

# Future Births: A Formal Perspective on Humanity's Yet-to-Be-Born Generations

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## Abstract

The global fall in fertility led to concerns about the prospects of population decline. Many discussions of ‘depopulation’ seem to imply that such a population collapse is imminent and presents a grave threat to humanity. Using data from the UN World Population Prospects we model future births over a very long-term period. We compute the total number and the relative fraction of births to be born in the future. We complement our analysis by considering different timing of births and computing the year when the global number of births would fall below one thousand.

Our hypothetical exercise provides three key insights. First, indefinite scenarios of low fertility, with a net reproduction rate around 0.9 or lower imply that most people who would ever live on Earth had already been born. Second, the mean age at childbearing impacts population dynamics in the long run: longer inter-generational span slows down the pace of births and population decline. Third, even when assuming a permanent continuation of very low fertility humanity’s

final demise would occur very slowly, with a critical threshold of extinction—a number of births falling below a thousand per year globally—reached more than 1,400 years from now.

**Keywords** Births, fertility, global, population projections, population decline, modeling, population dynamics, long-term perspective

## 1 Introduction

Two interrelated demographic trends are receiving prominent media coverage: the accelerating decline in fertility and the prospect of population decline in many countries and, eventually, globally. Eberstadt (2024) argues that this represents a major turning point for humanity, heralding an era of “pervasive and indefinite depopulation”. Other commentators consider these shifts a major threat, with Elon Musk (2022) famously tweeting in 2022 that “Population collapse due to low birth rates is a much bigger risk to civilization than global warming”. Some economists are alarmed about the ‘vanishing’ labor force, and the prospect of falling productivity, innovation, and economic output (Madgavkar et al., 2025).

To most demographers, falling fertility and population decline do not seem like major news. Fertility decline has become a global phenomenon since at least the 1970s, when fertility rates started dropping rapidly in many middle- and lower-income countries, including China. The ongoing fertility transition is perceived as a one-end road: once fertility decline starts, it is likely to continue—driven by expanding education, urbanization, development, access to contraception, and changing reproductive preferences—until a country reaches a low fertility level (Bongaarts and Hodgson, 2022). With the exception of temporary fertility stalls, especially in some countries of Sub-Saharan Africa in the 1990s and 2000s (Kebede et al., 2019), and fertility increase in Central Asia in the last two decades (Spoorenberg, 2015), most countries that had a relatively high fertility half a century ago have indeed experienced a continuous slide to much lower fertility levels.

Population decline is also not a new phenomenon. Many countries have experienced huge population drops in the past due to famine, health emergencies, wars and violent conflict, as well as economic, political, social or environmental upheavals. Large-scale depopulation often occurs in countries affected by armed conflict and mass outmigration (such as Ukraine; e.g., Ueffing et al., 2023), and “failed states” experiencing civil wars (such as Syria from 2011 to 2025), and in countries with dysfunctional governments and economic collapse, such as Venezuela (Garcia Arias, 2024).

Similar to falling fertility rates, population decline has now assumed global significance. Until recently it had been typical of countries with a long history of low fertility, such as Japan, whose population peaked in 2010 or countries that experienced conflict or economic instability that led to outmigration, especially in Eastern and South-Eastern Europe. But this dynamic has changed recently. Some larger countries, especially in East Asia, saw their number of deaths surpass the number of births for the first time during the COVID-19 pandemic due to both a temporary rise in mortality and accelerating decline in fertility. The populations of both South Korea and China peaked in 2021, earlier than envisioned in past population projections. As of 2024, their population had already peaked in 63 countries and areas representing 28% of global population (United Nations, 2024b). In countries that experience higher immigration rates—including most countries of the European Union, Canada, United States, and Australia—population decline may be temporarily reversed, but in other countries including China and South Korea it is likely to become entrenched due to the shrinking pool of women of reproductive age in the coming decades. All major population projections envision that the global population will peak in the second half of this century and thus reverse its extraordinary growth spurt that started in the 18th century and accelerated during the last 100 years when the world population quadrupled from 2 billion in 1920 to 8.1 billion in 2024.

The broad scientific agreement about the future global population reversal and the projected future of low fertility, declining populations, and an accelerating growth in the elderly population feeds the rising media interest in these demographic megatrends. Beyond dry scientific content focused on numbers and trends, national and global population projections fuel what has been termed by Armitage (2021) and Gietel-Basten (2023) “demographic imaginaries”—worries and ideas connected to the envisioned population collapse and its consequences for economy, society and national identity. These worries are often amplified by politicians keen to announce new policies aiming to slow down or even revert the almost inevitable demographic dynamics. But demographic imaginaries are also playing out in full speed among researchers, economists, and broader public. Countless reports warn of the future population collapse and economic crunch (report by McKinsey Global Institute by (Madgavkar et al. (2025) is among the more insightful studies). By contrast, some environmentalists point out that the global population is still growing, with the current numbers and projected trend constituting an unsustainable ‘overshoot’, depleting global ecosystems (Rees, 2023; Saraswati et al., 2024; O’Sullivan, 2023).

A specific argument is pursued by the ‘long-termism’ proponents. This concept aims to prioritize the wellbeing of “the near-endless stream of future people” (Spears and Geruso, 2023). From this perspective, population decline is viewed as

a clearly negative trend, and expanding populations are seen as enabling prosperity, technological progress, and innovation. Demographers provide a more nuanced perspective, and many highlight potentially positive aspects and consequences of low (but not very low) fertility and stagnating or gradually declining populations (Lutz, 2023; Skirbekk, 2022).

Proponents of the ‘depopulation debate’ often consider replacement-level Total Fertility Rate (TFR) and an eventual stabilization in population size and structure as desirable outcomes, which policymakers should strive to achieve. As Lutz (2024) (page 91) argues, “demographers and the general public alike seem to have a powerful intuition that if fertility is at or near replacement level, things are fine, but if it is far below this level, then there is something fundamentally wrong.” However, in reality, the periods with an even balance of births and deaths and with fertility stabilizing around replacement level have been historically unusual. There is no compelling reason why global or national population trends should converge to such an equilibrium: Weil (2024) argues it is “neither natural, nor optimal, nor likely”. Besides following longer-term trajectories, fertility often shows wild fluctuations, responding to external shocks, new policies, and upheavals (Sobotka, 2017). Such dynamic changes were especially common during the recent COVID-19 pandemic and the subsequent unfolding crises (Winkler-Dworak et al., 2024).

The future-oriented discussions about low birth rates and population decline span over widely different time horizons, and cover diverse concerns ranging from national and cultural identity to the expected shortage of labor force, army recruits, and the threat of pension system collapse. They often ignore that it would take several decades before any future rise in birth rates translates into a higher number of future workers and that the future rises in longevity may eventually turn such ‘extra babies’ into ‘additional elderly’, inflating the old-age dependency rate. More importantly, these discussions ignore the role of population characteristics that are key for economic growth, prosperity, and well-being. In the past decade, research in population economics has revealed that declining populations do not necessarily imply lower prosperity, lower living standards or slower economic growth per capita (Bucci and Prettnner, 2025; Boikos et al., 2023; Bucci, 2023; Bucci et al., 2025; Strulik, 2024; Feichtinger et al., 2025). These studies highlight the pivotal role of human capital investments for economic prosperity.

The term ‘depopulation’ itself is misleading as it suggests a shortage of people in places and regions that typically had populations in a small fraction of today’s numbers until a few centuries ago. Especially from a planetary perspective, it seems odd to use the term ‘depopulation’ for today’s human population of over 8 billion, putting humans roughly on a par with pandas, tigers, gorillas, and other endangered species now numbering in the thousands. It is clear that, even under projected trends, it would take centuries or even millennia for human populations

to become extinct.

But how long, actually, would it take before the number of births declines in a way that would signify the planetary demise of human species? This is a very hypothetical question for two reasons. First, fertility rates constantly evolve and do not stay stable even in the perspective of years and decades. Assuming that any ‘current’ or projected level of fertility would stay the same for centuries is as realistic as if anyone in 1850 would have expected the fertility rates recorded at that time would stay the same indefinitely. Second, potential ‘black swan’ events—major environmental, political and technological threats (Smil, 2008), including global climate change, global conflict involving nuclear weapons, new pandemics, pollutants threatening human health, or out-of-control development of artificial intelligence—could invalidate any assumptions about the continuity of population trends in the next centuries. The world of tomorrow will be radically different from the world we know today.

These are also important reasons why very few scientists dare to make population projections beyond 2100, unless they risk making silly conclusions. One unconventional example is the *Japanese Clock of Counting Children’s Population* at the Tohoku University in Sendai (Japan) that counts time until the last Japanese child would be born if the recent demographic dynamics persist indefinitely (JCCC, 2025). On 16 January 2025 it showed that less than 700 years remained to reach this troubling milestone, which would occur on 5 January 2720.<sup>1</sup> More serious long-term projection exercises at a global level were undertaken by Lutz and Scherbov (2008), by Basten et al. (2013) and by Raftery and Ševčíková (2023) who considered long-range global population scenarios until 2300 and by Spears and colleagues (2024), who presented very long-run scenarios of births and population size with different TFR levels. Assuming a persistence of the TFR at 1.66, a level recorded in the United States in 2022 (and not a very low level by current standards), Spears et al. (2024) suggest that the population explosion of the last 200 years would fade relatively ‘soon’ (i.e., within the next century or two) and that four-fifths of all people who will ever live on Earth, 120 billion in total, have already been born.

Our study elaborates on these very long-range global population prospects. Specifically, we focus on births expected in the future and the time horizon for the eventual global population extinction. We compute the average annual growth rate in the number of births, the total number of births, and the ratio of projected future births to all births in human history, assuming that different levels of fertility persist indefinitely. We then show how these projected births are distributed over the next centuries and millennia. We also analyze the potential long-term im-

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<sup>1</sup>This extreme long-term horizon did not discourage Hiroshi Yoshida, the director of Tohoku University’s Research Center for Aged Economy and Society, to declare that “Japan may become the first country to become extinct due to the declining birth rate” (a Newsweek’s article by McCartney (2025)).

impact of different intergenerational lengths as captured by an earlier or later mean age at childbearing, focusing especially on the scenarios of later fertility that are aligned with the current shift of parenthood to later reproductive ages. Finally, we compute the year when the total number of births would drop to a thousand, a critical threshold that would signify an almost complete eradication of humans from Earth.

Our hypothetical exercise provides three key insights. First, in line with Spears and colleagues (2024), indefinite scenarios of low fertility, with a net reproduction rate around 0.9 or lower (corresponding to the total fertility rate at around 1.85 or lower), imply that most people who would ever live on Earth have already been born. Second, the mean age at childbearing has a powerful impact in the long run, an effect discussed earlier by Goldstein et al. (2003). Under low fertility scenarios, delayed childbearing can slow down the pace of births and population decline as the fixed number of future births would be spread over a much longer time horizon. Third, even when assuming a permanent continuation of very low fertility, corresponding to the lowest 5% of the projected fertility distribution in the UN WPP 2024 and the current pattern of fertility timing, humanity’s final demise would only occur in a very distant future: the number of births would drop below a thousand per year globally around the year 3484.

## 2 Background

Actual or projected population decline, or ‘depopulation’, has long been considered a looming threat, especially in European countries. During the 20th century some countries in Europe experienced population declines in peace times, often driven by a combination of low fertility and outmigration, with the issue gaining attention already in the interwar period and then again in the 1970s (e.g., Council of Europe, 1978; Gauthier, 1993; Teitelbaum and Winter, 1985). Ireland (in its current borders) lost about half of its population between 1841 (6.5 million) and 1901 due to mass starvation (1845-1852) and long-term outmigration, with a slower decline continuing until 1961, when the population reached 2.8 million (CSO, 2025). In France, low fertility and the fear of looming population decline and the related loss of military power since the late 19<sup>th</sup> century led to establishment of pronatalist policies much earlier than in any other country.

In 1984, the European Parliament passed a resolution calling for “measures to combat this marked trend toward population decline, which is common to all the member states” (The European Parliament, 1984). However, in contrast to these expectations, population decline in the following decades took place in other parts of Europe, especially in the former state-socialist countries of Central, Eastern

and South-eastern Europe. Most countries in this region have experienced lasting and strong population declines due to a combination of low fertility, higher mortality, and outmigration (Sobotka and Fürnkranz-Prskawetz, 2020). The global ranking of countries with fastest population decline in the past 30 years is dominated by this region, with some countries' populations (e.g., Bulgaria, Romania, Latvia, and Lithuania) dropping by more than 20% since 1990 (United Nations, 2024a). However, even in other parts of Europe, the perception of a looming 'demographic winter' has taken a strong hold in the public imagination and among many policymakers.

Why is so much attention paid to low birth rates and the prospects of population declines today? Why is there such a sense of doom and gloom in the debates occurring around these issues? We highlight five broader factors explaining their current prominence: (1) the global acceleration of fertility decline, and the widespread emergence of extreme low fertility rates, (2) the emerging population decline in many countries, (3) the attention generated by the recent rounds of global population projections, (4) broader scientific and popular discussions about these trends, often focusing on their perceived negative consequences, and the looming 'population crisis', and (5) a common misperception that population aging is solely driven by low birth rates, thus ignoring a key role played by a rising life expectancy across the world.

The decline in fertility rates has accelerated in many countries and crossed, or is about to cross, several globally relevant thresholds. Both globally and nationally, it has become clear that fertility transition does not magically stop when fertility rates reach the 'replacement level' threshold, often simplistically measured by the total fertility rate declining below 2.1. During the last two decades, fertility rates fell to low or extreme low levels in many middle-income countries in Asia and Latin America, including China, Iran, Chile, Cuba, Thailand, Turkey, and Uruguay. Period TFR in China dropped from 1.7 in 2015 to 1.0 in 2022 despite the country abandoning its draconian birth-limiting policies, most notably allowing all couples to have two children since 2016 (Scharping, 2018). In higher-income regions, fertility plummeted in the group of countries that previously sat at the high end of the low fertility range, including Australia, United States, western European, and Nordic countries. But it also fell in East Asian countries that already had 'ultra-low' fertility, setting new records and creating a sense of desperation. South Korean total fertility rate dipped to 0.72 in 2023, with its capital city, Seoul, recording a TFR of 0.55 (Statistics Korea, 2024). As a result of these shifts, the global fertility decline accelerated recently, with a TFR dropping by 10% (from 2.5 to 2.25) between 2015 and 2023 (United Nations, 2024a). Today, a majority of the world's population lives in countries with a TFR of 2.1, the global TFR is just 4% above the replacement threshold, and almost one fifth of countries have a TFR

below 1.4 (United Nations, 2024b). Despite the still growing global population, the ‘peak babies’ – i.e., the highest number of babies born – were reached according to the UN estimates in 2012, when 146 million children were born worldwide. By 2023, the number dropped by a tenth to 132 million, and is expected to continue to fall gradually throughout the century (United Nations, 2024a).

As fertility rates continued to drop globally, the experience of population decline spread beyond European countries. The latest medium scenario of the UN World Population Prospects projects that the world population will peak in 2084 at 10.3 billion (United Nations, 2024a), whereas the Wittgenstein Centre projection (SSP2 scenario) puts the peak in 2080 (at 10.1 billion) (K.C. et al., 2024), the Institute of Health Metric and Evaluation projects it for 2064 (at 9.7 billion) (Vollset et al., 2020), and the US Census Bureau’s main scenario projects the peak in 2098, at just below 10.9 billion (US Census Bureau, 2024). Although these major projections are in a broad agreement about global population trajectories and the inevitability of eventual global population decline, they differ considerably in the projections for individual countries and regions owing, especially to different fertility and migration scenarios. Globally, the most remarkable population ‘implosion’ is envisioned by the UN WPP medium scenario for China, whose population is projected to drop by more than a half from 1 421 million in 2024 to 638 million in 2100, contributing strongly to the expected global reversal in population growth (United Nations, 2024a).

Some analysts argued that the accelerating fertility declines, either in Sub-Saharan Africa (The Economist, 2023) or in low-fertility countries (Burn-Murdoch, 2024), may, in turn, accelerate the global population reversal, bringing forward the year of the ‘peak population’. This argument gives more weight to the alternative (lower) scenarios of future population dynamics. The low variant in the UN 2024 projection, for instance, suggests that the global peak population, at 8.9 billion, might occur in less than three decades, in 2053.

The prospects of shrinking population fuel discussions on the perceived negative consequences of population decline, including, eventually, economic and societal collapse. These fears are strongly articulated by policy-makers. For instance, Japanese PM Fumio Kishida declared in his policy address in January 2023 that it is time to solve the issue of declining birth rates “now or never” (Yeung and Ogura, 2023). A former South Korean president Yoon Suk-Yeol, later impeached for unlawfully declaring martial law, declared in June 2024 “national demographic emergency” due to Korea’s declining population and vowed “to make all-out efforts to tackle the country’s ultralow birth rate” (Haye-ah, 2024). Russian authoritarian president Vladimir Putin comments regularly on the country’s very low birth rate, denounces “childfree propaganda” and encourages women to have more children, with the Russian news agency TASS (2024) stating in December 2024 that he

“ordered that the total fertility rate in the country be increased to 1.6 by 2030.”

This sense of panic and urgency is remarkable, since birth rates and aggregate population trends are hard to reverse through policies (Sobotka et al., 2017), and the major population trends will continue unfolding over many decades—well beyond the mandates of the current politicians—due to the built-in population momentum. Policymakers are often conspicuously quiet about the role of immigration and outmigration, that has been reshaping population trends in many countries. A poignant example is the highest population growth in several decades (at 1.0%) reported in the United States in 2024, and in the United Kingdom in 2023, which was largely fueled in both countries by a surge in immigration (US Census Bureau, 2024).

In the very long term population decline will be mostly driven by the familiar force of low fertility, combined in some countries with outmigration and relatively high mortality. But it is not only the level of fertility that may determine how quickly would populations shrink in the next centuries. When fertility rates are very low and populations are shrinking rapidly, the timing of births, or intergenerational length, has a powerful and seemingly counter-intuitive impact: assuming that cohort fertility rates remain stable (and would not be negatively affected by delayed childbearing), longer inter-generational length can moderate the pace of births and population decline, an effect first discussed by Demeny (2003) and considered in European population scenarios by Goldstein et al. (2003). We explicitly take this effect into account by comparing scenarios that keep the current mean age at childbearing among women—around 30 years—with three alternative scenarios of lower and higher intergenerational length, at ages 25, 35, and 50. The last scenario is completely unrealistic from today’s perspective, but it could be conceivable in the distant future if the use of medically assisted reproduction spreads massively and erases the biological limits imposed by menopause and the depletion of follicles (eggs) with age, which leads to a rapidly declining fecundity at higher reproductive ages.

### 3 Data and methods

To estimate the total number of children expected to be ever born and the ratio of future births to total human births, it is necessary to combine estimates of the number of children born in the past with the scenarios of future birth dynamics. A broad range of estimates exists for the number of people ever born on Earth, based on different assumptions and models—see Cohen (2014) and Sánchez-Romero et al. (2017) for an overview. Here, we use the values for the total number of people ever born up to the year 2010—i.e.,  $\pi(2010)$ —as reported in Table A-2 of Sánchez-

Romero et al. (2017).<sup>2</sup>

These estimates are based on a Generalized Inverse Population (GIP) model (Lee, 1985; Oeppen, 1993), which replicates the historical assumptions from Deevey (1960) and Haub (2011), as well as the UN population estimates for 1960 to 2010.

Drawing on these historical estimates, Table A-2 in Sánchez-Romero et al. (2017) reports both the lowest and highest plausible values for the total number of people ever born, which are used in this paper. Specifically, the number of people born up to 2010 is estimated at 77 249 million using Deevey’s assumptions, and 112 931 million using Haub’s assumptions.

To estimate the number of children ever born on Earth by 2024, we extend the estimates by Haub and Deevey until 2023, using annual birth numbers from the UN World Population Prospects (2024). We then project these data until 2100 using five distinct time series of global births for the period 2024–2100 from the UN World Probabilistic Projections (2024). By the year 2100, the estimated fertility profiles from the UN World Probabilistic Projections (2024) range from a TFR of 1.60 in the *Lower95* scenario, which corresponds to the lower bound of the 95% prediction interval, to a TFR of 2.30 in the *Upper95* scenario, corresponding to the upper bound of that interval (see Table 1). The TFR in the *Median scenario* (50% prediction interval) is 1.838 in 2100, corresponding to a Net Reproduction Rate (NRR) of 0.898 in low-mortality settings—i.e., with each subsequent generation shrinking by about 11% (see Table 1) for the average population growth rate and the mean-age of childbearing (MAC) in the Median scenario. These TFR levels, embedded in each scenario are assumed to remain constant from 2101 until the end of our projection period, which implies that humanity’s extinction will occur in three scenarios characterized by sub-replacement fertility (*Median scenario*, *Lower95*, and *Lower80*). The TFR in the *Upper80* scenario, 2.08, is just above the replacement-level threshold, therefore implying a slightly rising number of births and population expansion in the long-term.

Assuming fertility rates and the mean age at childbearing remain constant at the levels listed in Table 1, these scenarios imply annual rates of population growth ranging from  $-0.83\%$  (*Lower95*) to  $+0.32\%$  (*Upper95*). The projected number of births globally from 2101 onwards is based on our computations, and formal models specified in the next section.

We further expand our range of scenarios from 2100 on, by considering different mean ages at childbearing. Demeny (2003) and Goldstein et al. (2003) noted that when fertility is below replacement, longer generation length would slow down the pace of population decline, as the shrinking generations would be stretched over a longer period of time. This mechanism holds only when assuming that fertility

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<sup>2</sup>Note that all other historical figures in Sánchez-Romero et al. (2017) are based on the implicit assumption that demographic characteristics change abruptly between periods.

Projection scenario	TFR	MAC	Population growth rate
Lower_95	1.599	29.9	−0.008 26
Lower_80	1.673	29.9	−0.006 74
Median	1.838	29.7	−0.003 62
Upper_80	2.082	29.5	0.000 59
Upper_95	2.296	29.4	0.003 15

Table 1: Stable population growth rates from 2100 on implied by using UN WPP probabilistic fertility scenarios for 2100

rates are not negatively affected by delayed childbearing due to rising infertility or changing reproductive preferences. Next to the mean age at childbearing at around 30 years, implied in the UN WPP 2024 probabilistic scenario for 2100 (Table 1) we consider three alternative fertility schedules. First, a young childbearing schedule with a mean age at childbearing at 25 years. This corresponds to the observed mean age at childbearing in countries with low fertility and relatively early age at first birth, as in India today, or in the former state-socialist countries in Central and Eastern Europe in the 1980s. Second, an older childbearing schedule with a mean age at childbearing at 35 years. Such a late fertility schedule is not yet observed in any country today, but some countries that experienced a strong shift to late first birth are rather close, with South Korea having a mean age at childbearing at 33.6 in 2023 (Human Fertility Database, 2025). Third, we consider a scenario of extremely late fertility schedule, with the mean age at childbearing set at 50. This scenario is clearly unrealistic from today’s perspective, when mothers over age 50 account for fewer than 1 in 1 000 births (Human Fertility Database, 2025), and many if not most of these births are conceived using donor eggs. This scenario is useful to gauge the hypothetical impact of an extremely long intergenerational length on slowing down the pace of population decline (assuming a constant fertility).

Our birth timing scenarios are stylized and simplified. In our computations, all births are born to women who reach the mean age at childbearing in a given year. While such an extreme concentration of births is clearly unrealistic, the assumption should not bias the projected births and their dynamics over time. In addition, we did not account for the ‘tempo-quantum interaction’, i.e., the likely negative impact of a later age at childbearing on fertility rates, especially due to infertility, reduced chances of conception and higher rates of miscarriages and pregnancy complications with age. Finally, our scenarios ignore the *tempo effect* due to a later age at childbearing, which has a stronger (negative) impact on fertility in a shorter-term perspective, as illustrated by Goldstein et al. (2003) in their scenarios for European countries. If, for instance, the mean age at childbearing would shift

from 30 to 35 in the course of this century and cohort fertility rates would stay constant, period fertility rates would be negatively affected by this shift, dropping by about 5% on average (in other words, 5 years of childbearing would be ‘missing’ over the course of 100 years). While relevant in the time horizon of years, decades, and even a century, the *tempo effect* is less important in the extreme long-term perspective of centuries and millennia covered in our study, and therefore we are not accounting for it in our computations.

## 4 Formal background

In this section, we derive an analytical expression for the ratio of future to total human births, assuming a stable—i.e., constant—population growth rate. Based on the latter assumption, we prove that this ratio is equal to one when population growth is positive, and it is always below one when population growth rates are negative—i.e., for declining populations.

Assuming that the population grows at a constant rate  $r$  from time  $T$  onward, the fraction of all births that will occur after time  $T$  is defined as the ratio of the total number of future births (from time  $T$  onward) to the total number of births from time 0 to  $\infty$ . This fraction at time  $T$ , which we denote by  $\varphi(T)$ , is given by the following expression:

$$\varphi(T) = \frac{\int_T^\infty B(t)dt}{\int_0^\infty B(t)dt}, \quad (1)$$

where  $B(t)$  is the total number of births in year  $t$ .

As  $r$  is assumed to be constant, stable population theory (Lotka, 1925) implies that the total number of future births is

$$\int_T^\infty B(t)dt = B(T) \int_T^\infty e^{r(t-T)} dt = \begin{cases} \infty & r \geq 0, \\ \frac{B(T)}{-r} & r < 0. \end{cases} \quad (2)$$

Substituting (2) in (1) gives<sup>3</sup>

$$\varphi(T) = \begin{cases} 1 & r \geq 0, \\ \frac{(\pi(T)/-r)}{1+(\pi(T)/-r)} & r < 0, \end{cases} \quad (3)$$

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<sup>3</sup>Note that (1) can be rewritten as  $\int_T^\infty B(t)dt / (\int_0^T B(t)dt + \int_T^\infty B(t)dt)$ . Dividing the numerator and denominator of the new expression by  $\int_T^\infty B(t)dt$  gives  $1 / (\frac{\int_0^T B(t)dt}{\int_T^\infty B(t)dt} + 1)$ . Using this reformulation of (1), the derivation of (3) is straightforward.

where  $\pi(T) = B(T)/\int_0^T B(t)dt$  is the ratio of the current number of births to the total number of people ever born (Cohen, 2014; Sánchez-Romero et al., 2017). Recalling from equation (2) that for negative values of  $r$  all future births are given by  $\frac{B(T)}{-r}$  it follows that the term  $\frac{\pi(T)}{-r}$  represents the ratio of future to past births. Obviously this latter term is always positive, and hence, (3) implies that  $\varphi(T)$  takes values between 0 and 1 and depends on i) the ratio of the current number of births to the total number of people ever born—i.e.,  $\pi(T)$ —and ii) the population growth rate—i.e.,  $r$ , which can be approximated as

$$r \approx \frac{\log(\text{NRR})}{\text{MAC}}, \quad (4)$$

where NRR denotes the net reproduction rate, or the average number of daughters that a woman would have, adjusted for mortality, and MAC denotes the mean age at childbearing. For notational simplicity, let  $\theta(T) \geq 0$  denote the ratio of future to past births in year  $T$ ; i.e.,  $\theta(T) = \pi(T)/(-r) \geq 0$ . Substituting  $\theta(T)$  in (3) gives

$$\varphi(T) = \begin{cases} 1 & r \geq 0, \\ \frac{\theta(T)}{1+\theta(T)} & r < 0. \end{cases} \quad (5)$$

Eq. (5) indicates that the ratio of future to total human births approaches zero when the ratio of future to past births tends to zero, a dynamic corresponding to rapid population decline. In contrast, this fraction approaches one when the ratio of future to past births tends to infinity, a dynamic corresponding to indefinite population growth or the situation when the population becomes stationary; i.e.,  $r \geq 0$ .<sup>4</sup>

Recalling eq. (4) it follows that the population growth rate,  $r$ , depends positively on the logarithm of the NRR and negatively on MAC. Thus, a lower mean age of childbearing (MAC) implies a faster population growth when the NRR is above 1, and a faster population decline when the NRR is below 1. Conversely, a later age at childbearing can slow down population growth when the NRR is above 1 and speed it up when the NRR is below 1. These relations are shown in Figure 1 where the population growth is plotted against the total fertility rate for different levels of the mean age of childbearing. Note that the fraction of all future births,  $\varphi(T)$ , is less than 1 for negative population growth rates, and equal to 1 for positive population growth rates. A higher MAC reduces population growth rates in cases of increasing populations and reduces population decline when population growth rates are negative.

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<sup>4</sup>Note that the  $\lim_{r \rightarrow 0^-} \frac{\theta(T)}{1+\theta(T)} = 1$ , i.e., there is a smooth and continuous transition from the fraction (active for  $r < 0$ ) to the value 1 (active for  $r \geq 0$ ).

To understand how the ratio of future births to total births ever born under negative population growth rates is influenced by (i) the ratio of the current to total births ever born  $\pi(T)$ , as well as by (ii) the population growth rate,  $r$ , it is sufficient to focus on the first and second partial derivatives of the ratio of future to past births with respect to these components—since  $\varphi(T)$  is monotonically increasing with respect to  $\theta(T)$ . In particular, an increase in  $\pi(T)$  has a positive impact on  $\theta(T)$  because, given a fixed population growth rate, a higher number of children born at time  $T$  implies that more children will be born in the future as well; i.e.,  $\frac{\partial\theta(T)}{\partial\pi(T)} > 0$ . In contrast, an acceleration of the speed of population decline reduces the ratio of future to past births, since fewer children will be born in the future; i.e.,  $\frac{\partial\theta(T)}{\partial(-r)} < 0$ . The fact that the second derivative of  $\theta(T)$  with respect to the speed of population decline,  $-r$ , is positive, while the first derivative is negative, implies that increasingly faster rates of population decline are needed to further reduce the ratio of future to past births—making it increasingly harder to drive the population to extinction in the short run.

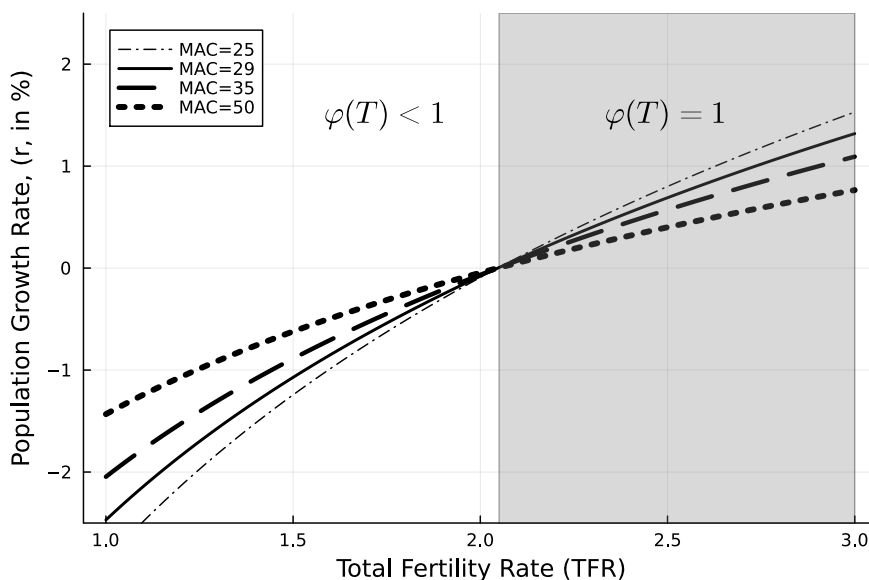


Figure 1: The impact of total fertility rate on long-run population growth rate in a closed population with different mean ages at childbearing (MAC)

Assuming constant population growth rates, it is of interest to study whether the current intrinsic negative population growth rates would be sufficient for the global population to become extinct in the coming centuries. The next section, therefore, focuses on empirically estimating the last year when the annual number of births would reach at least 1 000, a clear marker of a looming human extinction.

## 5 Empirical estimates

Based on the data and formal relations presented in sections 3 and 4, we estimate the ratio of births projected in the future to total human births. We first look at an empirical relationship between the TFR and population growth rate on one side, and the fraction of future births on the other, considering different mean ages at childbearing. Second, we present results for three key variables—total projected future births, ratio of future births to all births, and the last year when the number of births reaches at least 1 000, using selected scenarios from fertility in the latest (2024) UN world population projections.

### 5.1 The links between TFR, population growth rate and future births dynamics

Figure 2 summarizes the estimates of the fraction of future births (from 2024 onwards) to all births in human history as a function of the total fertility rate (TFR) (upper panels) and population growth rate (lower panels). We present two sets of estimates based on the number of people ever born, provided by Haub (left panels) and by Deevey (right panels). For each figure, we consider four scenarios with different mean ages at childbearing (MAC). We only focus on sub-replacement fertility ranges, implying negative population growth rates and a declining population in the future.

The upper panels illustrate the positive relation between the TFR and the fraction of all births expected to occur in the future. The figures also illustrate that, for below-replacement TFR, higher MAC results in a greater share of total human births happening in the future. For example, for a TFR of 1.5, increasing the MAC from 25 to 50 raises the fraction of future human births from approximately 0.10 to nearly 0.20 under Haub (2011), and to slightly above 0.15 under Deevey (1960).

This result is seemingly counterintuitive: keeping the same TFR level indefinitely while changing intergenerational length should redistribute births, with a later childbearing schedule further into the future, but should not change their total number. In fact, the result reflects a hypothetical reproductive shift among some of the current generations of women: for instance, changing the mean age at childbearing from 25 to 50 years would reset the reproductive clock for these women and shift the reproduction from the past to the future for 25 cohorts. Of course, this is a purely hypothetical scenario, since the past births among women

currently of childbearing ages have already occurred and cannot take place again in the future. The bottom panels show the exponential relationship between the population growth rate ( $r$ ) and the future share of total human births. Specifically, when the annual growth rate drops below -0.5 percent, the fraction of human births occurring in the future,  $\varphi(2024)$ , falls below 0.2, implying that 80 percent of all births on Earth, past and future, already occurred in the past. If population growth rates further decline to a value below -1.5 percent,  $\varphi(2024)$  falls below 0.1, implying that 90 percent of all births already occurred in the past.

## 5.2 Future births dynamics based on the UN WPP scenarios

To complete the analysis, we assume that by the year 2100, mortality before menopause is negligible. This assumption implies that the net reproduction rate is equal to the product of the total fertility rate and the proportion of female births, which we assume to be 0.4886. Thus, we can calculate the population growth rate ( $r$ ) based on the age-specific fertility rates from the UN World Probabilistic Projections (UN-WPP), considering five scenarios: lower 95, lower 80, median, upper 80, and upper 95.

Table 1 in Section 3 presents the total fertility rate (TFR), mean age of child-bearing (MAC), and the resulting population growth rates for each of the five UN WPP scenarios analyzed here. In all scenarios, the MAC is approximately 30 years. The TFR ranges between 1.60 and 2.30 births per woman. Consequently, keeping the same parameters constant, the annual population growth rate after 2100 is projected to be negative in the lower 95 (-0.85%), lower 80 (-0.70%), and median (-0.37%) scenarios, while it is expected to be positive in the upper 80 (0.06%) and upper 95 (0.40%) scenarios.

Figure 3 shows the projected fraction of future births (from 2024 onwards) to all human births for these five scenarios. As proven in equation (5), the value of  $\varphi(2024)$  is equal to one for positive population growth rates. For negative population growth rates in the lower three scenarios of the UN WPP,  $\varphi(2024)$  ranges between 0.14 and 0.25 for the estimates by Haub (2011), and between 0.19 and 0.33 for those by Deevey (1960), based on the lower 95th and median population projections.

Figure 4 displays the projected evolution of the total number of births (in millions) from 2024 until the year 3000 for each scenario analyzed. From the year 2100 onward, the annual growth rate of births is determined by the rates reported in the last column of Table 1. The total number of births is halved every 80 years in the lower 95th percentile scenario, every 100 years in the lower 80th percentile

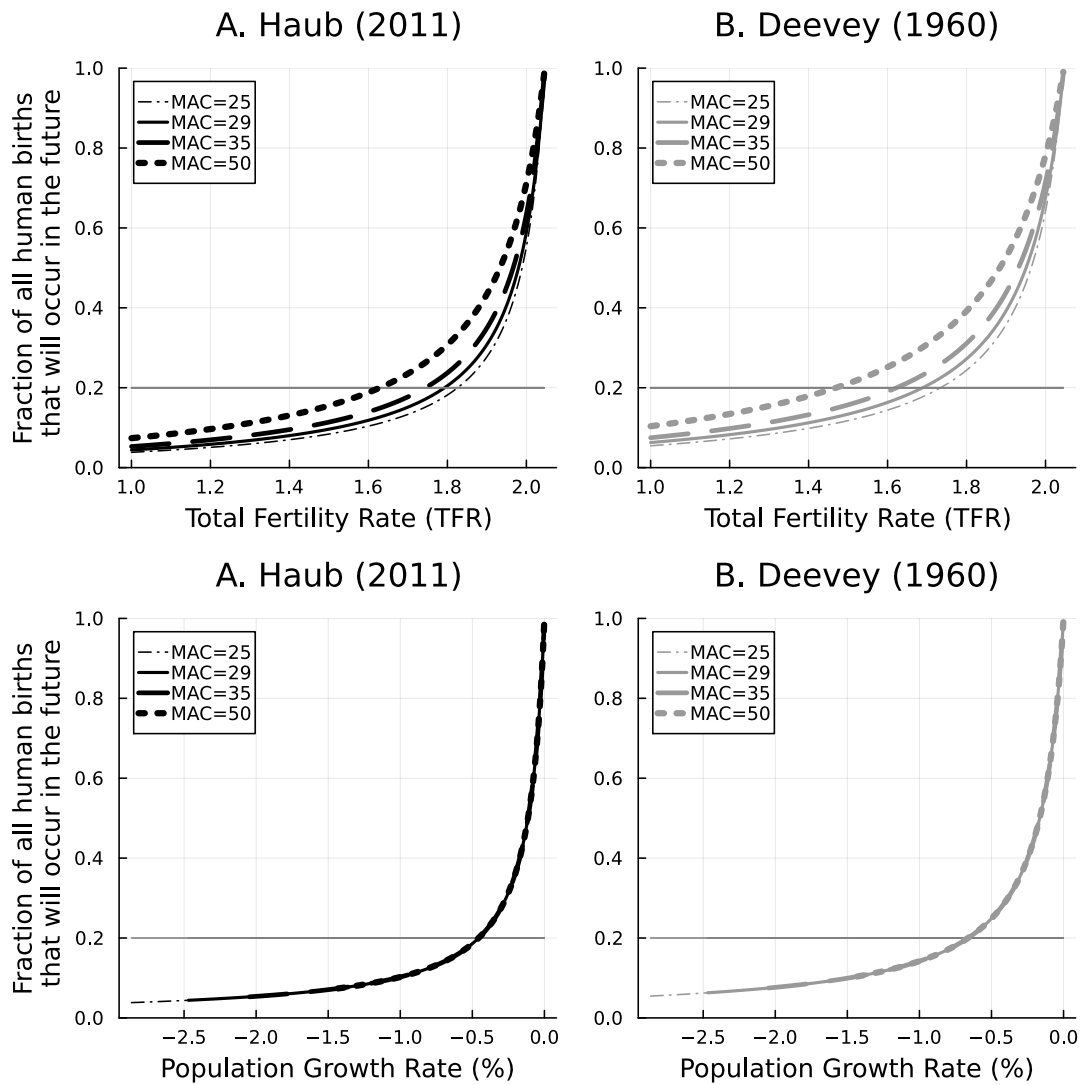


Figure 2: Fraction  $\varphi(T)$  of future births to all human births (future births from year  $T=2024$ ). Notes: Black curves are based on estimates from the population ever born, as reported by Haub (2011), while gray curves use data from Deevey (1960).

scenario, and every 185 years in the median scenario. By contrast, number of births increases indefinitely in the other two scenarios considered, upper 80 and upper 95 percentiles. Under the median scenario, the total number of births in the year 2200 remains above 75 million—at more than half of the current level. Under the lower 95th and 80th percentile scenarios, the expected number of births by 2200 falls between 40 and 50 million, which is approximately one-third of today’s value. Table 2 examines at the same scenarios, summarizing the projected ratio of future births to total human births during this and the next two millennia. We present the results separately for the Haub’s and Deevey’s estimates of total births in the past and distinguish different intergenerational length, ranging from a low mean age at childbearing at 25 years to an extremely late one at 50 years. We only consider the results for the three scenarios with negative population growth rates.<sup>5</sup> Considering the median population projections and using the Haub’s (2011) estimates for past population numbers, the ratio of future births to total births ranges from about 23% (MAC=25) up to 30%(MAC=50) in this Millennium. These numbers decline to very low values in the next millennium, between 0.4% (MAC=25) and 3.7% (MAC=50), and then drop to between zero (MAC=25) and 0.4% (MAC=50) in the fifth Millennium. The numbers are slightly higher when applying the Deevey’s (1960) estimates of the past population numbers.

How long would it take under these scenarios for the number of births globally to drop to fewer than a thousand per year? In Table 3 we show the year after which the number of births would decline below 1 000. This critical point is reached faster with a lower future TFR and an earlier timing of childbearing. Depending on the assumed MAC this would happen for the median projections between the year 4798 (MAC=25) and 7374 (MAC=50). In the Lower 95 percentile scenario, the last year with at least 1 000 births would happen between 3247 (MAC=25) and 4417 (MAC=50).

Overall, our simulations show that scenarios of indefinite below-replacement fertility imply that most people who would ever live on Earth have already been born. However, the mean age of childbearing has a decisive impact on the speed of this decline, with later mean ages shifting this point towards a more distant future.

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<sup>5</sup>For the upper-80 and upper-95 scenario the fraction is zero for each of the millennia depicted in Table 1 and one for the open-ended time horizon.

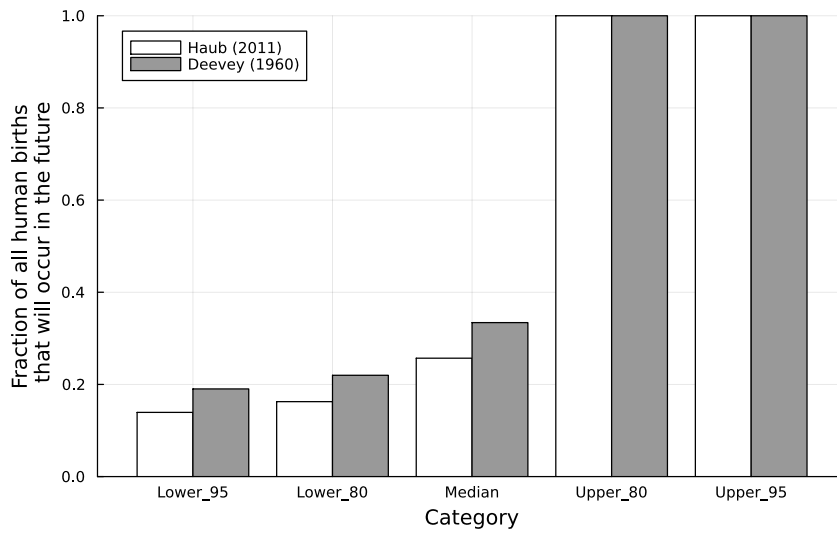


Figure 3: Probabilistic projection of the fraction of future births to all births in human history (baseline MAC  $\approx 30$  years). Source: The total number of births until 2100 is based on the UN WPP 2024 probabilistic scenarios. Beyond 2100, birth dynamics is estimated extending indefinitely the birth growth rate projected for 2100 in the WPP probabilistic projection scenarios.

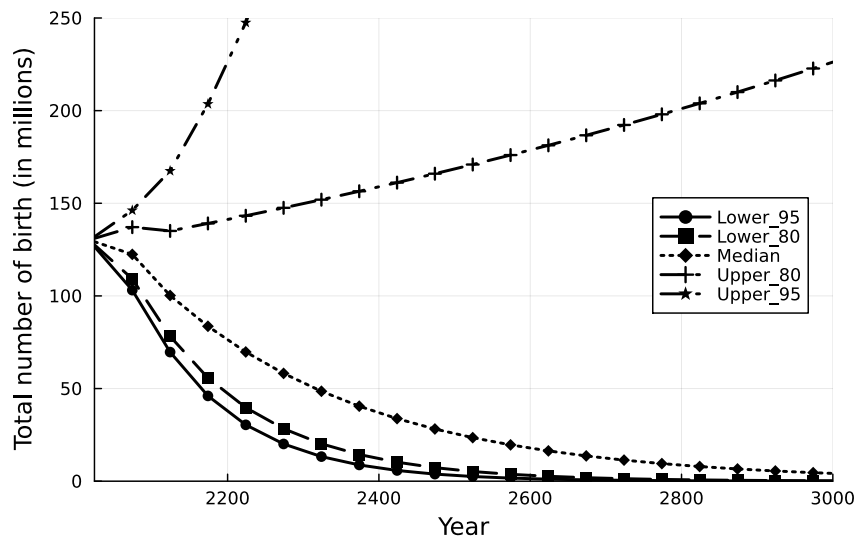


Figure 4: Probabilistic projection of the total number of birth per year from 2024 to 3000. Source: The total number of births until 2100 is based on the UN WPP 2024 probabilistic scenarios. Beyond 2100, birth dynamics is estimated extending indefinitely the birth growth rate projected for 2100 in the UN WPP probabilistic projection scenarios.

<b>Projection scenario</b>		<b>Lower_95</b>	<b>Lower_80</b>	<b>Median</b>	<b>Upper_80</b>	<b>Upper_95</b>
TFR		1.599	1.673	1.838	2.083	2.296
NRR		0.781	0.818	0.898	1.018	1.122
Fraction of total births in each Millennium (MAC=25)						
Number of children to be born (in billions)		16.9	20.1	34.9	$\infty$	$\infty$
Haub (2011)	3rd Millennium	0.1283	0.1489	0.2298	–	–
	4th Millennium	0.0000	0.0001	0.0035	–	–
	5th Millennium	0.0000	0.0000	0.0000	–	–
Deevey (1960)	3rd Millennium	0.1761	0.2025	0.3018	–	–
	4th Millennium	0.0000	0.0001	0.0046	–	–
	5th Millennium	0.0000	0.0000	0.0001	–	–
Fraction of total births in each Millennium (MAC $\approx$ 30, baseline)						
Number of children to be born (in billions)		18.6	22.4	40.0	$\infty$	$\infty$
Haub (2011)	3rd Millennium	0.1396	0.1629	0.2507	–	–
	4th Millennium	0.0000	0.0002	0.0076	–	–
	5th Millennium	0.0000	0.0000	0.0002	–	–
Deevey (1960)	3rd Millennium	0.1905	0.2202	0.3259	–	–
	4th Millennium	0.0001	0.0003	0.0099	–	–
	5th Millennium	0.0000	0.0000	0.0003	–	–
Fraction of total births in each Millennium (MAC=35)						
Number of children to be born (in billions)		20.3	24.7	45.1	$\infty$	$\infty$
Haub (2011)	3rd Millennium	0.1504	0.1762	0.2681	–	–
	4th Millennium	0.0002	0.0006	0.0134	–	–
	5th Millennium	0.0000	0.0000	0.0006	–	–
Deevey (1960)	3rd Millennium	0.2044	0.2368	0.3452	–	–
	4th Millennium	0.0002	0.0009	0.0172	–	–
	5th Millennium	0.0000	0.0000	0.0008	–	–
Fraction of total births in each Millennium (MAC=50)						
Number of children to be born (in billions)		25.5	31.5	60.3	$\infty$	$\infty$
Haub (2011)	3rd Millennium	0.1804	0.2113	0.3029	–	–
	4th Millennium	0.0014	0.0041	0.0371	–	–
	5th Millennium	0.0000	0.0001	0.0043	–	–
Deevey (1960)	3rd Millennium	0.2420	0.2794	0.3805	–	–
	4th Millennium	0.0019	0.0054	0.0466	–	–
	5th Millennium	0.0000	0.0001	0.0054	–	–

Table 2: Number and fraction of future births to total births in human history projected in each analyzed scenario by millennium, considering different timing of births and projections scenarios from UN WPP.

Note: TFR: Total fertility rate; NRR: Net reproduction rate; MAC: Mean age at childbearing

Projection scenario	Lower_95	Lower_80	Median	Upper_80	Upper_95
TFR	1.599	1.673	1.838	2.083	2.296
NRR	0.781	0.818	0.898	1.018	1.122
<hr/>					
MAC=25					
Average population growth	-0.0099	-0.0081	-0.0043	0.0007	0.0046
Last Year with Total Births = 1000	3247	3511	4798	–	–
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MAC≈30					
Average population growth	-0.0083	-0.0067	-0.0036	0.0006	0.0039
Last Year with Total Births = 1000	3484	3806	5323	–	–
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MAC=35					
Average population growth	-0.0071	-0.0058	-0.0031	0.0005	0.0033
Last Year with Total Births = 1000	3699	4071	5843	–	–
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MAC=50					
Average population growth	-0.0049	-0.0040	-0.0022	0.0003	0.0023
Last Year with Total Births = 1000	4417	4958	7374	–	–

Table 3: Average future population growth rate and the last year when the projected total number of births on Earth would reach 1 000 in each analyzed scenario, considering different timing of births and projections scenarios from UN WPP.

Note: The formula applied is  $B(T^*) = B(t) \exp\{r(T^* - t)\} \implies T^* = t + \frac{1}{r} \log\left(\frac{B(T^*)}{B(t)}\right)$ , where  $t = 2100$ ,  $B(T^*) = 1000$  and  $r$  is the average population growth rate. TFR: Total fertility rate; NRR: Net reproduction rate; MAC: Mean-age at childbearing.

## 6 Discussion

Persistent low fertility rates and accelerating fertility declines in many world regions have fostered the fear of falling numbers of births and population declines that might threaten economic growth, prosperity, and social security systems. Many economists argue that increasing numbers of elderly dependent populations will inflate fiscal imbalances and reduce innovation and investment in research and technology. Politicians often fear that an accelerated population decline would lead to economic and societal collapse. While many of these fears are overblown and often ignore the role of other drivers of population dynamics, especially rising longevity and international migration, this study contributes to our understanding of long-term population dynamics under low fertility. We apply formal demographic modeling to systematically explore very long-term scenarios of global births, considering different scenarios of low fertility and intergenerational length.

Our formal models allow us to prove that for constant positive population growth rates, the fraction of future births to all human births tends toward one. In the case of constant negative population growth rates in the future, this ratio is always below one and approaches zero when fertility rates are extremely low and population declines rapidly. We also prove that a higher mean age at childbearing slows population decline when the population growth rate is negative, and slows population increase when the population growth rate is positive.

Drawing from the range of probabilistic fertility scenarios envisioned in the latest round of the UN World Population Prospects for the period through 2100 and keeping these rates fixed indefinitely, we estimated the future total number of births to be born on Earth, their ratio to the total number of births in human history, and the last year when the total number of births would drop to one thousand. We combined probabilistic fertility scenarios for 2100 in the UN WPP with different scenarios of the mean age at childbearing, a novel perspective in very long-range population projections.

Our research yields three main insights about the very long-term birth and population dynamics. First, in line with earlier results by Spears and colleagues (2024), we show that if sub-replacement fertility persists indefinitely, most of the people who will ever live on Earth have already been born. Taking the UN median fertility projection scenario for 2100, with a TFR at 1.84 and the mean age at childbearing close to 30 years, brings about 40 billion future births. Depending on the past estimates of total births, this represents 26% or 34% of all births in human history, past and future. Assuming a TFR at the lower 95 percent prediction interval reduces the number of future births to below 19 billion and their share of all births in history to just 14% or 19%, respectively.

Second, intergenerational length plays a key role in determining both the number of future births and their distribution over time. When fertility is below

replacement level, a later age at childbearing implies more births in the future (as more of the women currently of childbearing age will still reproduce in the future), a slower rate of population decline, and a later timing of the eventual human extinction, as the future births are spread out over a longer time horizon.

Third, our study shows that the fears of humanity's looming depopulation are greatly exaggerated. All major agencies producing global population projections envision that the global peak population will be reached later in this century, marking a reversal of the unprecedented population growth of the last 250 years, when the global population increased ten-fold from about 800 million in 1800 to 8.2 billion today. Annual estimates of global births show that peak births were already reached in the early 2010s, at 146 million births per year. However, our analyses based on fertility scenarios in the UN WPP suggest that the global birth and population declines would continue for centuries and even millennia before the global population starts facing an imminent extinction. Taking the indicator of one thousand births per year globally as a marker of imminent extinction, the range of the UN WPP 2024 probabilistic fertility scenarios for 2100 implies that such a critical point would be reached either in the next millennium (lower 95 per cent and lower 80 per cent scenarios) or even much later, about three thousand years from now (median scenario). The upper 80 per cent and the upper 95 per cent prediction intervals even imply a perpetual future birth and population growth. Shifting the mean age at childbearing from 30 to 35, a realistic possibility, would postpone the year after which the number of births falls below one thousand by about 200 years in the lower 95 per cent and lower 80 per cent scenarios and by about 500 years in the median scenario.

Our models and scenarios should be understood as purely hypothetical. Humanity's final demise would unfold gradually if it were driven solely by low fertility and our projections cover the period of up to five thousand years into the future. Our study thus demonstrates that fears of population decline and humanity's extinction due to low birth rates are relevant only over extremely long time horizons, for which plausible demographic developments cannot be modeled.

We highlight four relevant limitations when considering plausibility of our assumptions and scenarios. First, fertility rates are never stable, especially from a period perspective: fertility often drops, rises or fluctuates due to institutional factors, economic ups and downs, technological and policy changes, changes in partnership behavior and access to contraception and abortion. Recent fertility ups and downs during the COVID-19 pandemic and other recent shocks and crises have illustrated this volatility, which makes fertility trends hard to predict. Our scenarios, freezing fertility rates at the same level for centuries, therefore do not conform to any past experience. Second, we did not explore scenarios of perpetual global persistence of very low fertility, with a TFR at or below 1.4. This

range is outside of most of the current global projection scenarios, but it is not completely implausible, as a rising number of countries globally, including China, Japan, Italy and South Korea, have experienced such low fertility rates for several decades. Future research should incorporate such scenarios. Third, our models ignored the negative impact of delayed parenthood on completed fertility due to infertility and changes in reproductive preferences across the life course. Advances in medically assisted reproduction and egg freezing may moderate this effect, but they are unlikely to eliminate it entirely. Further, our extreme-late childbearing age scenario (with a mean age at childbearing at 50) is illustrative, but unrealistic considering the current reproductive behavior and technologies. Fourth, our exercise is performed at a global level and ignores migration. In individual countries, a growth or decline in total population or the number of births may unfold much more rapidly due to international migration and imbalances in age and sex structure of their populations. Currently, countries with the most rapidly shrinking populations globally also tend to have high rates of outmigration.

Future population growth in many countries will depend more on their potential to attract migrants or prevent outmigration than on their fertility levels.

In today's public discourse, worries about future population declines dominate over voices highlighting its potentially positive consequences. It may be argued, however, that fewer people may increase global well-being, prosperity, and happiness rather than bringing about a disaster. Recent economic research shows the central role of population quality (human capital) rather than the number of people as the engine of economic growth. Population decline may even foster human capital investment, innovation and technological progress. Population decline can also contribute to reducing the negative impact humans have on the environment, resources and climate change. However, in the end, it is the pattern of consumption and production that will determine human's impact on the environment.

By modeling long-term population and birth dynamics in scenarios of low and late fertility, we gain unique insights about the extent and speed of population shrinkage at a global level. Future research needs to move to a more granular perspective and study long-term population dynamics at national and subnational levels, considering migration scenarios and abandoning the assumption of constant demographic characteristics, which we have adopted in this paper. Neither the fertility rates nor the age at childbearing will remain constant over the next centuries. Population decline is a more relevant issue in individual countries than globally and in some countries the potential threshold for extinction may be reached in the course of a few centuries rather than millennia.

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