortality leading to lower female fertility. However, the relationship is not entirely linear. Instead, there is a precipitous decline in national-level total fertility when infant mortality drops below approximately 0.0282. Other determinants such as lower household size (as a proxy for population density), greater access to any form of contraception, and higher quality of family-planning services available contribute to lower national-level total fertility, but much less so than reductions in child mortality[29]. Below we explore the associations between infant mortality rate and fertility rate across different countries.

Improving long-term child health outcomes

Achieving lower infant mortality rates (i.e., better child health) is a global priority, addressed by target 3.2 of the United Nations' Sustainable Development Goals. However, few studies have quantified which actions make the most difference to better child health outcomes. Our previous study focusing on African nations correlated various socio-economic indicators with child health outcomes at the national level, and we found that greater per-capita wealth (gross domestic product), better water quality, improved sanitation, lower household size (as a proxy for population density), higher environmental performance, and better air quality (in that descending order) made the largest improvements to long-term child health outcomes[53].

Given that infant mortality is the most important correlate of among-country fertility[29], it follows that strategies to reduce infant mortality should be prioritised if the target is also to reduce fertility. Undernutrition underlies approximately 45% of deaths (3.1 million annually) among children under five years of age worldwide[54,55]. Not only does undernutrition during childhood result in acute pathologies such as stunting, wasting, and vulnerability to infectious diseases[56], it also has lifelong consequences including impaired cognition, increased metabolic and cardiovascular disease and lower birthweight offspring for women, which subsequently affect future generations[57]. Delayed childhood developmental is associated with malnourishment, exacerbated by poor maternal education and more children under 5 years of age within the family unit[58,59]. A disproportionate burden of disease is experienced in low- and middle-income countries, particularly in Africa and South-East Asia[60]. Childhood pneumonia is strongly linked to undernutrition and is therefore largely a disease of lower- and middle-income countries[60,61]. Worldwide, the leading cause of child deaths beyond the neonatal period due to infectious diseases is pneumonia, with approximately 700,000 child deaths per year[62]. Possible solutions for reducing childhood mortality and morbidity from pneumonia provided by the United Nations Children's Fund (UNICEF) include breastfeeding exclusively, supplementary feeding to reduce malnutrition, vitamin A supplementation, improved access to immunisation and healthcare, and living in an environment with low exposure to infectious disease[62]. Malaria is the second leading cause of child death, with approximately 475,000 child deaths in 2021 alone, and while global malaria mortality is declining yearly, the proportion of under-five mortality has remained unchanged since 2015, at approximately 76.8%[63]. Additionally, in 2021 there were an estimated 13.3 million pregnancies exposed to malaria infection in Africa, which without intervention could have resulted in 961,000 children with low birthweight, a known risk factor for child mortality[63]. Thankfully, pregnancy-specific interventions averted an estimated 457,000 low-birthweight infants[63]. Expanded mosquito eradication programs and increased access to chemoprevention interventions, insecticide-treated bed nets and vaccination are required to lower malaria-related child deaths[63].

The many potential solutions to lowering child mortality suggest an application framework involving: (*i*) protective measures (e.g., reducing undernutrition), (*ii*) preventative measures (e.g., immunisation, access to clean water/improved sanitation/exclusive breastfeeding), and (*iii*) access to healthcare. Put simply, policies that approach child health with this holistic perspective, especially in low- and middle-income nations, will likely reduce childhood mortality and concomitantly alleviate the crisis of overpopulation by reducing fertility[64-67].

The causal pathways between improved child health outcomes and fewer births in a family are difficult to identify, but several studies have attempted an explanation[68-71]. Two proposed mechanisms linking high childhood mortality and high fertility rates for which there is some evidence[69,70,72-75] include 'child replacement', where parents who have experienced a child's death might decide to have an additional birth to 'replace' the deceased child, and 'child hoarding', where a family decides to have more births than the number of children they want in case of deaths. The latter is understandable in situations where infant mortality rates are high. Indeed, fertility is strongly affected by childhood mortality based on evidence from 118 developed and developing countries between 1960 and 2000, and a decline in mortality only results in a decline in fertility rates after a 10-year lag[68].

Access to modern family planning

Despite the lower relative impact on fertility of higher uptake of family-planning services compared to reducing infant mortality, the drive to make freely available, high-quality, non-coercive, and culturally and socially acceptable family-planning services will contribute to some extent, as well as providing many corollary benefits to families across the world[76]. However, the United Nations Sustainable Development Goal 3.7 (universal access to reproductive health services) is so far unachieved in many low- and middle-income nations[77].

Whether a country's total fertility is high or low does not indicate the accessibility of family planning therein. While many countries that have transitioned successfully from high to low fertility since the 1950s have had access to quality family planning, such as Costa Rica (fertility

= 6.3 in 1950 to 1.5 in 2021), Indonesia (5.2 to 2.2), Iran (7.0 to 1.7), and South Korea (6.0 to 0.9), many others have not. For example, Kenya is a country with a national network of quality family planning, yet still had a total fertility of 3.3 as of 2021 (albeit declining from 7.3 in 1950). Rwanda is another African nation with good family planning available, yet has a current total fertility of 3.8 (declining from 7.9 in 1950)[31].

While the availability and quality of family-planning services in many low- and middle-income nations is increasing[78], additional investment is required[77] to address remaining unmet needs[78]. Indeed, an additional US$4.80 per person per year is all that would be required to meet all women's sexual and reproductive health services in low- and middle-income nations[77]. For example, countries with < 20% mean demand for family planning satisfied with modern methods such as Albania, Azerbaijan, Benin, Chad, and the Democratic Republic of Congo, require more attention to provide services especially to young, poor, under-educated rural women[78,79]. A particular challenge is changing social norms inhibiting the uptake of contraception irrespective of adequate supply[79].

As of 2020, 218 million women of reproductive age who wanted to prevent pregnancy in low- and middle-income nations were unable to access modern contraception; put another way, a quarter of women who need modern contraception, most of them in low- and middle-income nations, are unable to access it[77]. Of these women, unmet need is disproportionately highest for adolescents (women aged 15–19) at 43%. If the unmet need for modern contraceptives was fulfilled, unintended pregnancies and unplanned births would both drop by two-thirds: unintended pregnancies would decline from 111 million to 35 million annually (68% decrease), and unplanned births would decline from 30 million to 9 million annually (71% decrease)[77]. Additional challenges are related to myths and misconceptions surrounding family planning, particularly related to the return of fertility after use of modern contraception methods[80,81].

Female educational attainment

Like the availability of quality family planning, female educational attainment is only a weak driver of variation in fertility among nations[29,82]. Regardless, better female education is a basic human right with outcomes of delayed marriage, improved autonomy, and providing women with more career and life choices[83,84], thereby improving lives and directly facilitating the pathway to meeting Sustainable Development Goals 4 (quality education), 5 (gender equality), and 10 (reduced inequalities). Educated women are less willing to forgo income and therefore choose fewer children, have healthier children and are healthier themselves, and are more informed on modern contraceptive methods[85].

Economics of populations — As of 2017, 72% of the world's population lived in countries classified as both low-income and in biocapacity deficit; i.e., they live in places where the population exceeds the biological capacity to provide for those people, and they cannot afford to acquire resources, including food [5]. It is therefore axiomatic that slowing human population growth will benefit individuals and their families, particularly those that are most vulnerable. A major mechanism of improvement will be via the slowing of climate change[86], as well as mitigating the extinction crisis underway[6] that will itself improve or maintain biocapacity. To achieve these aims, we are also obliged to reduce consumption globally[5,87] within an economic system that is essentially 'broken'[88]. Shrinking human populations will contribute to that goal, provided we simultaneously reduce per-capita consumption that is currently still growing [10].

The oft-touted 'crisis' of ageing populations[89-91] is founded on the erroneous notion that it will lead to economic catastrophes for the affected countries. Indeed, countries like South Korea and Japan have declining populations[31,92], others like Italy are stable and will be declining soon[92], and some countries like Australia are only growing because of net immigration[32]. The reason for exaggeration of a 'crisis' generally comes down to the overly simplistic 'dependency ratio'[93], which has several different forms but generally compares the number of people in the labour force against those who have retired from it. The idea here is that once the number of people no longer in the labour force exceeds the number of those in the labour force, the latter can no longer support the entirety of the former. This relationship essentially assumes that one working person is needed to support one retired person. But this is a flawed interpretation because a declining population also has a changing age structure, meaning that there are fewer young people (children), with which comes fewer societal expenses in many sectors (e.g., education, transport, housing, etc.). Once children are included, dependency ratios do not change as much as those including only adults[32,94].

The argument also assumes that an increasing proportion of retired people increases medical spending. But this is an oversimplification because people are today living longer and have more years of healthy life than they have ever before[93], and public healthcare is a self-sustaining concept given that support for healthy people in their younger years reduces the time spent unhealthy later. Dependency ratios also assume a static set of conditions between labourers and retirees. However, most people no longer retire at the age of 55 and cease any meaningful contribution to the economy. People are working much later in life, with flexible work arrangements, and are generally contributing to economies well into their retirement years. Assuming retirees are 'unproductive' also ignores unpaid volunteer work (a large, yet under-valued aspect of most economies)[95-97]. Economic models assuming fixed conditions therefore rely on an ageist concept that erroneously treats retirees as useless members of society.

Simplistic dependency ratios used to justify a looming demographic 'crisis' are also inherently xenophobic and racist. Because the Earth's human population will not soon reach a peak or decline (Fig. 5), there is a plentiful pool of able-bodied people of working age in most countries of the world. The problem of insufficient number of labourers in any one country is therefore based mostly on a distribution issue — limited or suffocating immigration policies (including welcoming and open refugee policies) could 'fix' any labour shortages anywhere with the right legal framework. There is ample evidence now that migrants provide net benefits to the receiving economies[98], not the other way around.

Conclusions

The developed world has for too long been consuming a disproportionately large amount of the Earth's resources and contributing a high amount of waste compared to developing countries. It is therefore unjust to sit in silence while developing countries grow in population size at the same time the planet has diminishing resources per capita and is undergoing degradation at unprecedented rates. The children of the future in low- and middle-income countries will ultimately be the ones that bear the burden of ecological overshoot — an unconscionable outcome. This is further highlighted by the fact that reducing child mortality now in low- and middle-income countries is the most effective way to reduce population growth organically in these nations.

While moving toward meeting Sustainable Development Goals can contribute to the entirely justifiable aim of lowering population growth[53], reducing infant mortality is the fastest and least-controversial way to achieve this outcome at the global scale. Increasing access to contraception is also an important means to reduce growth, whereas availability of modern family-planning services and improving female education are of course entirely worthy aims in their own right, but are less effective mechanisms for reducing fertility at the highest possible rate, and ultimately the growth rate and size of the world human population. Of course, implementing many strategies simultaneously will achieve faster and larger reductions in fertility than focussing all effort on single levers, but policy makers should be aware of the degree to which reductions can occur from any single policy change.

Acknowledgements

The authors are grateful for the funding provided by *Population Matters* to support this work.

References

1 Malthus, T. R. *et al. An Essay on the Principle of Population - The 1803 Edition*. (Yale University Press, 2018).

2 Shermer, M. Why Malthus is still wrong. *Scientific American* **314**, 72 (2016). https://doi.org:10.1038/scientificamerican0516-72

3 Mayhew, R. J. in *New Perspectives on Malthus* (Cambridge University Press, Cambridge, 2016).

4 Craffey, M. S.-H. *Maternal Health and the Relaxation of the One-Child Policy in China, 2004-2015* Honors thesis, Wesleyan University, (2018).

5 Wackernagel, M. *et al.* The importance of resource security for poverty eradication. *Nature Sustainability* **4**, 731-738 (2021). https://doi.org:10.1038/s41893-021-00708-4

6 Bradshaw, C. J. A. *et al.* Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science* **1**, 615419 (2021). https://doi.org:10.3389/fcosc.2020.615419

7 Engelman, R. Human Numbers and a Changing Climate: Reducing Emissions Through Cost-Effective Strategies. *Georgetown Journal of International Affairs* **15**, 10-16 (2014).

8 Ezeh, A. Family Planning: Human Capital and Population Growth. (2018).

9 O'Neill, D. W., Fanning, A. L., Lamb, W. F. & Steinberger, J. K. A good life for all within planetary boundaries. *Nature Sustainability* **1**, 88-95 (2018). https://doi.org:10.1038/s41893-018-0021-4

10 Rees, W. The human eco-predicament: Overshoot and the population conundrum. *Vienna Yearbook of Population Research* **21** (2023). https://doi.org:10.1553/p-eznb-ekgc

11 Raworth, K. A Safe and Just Space for Humanity: Can We Live Within the Doughnut? , (Oxfam, 2012).

12 Hickel, J. Is it possible to achieve a good life for all within planetary boundaries? *Third World Quarterly* **40**, 18-35 (2019). https://doi.org:10.1080/01436597.2018.1535895

13 Sinding, S. W. Population, poverty and economic development. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **364**, 3023-3030 (2009). https://doi.org:10.1098/rstb.2009.0145

14 Boyce, M. R., Katz, R. & Standley, C. J. Risk factors for infectious diseases in urban environments of Sub-Saharan Africa: a systematic review and critical appraisal of evidence. *Tropical Medicine and Infectious Disease* **4** (2019). https://doi.org:10.3390/tropicalmed4040123

15 Unwin, N. & Alberti, K. G. Chronic non-communicable diseases. *Annals of tropical medicine and parasitology* **100**, 455-464 (2006). https://doi.org:10.1179/136485906x97453

16 Eckert, S. & Kohler, S. Urbanization and health in developing countries: a systematic review. *World Health and Population* **15**, 7-20 (2014). https://doi.org:10.12927/whp.2014.23722

17 Fink, G., Gunther, I. & Hill, K. Slum residence and child health in developing countries. *Demography* **51**, 1175-1197 (2014). https://doi.org:10.1007/s13524-014-0302-0

18 Veldkamp, T. I. E., Wada, Y., Aerts, J. C. J. H. & Ward, P. J. Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability. *Environmental Research Letters* **11**, 024006 (2016). https://doi.org:10.1088/1748-9326/11/2/024006

19 Downey, D. B. When Bigger Is Not Better: Family Size, Parental Resources, and Children's Educational Performance. *American Sociological Review* **60**, 746-761 (1995). https://doi.org:10.2307/2096320

20 United Nations General Assembly. (1969).

21 Ritchie, H., Mathieu, E., Rodes-Guirao, L. & Gerber, M. Five key findings from the 2022 UN Population Prospects. (2022). <ourworldindata.org/world-population-update-2022>.

22 Roser, M., Ritchie, H., Ortiz-Ospina, E. & Rodés-Guirao, L. World Population Growth. *Our World in Data* (2013). <ourworldindata.org/world-population-growth>.

23 Ghosh, I. *The World Population in 2100, by Country*, <visualcapitalist.com/world-population-2100-country/> (2020).

24 Hoornweg, D. & Pope, K. Socioeconomic Pathways and Regional Distribution of the World's 101 Largest Cities. (2014).

25 Smallwood, S. & Chamberlain, J. Replacement fertility, what has it been and what does it mean? *Population Trends*, 16-27 (2005).

26 World Population Review. Developed countries 2023. (2023). <worldpopulationreview.com/country-rankings/developed-countries>.

27 The World Bank. Population Growth (annual %). (2022). <data.worldbank.org/indicator/SP.POP.GROW>.

28 Vollset, S. E. *et al.* 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. *The Lancet* **396**, 1285-1306 (2020). https://doi.org:10.1016/S0140-6736(20)30677-2

29 Bradshaw, C. J. A. *et al.* Lower infant mortality, lower household size, and more access to contraception reduce fertility in low- and middle-income nations. *PLoS One* **18**, e0280260 (2023). https://doi.org:10.1371/journal.pone.0280260

30 United Nations. World Population Prospects 2022: Summary of Results. Report No. UN DESA/POP/2022/TR/NO. 3, (New York, 2022).

31 United Nations. in *Department of Economic and Social Affairs Population Division* (2022).

32 Bradshaw, C. J. A. & Brook, B. W. Implications of Australia's population policy for future greenhouse gas emissions targets. *Asia and the Pacific Policy Studies* **3**, 249-265 (2016). https://doi.org:10.1002/app5.135

33 United Nations, P. D. *International Migrant Stock*, <un.org/development/desa/pd/content/international-migrant-stock> (2020).

34 Hasell, J. *Do famines curb population growth?*, <ourworldindata.org/do-famines-check-population-growth> (2018).

35 Lutz, W., Stilianakis, N., Stonawski, M., Goujon, A. & Samir, K. Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries. (European Commission-Joint Research Centre, 2018).

36 Wittgenstein Centre for Demography and Global Human Capital. *Wittgenstein Centre Human Capital Data Explorer Version 2.0*, <dataexplorer.wittgensteincentre.org/wcde-v2/> (2018).

37 Institute for Health Metrics and Evaluation. *Global Fertility, Mortality, Migration, and Population Forecasts 2017-2100*, <ghdx.healthdata.org/record/ihme-data/global-population-forecasts-2017-2100> (2020).

38 United Nations Department of Economic and Social Affairs Population Division. World Population Prospects 2022: Methodology of the United Nations population estimates and projections. (2022).

39 Lutz, W., Butz, W. P. & Samir, K. C. World Population and Human Capital in the Twenty-first Century: Executive Summary. (International Institute for Applied Systems Analysis, Laxenburg, Austria, 2014).

40 Samir, K. C. Updated demographic SSP4 and SSP5 scenarios complementing the SSP1-3 scenarios published in 2018. (Laxenburg, Austria, 2020).

41 Samir, K. C. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* **42**, 181-192 (2017). https://doi.org:10.1016/j.gloenvcha.2014.06.004

42 O'Sullivan, J. N. Trends in population health and demography. *The Lancet* **398**, 580 (2021). https://doi.org:10.1016/S0140-6736(21)01050-3

43 Moyer, J. D. & Hedden, S. Are we on the right path to achieve the sustainable development goals? *World Development* **127**, 104749 (2020). https://doi.org:https://doi.org/10.1016/j.worlddev.2019.104749

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

45 Alkema, L., Kantorova, V., Menozzi, C. & Biddlecom, A. National, regional, and global rates and trends in contraceptive prevalence and unmet need for family planning between 1990 and 2015: a systematic and comprehensive analysis. *The Lancet* **381**, 1642-1652 (2013). https://doi.org:10.1016/s0140-6736(12)62204-1

46 Cleland, J., Harbison, S. & Shah, I. H. Unmet Need for Contraception: Issues and Challenges. *Studies in Family Planning* **45**, 105-122 (2014). https://doi.org:10.1111/j.1728-4465.2014.00380.x

47 Beeharry, G. The pathway to progress on SDG 4 requires the global education architecture to focus on foundational learning and to hold ourselves accountable for achieving it. *International Journal of Educational Development* **82**, 102375 (2021). https://doi.org:https://doi.org/10.1016/j.ijedudev.2021.102375

48 Frejka, T. in *The Future Population of the World: What Can We Assume Today* (ed W. Lutz) 3-15 (International Institute of Applied Systems Analysis, 1994).

49 United Nations. World Population Prospects: the 1992 Revision. p. 677 (Department of Economic and Social Affairs, Population Division, New York, 1993).

50 United Nations. World Population Prospects: the 1994 Revision. 886 (Department of Economic and Social Affairs, Population Division, New York, 1995).

51 United Nations. World Population Prospects: the 1996 Revision. 839 (Department of Economic and Social Affairs, Population Division, New York, 1998).

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

53 Bradshaw, C. J. A. *et al.* Testing the socioeconomic and environmental determinants of better child-health outcomes in Africa: a cross-sectional study among nations. *BMJ Open* **9**, e029968 (2019). https://doi.org:10.1136/bmjopen-2019-029968

54 Black, R. E. *et al.* Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* **382**, 427-451 (2013). https://doi.org:10.1016/s0140-6736(13)60937-x

55 World Health Organisation. *Malnutrition*, <who.int/news-room/fact-sheets/detail/malnutrition> (2021).

56 Salam, R. A., Das, J. K. & Bhutta, Z. A. Current issues and priorities in childhood nutrition, growth, and infections. *Journal of Nutrition* **145**, 1116s-1122s (2015). https://doi.org:10.3945/jn.114.194720

57 Victora, C. G. *et al.* Maternal and child undernutrition: consequences for adult health and human capital. *The Lancet* **371**, 340-357 (2008). https://doi.org:10.1016/S0140-6736(07)61692-4

58 Oumer, A. *et al.* Stunting and underweight, but not wasting are associated with delay in child development in southwest Ethiopia. *Pediatric Health, Medicine and Therapeutics* **13**, 1-12 (2022). https://doi.org:10.2147/phmt.S344715

59 Saleem, J., Zakar, R., Mushtaq, F., Bukhari, G. M. J. & Fischer, F. Comparative analysis of developmental profile between normal and severe acute malnourished under-five children in Pakistan: a multicentre cross-sectional study. *BMJ Open* **11**, e048644 (2021). https://doi.org:10.1136/bmjopen-2021-048644

60 Walker, C. L. F. *et al.* Global burden of childhood pneumonia and diarrhoea. *The Lancet* **381**, 1405-1416 (2013).

61 Kaler, S. G. Diseases of poverty with high mortality in infants and children: malaria, measles, lower respiratory infections, and diarrheal illnesses. *Annals of the New York Academy of Sciences* **1136**, 28-31 (2008). https://doi.org:10.1196/annals.1425.035

62 UNICEF. *Childhood diseases*, <unicef.org/health/childhood-diseases> (2022).

63 World Health Organization. World Malaria Report 2022. Report No. CC BY-NC-SA 3.0 IGO, (Geneva, CC BY-NC-SA 3.0 IGO, 2022).

64 Angko, W., Arthur, E. & Yussif, H. M. Fertility among women in Ghana: Do child mortality and education matter? *Scientific African* **16**, e01142 (2022). https://doi.org:https://doi.org/10.1016/j.sciaf.2022.e01142

65 Raziq, A. *et al.* Forecasting fertility and child mortality rates of Pakistan using time series Model. *Linguistica Antverpiensia* **2**, 1194-1213 (2021).

66 Marco-Gracia, F. J. Adapting Family Size and Composition: Childhood Mortality and Fertility in Rural Spain, 1750–1949. *The Journal of Interdisciplinary History* **51**, 509-531 (2021). https://doi.org:10.1162/jinh_a_01626

67 Nannan, N. *et al.* Estimating the changing burden of disease attributable to childhood stunting, wasting and underweight in South Africa for 2000, 2006 and 2012. *South African Medical Journal* **112**, 676-683 (2022). https://doi.org:10.7196/SAMJ.2022.v112i8b.16497

68 Angeles, L. Demographic transitions: analyzing the effects of mortality on fertility. *Journal of Population Economics* **23**, 99-120 (2010). https://doi.org:10.1007/s00148-009-0255-6

69 Palloni, A. & Rafalimanana, H. The effects of infant mortality on fertility revisited: new evidence from latin america. *Demography* **36**, 41-58 (1999). https://doi.org:10.2307/2648133

70 Nerlove, M. Household and economy: toward a new theory of population and economic growth. *Journal of Political Economy* **82**, S200-S218 (1974). https://doi.org:10.1086/260301

71 Roser, M. Fertility Rate. *Our World in Data* (2014). <ourworldindata.org/fertility-rate>.

72 Reher, D. S., Sandström, G., Sanz-Gimeno, A. & van Poppel, F. W. A. Agency in Fertility Decisions in Western Europe During the Demographic Transition: A Comparative Perspective. *Demography* **54**, 3-22 (2017). https://doi.org:10.1007/s13524-016-0536-0

73 Kalemli-Ozcan, S. A stochastic model of mortality, fertility, and human capital investment. *Journal of Development Economics* **70**, 103-118 (2003). https://doi.org:https://doi.org/10.1016/S0304-3878(02)00089-5

74 Ben-Porath, Y. Fertility Response to Child Mortality: Micro Data from Israel. *Journal of Political Economy* **84**, S163-S178 (1976). https://doi.org:10.1086/260537

75 Sah, R. K. The Effects of Child Mortality Changes on Fertility Choice and Parental Welfare. *Journal of Political Economy* **99**, 582-606 (1991).

76 Prata, N. Making family planning accessible in resource-poor settings. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **364**, 3093-3099 (2009). https://doi.org:10.1098/rstb.2009.0172

77 Sully, E. A. *et al.* Adding It Up: Investing in Sexual and Reproductive Health 2019. (Guttmacher Institute, New York, 2020).

78 Hellwig, F., Coll, C. V. N., Ewerling, F. & Barros, A. J. D. Time trends in demand for family planning satisfied: analysis of 73 countries using national health surveys over a 24-year period. *Journal of Global Health* **9**, 020423 (2019). https://doi.org:10.7189/jogh.09.020423

79 Ewerling, F. *et al.* Demand for family planning satisfied with modern methods among sexually active women in low- and middle-income countries: who is lagging behind? *Reproductive health* **15**, 42 (2018). https://doi.org:10.1186/s12978-018-0483-x

80 Mwaisaka, J. *et al.* Exploring contraception myths and misconceptions among young men and women in Kwale County, Kenya. *BMC Public Health* **20**, 1694 (2020). https://doi.org:10.1186/s12889-020-09849-1

81 Jonas, K., Duby, Z., Maruping, K., Harries, J. & Mathews, C. Rumours, myths, and misperceptions as barriers to contraceptive use among adolescent girls and young women in South Africa. *Frontiers in Reproductive Health* **4** (2022). https://doi.org:10.3389/frph.2022.960089

82 Psaki, S. R., Chuang, E. K., Melnikas, A. J., Wilson, D. B. & Mensch, B. S. Causal effects of education on sexual and reproductive health in low and middle-income countries: A systematic review and meta-analysis. *SSM Population Health* **8**, 100386 (2019). https://doi.org:10.1016/j.ssmph.2019.100386

83 Namasivayam, A., Graves, A., Kwauk, C. & Frischmann, C. Drawdown's Health and Education Solution: the Cascading Benefits of Access to Universal Education and Voluntary Family Planning. 12 (2022).

84 Marphatia, A. A. *et al.* How Much Education Is Needed to Delay Women's Age at Marriage and First Pregnancy? *Frontiers in public health* **7**, 396 (2019). https://doi.org:10.3389/fpubh.2019.00396

85 Kim, J. Female education and its impact on fertility. *IZA World of Labor* **228** (2016). https://doi.org:10.15185/izawol.228

86 Intergovernmental Panel on Climate Change. Climate Change 2022: Impacts, Adaptation, and Vulnerability. 3056 pp (Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).

87 Wackernagel, M., Lin, D., Evans, M., Hanscom, L. & Raven, P. Defying the Footprint Oracle: Implications of Country Resource Trends. *Sustainability* **11**, 2164 (2019).

88 Dasgupta, P. The Economics of Biodiversity: The Dasgupta Review. (HM Treasury, London, 2021).

89 Population Matters. Which planet is he on? Elon Musk and the population apocalypse. 19 (London, UK, 2022).

90 Australian Financial Review. Australia's stalled population growth must be resumed. **December** (2021). <afr.com/politics/federal/australia-s-stalled-population-growth-must-be-resumed-20211220-p59iy9>.

91 Longman, P. The Global Baby Bust. *Foreign Affairs* **83**, 64-79 (2004). https://doi.org:10.2307/20033976

92 Our World in Data. *Population, including UN projections, 1950 to 2100 for US, Brazil, Japan, Italy and South Korea*, <ourworldindata.org/grapher/un-population-projection-medium-variant?country=BRA~USA~JPN~ITA~KOR> (2022).

93 Ritchie, H. & Roser, M. Age Structure. *Our World in Data* (2019). <ourworldindata.org/age-structure>.

94 Bradshaw, C. J. A. & Brook, B. W. Human population reduction is not a quick fix for environmental problems. *Proceedings of the National Academy of Sciences of the USA* **111**, 16610-16615 (2014). https://doi.org:10.1073/pnas.1410465111

95 Dunn, H. The economic value of volunteering. *Pro Bono Economics* (2017). <probonoeconomics.com/News/the-economic-value-of-volunteering>.

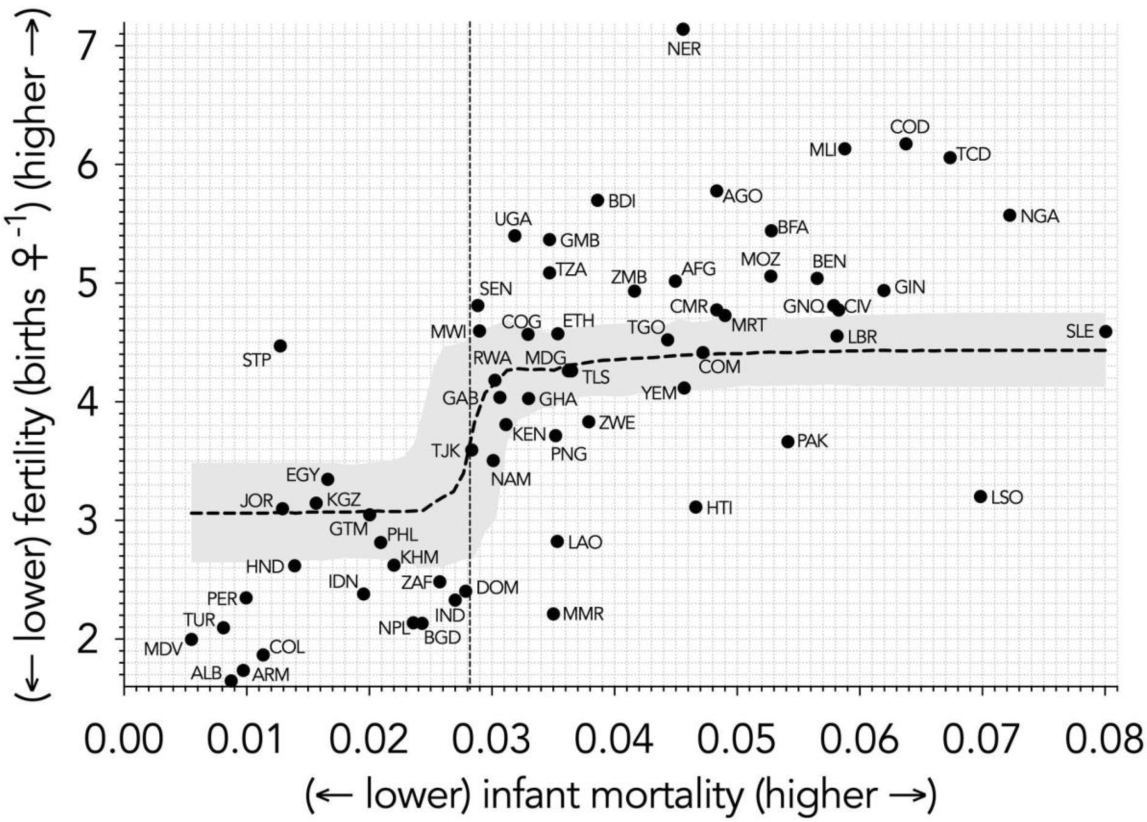
96 Ironmonger, D. The Economic Value of Volunteering in Queensland Updated Report. (Queensland Department of Communities, Brisbane, Australia, 2006).

97 Gottlieb, B. H. & Gillespie, A. A. Volunteerism, health, and civic engagement among older adults. *Can J Aging* **27**, 399-406 (2008). https://doi.org:10.3138/cja.27.4.399

98 Bahar, D. Why accepting refugees is a win-win-win formula. (2018). <brookings.edu/blog/up-front/2018/06/19/refugees-are-a-win-win-win-formula-for-economic-development/>.

Supplementary Information

Figure A1. Predicted fertility as a function of variation in infant mortality (raw data from 64 countries for which both variables were available superimposed onto boosted regression tree relationship). Once infant mortality has exceeded a threshold of approximately 0.0282 (28.2/1000 live births), fertility increases precipitously. Figure reproduced with permission from Bradshaw et al. (2023) (23).



Three-letter ISO country codes: AFG = Afghanistan, AGO = Angola, ALB = Albania, ARM = Armenia, BDI = Burundi, BEN = Benin, BFA = Burkina Faso, BGD = Bangladesh, CIV = Côte d'Ivoire, CMR = Cameroon, COD = Democratic Republic of Congo, COG = Congo, COL = Columbia, COM = Comoros, DOM = Dominican Republic, EGY = Egypt, ETH = Ethiopia, GAB = Gabon, GHA = Ghana, GIN = Guinea-Bissau, GMB = Gambia, GNQ = Equatorial Guinea, GTM = Guatemala, HND = Honduras, HTI = Haiti, IDN = Indonesia, IND = India, JOR = Jordan, KEN = Kenya, KGZ = Kyrgyzstan, KHM = Cambodia, LAO = Laos, LBR = Liberia, LSO = Lesotho, MDG = Madagascar, MDV = Maldives, MLI = Mali, MMR = Myanmar, MOZ = Mozambique, MRT = Mauritania, MWI = Malawi, NAM = Namibia, NER = Niger, NGA = Nigeria, NPL = Nepal, PAK = Pakistan, PER = Peru, PHL = Philippines, PNG = Papua New Guinea, RWA = Rwanda, SEN = Senegal, SLE = Sierra Leone, STP = Sao Tome and Principe, TCD = Chad, TGO = Togo, TJK = Tajikistan, TLS = Timor-Leste, TUR = Turkey, TZA = Tanzania, UGA = Uganda, YEM = Yemen, ZAF = South Africa, ZMB = Zambia, ZWE = Zimbabwe

Figure A2. Relationship between the natural logarithms of total fertility and infant mortality shown as time series per country. The overall correlation (ignoring country) between the two $\log_e$-transformed variables is shown by the black line (least-squares linear fit to the $\log_e$-transformed data). Also shown are the prediction intervals (shaded areas) for the six countries above the infant mortality threshold of 0.0282 (red) and the seven countries below the threshold (green: IND = India, IDN = Indonesia, BGD = Bangladesh, PHL = Philippines, EGY = Egypt, ZAF = South Africa, NPL = Nepal) and six countries with current infant mortality > 0.0282 (in red: ETH = Ethiopia, TZA = Tanzania, KEN = Kenya, UGA = Uganda, RWA = Rwanda, GHA = Ghana).

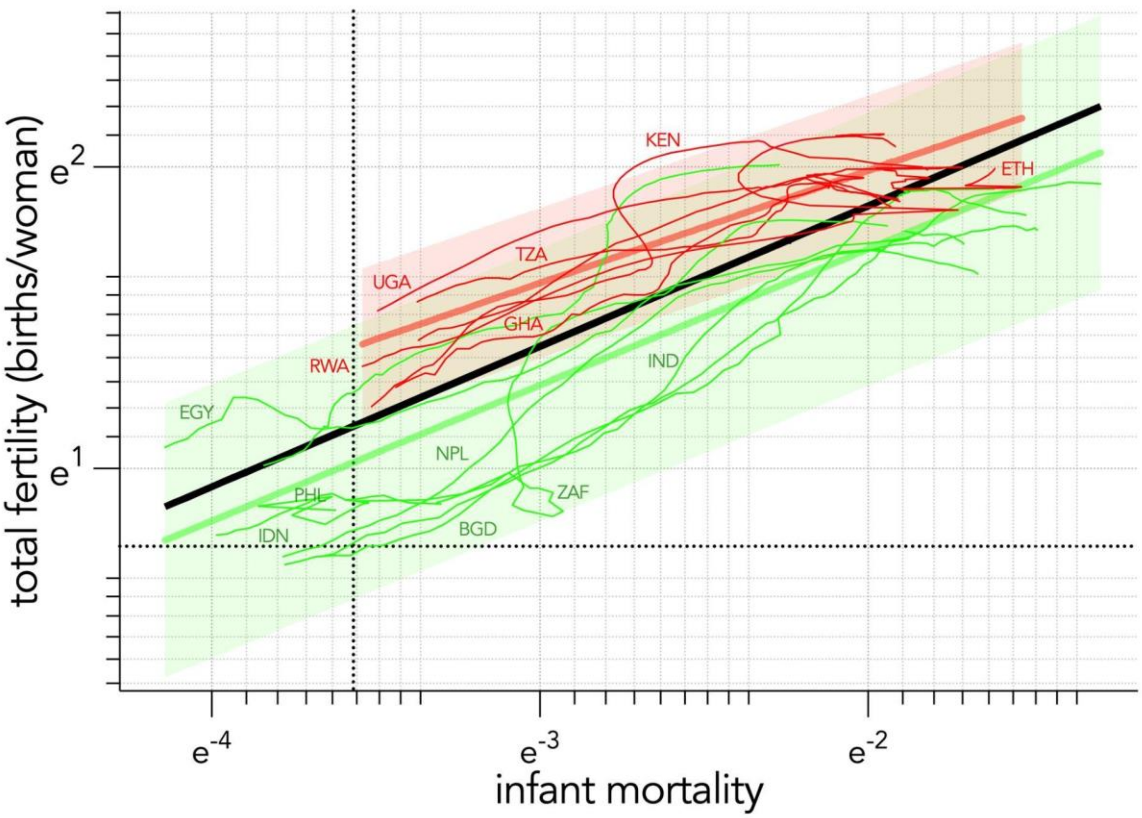


Figure A3. Additional historical global population projections to 2000 compared to the observed population. All citations and values provided in reference (38).

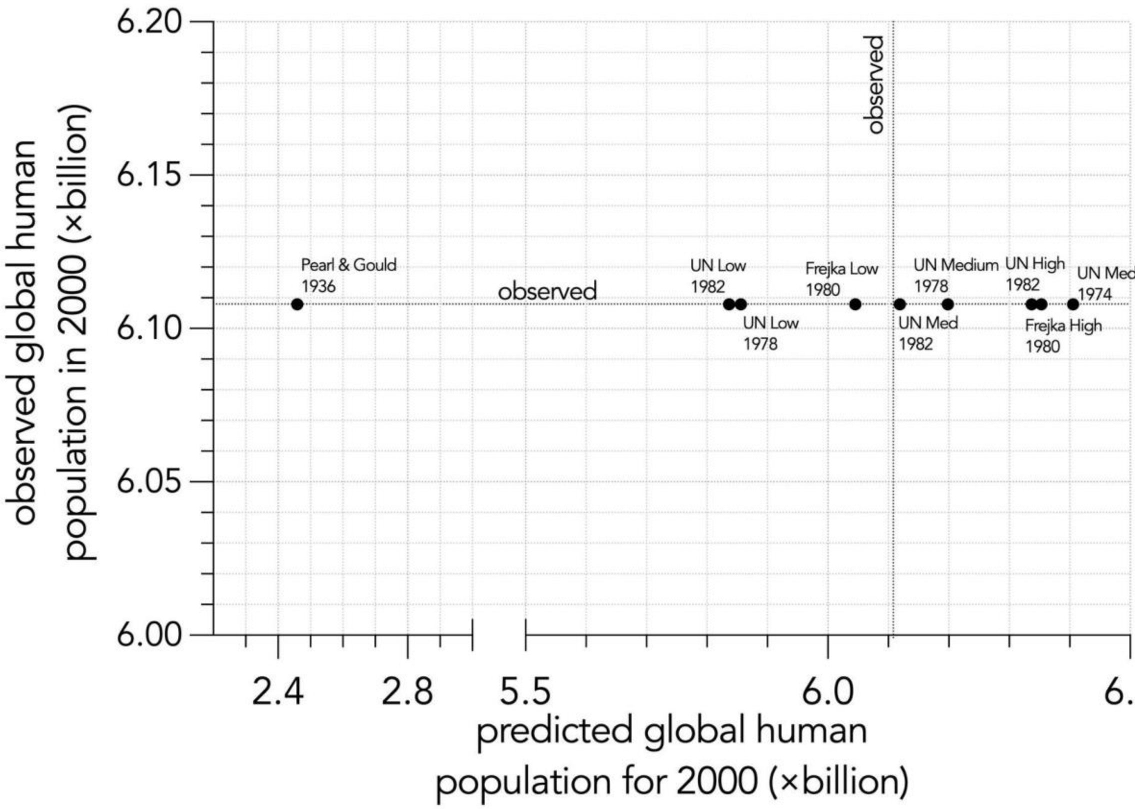


Table A1. Assumptions for the main United Nations population-projection scenarios based on variation in assumptions regarding fertility trajectories. Source: United Nations 2022 (28).

Scenario	**Assumption**
Medium	medium fertility and medium mortality: based on median probabilistic projection
Low	0.5 births below medium fertility, medium mortality
High	0.5 births above medium fertility, medium mortality
Constant fertility	fertility constant at 2022 values, medium mortality
Instant replacement fertility	reproduction rate = 1.0 starting in 2022, medium mortality
No change	fertility and mortality constant at 2022 values

Table A2. Projected global populations by 2100 according to the main United Nations fertility scenarios. Source: United Nations 2022 (28).

Scenario	**Total Population (billions)**
Medium	10.35
High	14.81
Low	7.01
Constant fertility (2022)	19.21
Instant replacement	10.62
No change	16.01