Human population reduction is not a quick fix for environmental problems

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The inexorable demographic momentum of the global human population is rapidly eroding Earth's life-support system. There are consequently more frequent calls to address environmental problems by advocating further reductions in human fertility. To examine how quickly this could lead to a smaller human population, we used scenario-based matrix modeling to project the global population to the year 2100. Assuming a continuation of current trends in mortality reduction, even a rapid transition to a worldwide one-child policy leads to a population similar to today's by 2100. Even a catastrophic mass mortality event of 2 billion deaths over a hypothetical 5-y window in the mid-21st century would still yield around 8.5 billion people by 2100. In the absence of catastrophe or large fertility reductions (to fewer than two children per female worldwide), the greatest threats to ecosystems—as measured by regional projections within the 35 global Biodiversity Hotspots—indicate that Africa and South Asia will experience the greatest human pressures on future ecosystems. Humanity's large demographic momentum means that there are no easy policy levers to change the size of the human population substantially over coming decades, short of extreme and rapid reductions in female fertility; it will take centuries, and the long-term target remains unclear. However, some reduction could be achieved by midcentury and lead to hundreds of millions fewer people to feed. More immediate results for sustainability would emerge from policies and technologies that reverse rising consumption of natural resources.

demography | fertility | catastrophe | war | mortality

The size of the global human population is often considered unsustainable in terms of its current and future impact on the Earth's climate, its ability to distribute food production equitably, population and species extinctions, the provision of adequate ecosystem services, and economic, sociological, and epidemiological well-being (1–8). Others argue that technology, ingenuity, and organization are stronger mediators of the environmental impact of human activities (9–11). Regardless, *Homo sapiens* is now numerically the dominant large organism on the planet. According to the United Nations, the world human population reached nearly 7.1 billion in 2013, with median projections of 9.6 billion (range: 8.3–11.0 billion) by 2050 and 10.9 billion (range: 6.8–16.6 billion) by 2100 (12), with more recent refinements placing the range at 9.6 to 12.3 billion by 2100 (13). So rapid has been the recent rise in the human population (i.e., from 1.6 billion in 1900), that roughly 14% of all of the human beings that have ever existed are still alive today (14).

Worldwide, environmental conditions are threatened primarily because of human-driven processes in the form of land conversion (agriculture, logging, urbanization), direct exploitation (fishing, bushmeat), species introductions, pollution, climate change (emissions), and their synergistic interactions (15). Although it is axiomatic that a smaller human population would reduce most of these threatening processes (16), separating consumption rates and population size per se is difficult (17) because of their combined effects on the loss of biodiversity and nonprovisioning natural capital (3, 18, 19), as well as the variation in consumption patterns among regions and socio-economic classes (20, 21). Sustainability requires an eventual stabilization

of Earth's human population because resource demands and living space increase with population size, and proportional ecological damage increases even when consumption patterns stabilize (22, 23); it is therefore essential that scenarios for future human population dynamics are explored critically if we are to plan for a healthy future society (24).

There have been repeated calls for rapid action to reduce the world population humanely over the coming decades to centuries (1, 3), with lay proponents complaining that sustainability advocates ignore the "elephant in the room" of human overpopulation (25, 26). Amoral wars and global pandemics aside, the only humane way to reduce the size of the human population is to encourage lower per capita fertility. This lowering has been happening in general for decades (27, 28), a result mainly of higher levels of education and empowerment of women in the developed world, the rising affluence of developing nations, and the one-child policy of China (29–32). Despite this change, environmental conditions have worsened globally because of the overcompensating effects of rising affluence-linked population and consumption rates (3, 18). One of the problems is that there is still a large unmet need for more expansive and effective family-planning assistance, which has been previously hindered by conservative religious and political opposition, premature claims that rapid population growth has ended, and the reallocation of resources toward other health issues (33). Effective contraception has also been delayed because of poor education regarding its availability, supply, cost, and safety, as well as opposition from family members (33). Notwithstanding, some argue that if we could facilitate the transition to lower fertility

Significance

The planet's large, growing, and overconsuming human population, especially the increasing affluent component, is rapidly eroding many of the Earth's natural ecosystems. However, society's only real policy lever to reduce the human population humanely is to encourage lower per capita fertility. How long might fertility reduction take to make a meaningful impact? We examined various scenarios for global human population change to the year 2100 by adjusting fertility and mortality rates (both chronic and short-term interventions) to determine the plausible range of outcomes. Even one-child policies imposed worldwide and catastrophic mortality events would still likely result in 5–10 billion people by 2100. Because of this demographic momentum, there are no easy ways to change the broad trends of human population size this century.

rates, most of the sustainability problems associated with the large human population would be greatly alleviated (3, 34–36).

Even in an ideal socio-political setting for lower birth-rate policies and the commitment to global-scale family planning, however, several questions remain: (*i*) How quickly could we achieve a smaller human population by adjusting such sociological levers (or via unexpected, large-scale stressors), and (*ii*) where in the world are human populations likely to do the most damage to their supporting environment over the coming century? To address the first of these questions on population trajectories, we built deterministic population models for humans, based on broad, multiregion geographical data drawn from the World Health Organization (WHO) and the United States Census Bureau. Using a Leslie-matrix approach, we projected the 2013 world population through to the year 2100 with several adjustments to fertility, mortality, and age at first childbirth (primiparity) to investigate the relative importance of different vital rates (representing possible policy interventions or stressors) on the trajectory and population size at the end of this century, and on the ratio of the "dependent" component of the population (<15 and >65 y) to the remainder (28). Existing projections of the human population typically do not include mass mortality events, of which there has been no prior experience, such as worldwide epidemics, nuclear wars, or climate change (32). We therefore also added four "catastrophe" scenarios to simulate the possible effects of climate disruption, world wars, or global pandemics on population trends. Our aim was not to forecast the actual population size at the end of this century; rather, we sought to compare the sensitivity of population trajectories to plausible and even unlikely social phenomena, and consider how these might influence long-term human demography.

To address the second question on environmental impacts of future populations, we focused on 14 region-specific projections of the human population, and related these to the areas of the planet most in need of environmental protection from the perspective of unique ecosystems: Biodiversity Hotspots (37). Although there are other ways of measuring regional patterns in environmental degradation and susceptibility (18), today's 35 Biodiversity Hotspots are internationally recognized as regions containing the most unique (endemic) species that are currently experiencing the greatest threats from human endeavors (37, 38). Previous studies have shown that current human population densities and growth rates are higher on average in Biodiversity Hotspots than elsewhere (39, 40), contributing to higher rates of deforestation and species loss (41). We used a similar framework to consider future human population trajectories of different regions relative to the distribution of global Biodiversity Hotspots, with the goal of assessing the relative change in threat to these unique environments after accounting for geographical differences in growth rates.

Methods

Demographic Data. Most published human demographic data are expressed as mortality and birth rates per 5-y age class, often with the first year of life provided separately. The most reliable age-specific mortality rates are reported by the WHO under the auspices of the WHO-CHOICE project (www.who.int/choice). Although originally compiled for modeling the progression of diseases in the human population, we opted to use these data because they are conveniently expressed as mortality rates per yearly age class and per WHO subregion (42), and so do not require smoothing or interpolation. The 14 WHO-CHOICE subregions, based on geographical location and demographic profiles and their constituent countries (www.who.int/choice), are listed in the legend of Fig. 4.

For globally averaged, age-specific (0–100+ y) mortalities, we aggregated the mean mortalities across each WHO subregion, with each age-specific (*x*) mortality (M_x) weighted by its population size vector (N_x) for each subregion. We estimated the 2013 N_x from the 2005 N_x provided by the WHO-CHOICE project by multiplying each N_x by the ratio of $N_{2013}:N_{2005}$, with N_{2013} sourced for each subregion from the US Census Bureau International Database (www.census.gov/population/international/data/idb).

We accessed 2013 fertility data by 5-y age groups from the US Census Bureau International Database. We converted the births per 1,000 women into age-specific fertilities (m_x) by dividing the 5-y classes equally among their constituent years and accounting for breeding female mortality within each of the 5-y classes. All age-specific population size, mortality, and fertility data we derived from these sources are available online at dx.doi.org/10.4227/05/5386F14C65D34.

Leslie Matrix. We defined a prebreeding 100 (*i*) × 100 (*j*) element, Leslie matrix (**M**) for females only, multiplying the subsequent projected population vector by the overall sex ratio to estimate total population size at each time step. Fertilities (m_x) occupied the first row of the matrix (ages 15–49), survival probabilities (1 – M_x) were applied to the subdiagonal, and the final diagonal transition probability ($M_{i,j}$) represented survival of the 100+ age class. Complete R code (43) for the scenario projections is provided in Datasets S1 and S2.

Global Scenarios. For each projection, we multiplied the N_x vector by **M** for 87 yearly time steps (2013–2100, except for one fertility-reduction scenario that was extended to 2300). All projections were deterministic. Scenario 1 was a business-as-usual (BAU) "control" projection, with all matrix elements kept constant at 2013 values. Scenario 2a was a "realistic" projection with a linear decline in M_x, starting in 2013, to 50% of their initial values by 2100 (i.e., via improving diet, affluence, medicine, female empowerment, and so forth). We also emulated a shift toward older primiparity by allocating 50% of the fertility in the youngest reproductive age class (15–24) evenly across the older breeding classes (25–49), following a linear change function from 2013 to 2100 (as per the decline in M_x). We then implemented a linear decline in total fertility from the 2013 starting value of 2.37 children per female to 2.00 by 2100 (to simulate the ongoing trend observed in recent decades). The rate of fertility decline was thus 0.0042 children per female per year. Scenario 2b was identical to Scenario 2 in all respects except mortality remained constant over the projection interval. Scenario 3 was similar to Scenario 2a, except that we reduced total fertility more steeply, to one child per female by 2100 to emulate, for example, a hypothetical move toward a worldwide one-child policy by the end of the century. This rate of fertility decline was thus 0.0157 children per female per year. In scenario 4, we reduced fertility even more rapidly to one child per female by 2045 (fertility decline rate = 0.0427) and kept it constant thereafter to 2100; we also removed the assumption that mortality (M_x) would decline over the projection interval, so we maintained M_x at 2013 values. In Scenario 5, we examined how a global avoidance of unintended pregnancies resulting in births, via reproduction education, family planning, and cultural shift (3), would affect our projections to 2100. Using data from 2008, there were 208 million pregnancies globally, of which an estimated 86 million were unintended (44). Of these 86 million, ~11 million were miscarried, 41 million aborted, and 33 million resulted in unplanned births (44). In this scenario, therefore, we assumed that 33 of 208 (15.8%) births per year of the projection would not occur if unwanted pregnancies were avoided entirely.

Scenarios 6–9 represent a comparative "what if?" exploration of different levels of chronic or acute elevated mortality rates, spanning the plausible through to the highly unlikely. Scenario 6 used the BAU matrix, but with childhood mortality increasing linearly to double the 2013 values by 2100 to simulate food shortages caused by, for example, climate-disruption impacts on crop yields (45). Scenario 7 implemented a broad-scale mortality event equivalent to the approximate number of human deaths arising from the First and Second World Wars and the Spanish flu combined (Σ = 131 million deaths; http://necrometrics.com) as a proportion of the midway (i.e., 2056) projected population size (9.95 billion) (*Results*). Based on a world population of 2.5 billion at the end of the Second World War, this combined death toll from these historical events represented 5.2% of the global population; thus, we applied this proportional additional mortality to the 2056 (midway) world population estimate, which equates to about 500 million deaths over 5 y. For Scenario 8, we implemented a mass mortality event that killed 2 billion people worldwide (again, implemented over a 5-y period from 2056 onwards). Scenario 9 was identical to Scenario 8, only we increased the death toll substantially, to 6 billion, and implemented the catastrophe one-third of the way through the projection interval (i.e., 2041) to allow for a longer recovery from its consequences. A summary of the initial parameter values and their temporal changes for all scenarios is provided in Table S1.

Although potentially exaggerated, we also assumed that the demographic rates of the overall human population would shift markedly following such large mortality events, thus mimicking a type of postwar condition similar to that observed in the 1950s (i.e., the "baby boom"). Following the final year of the mass mortality catastrophe, we (arbitrarily) assumed that fertility would double, but then decline linearly to 2013 values by 2100. We also assumed that overall
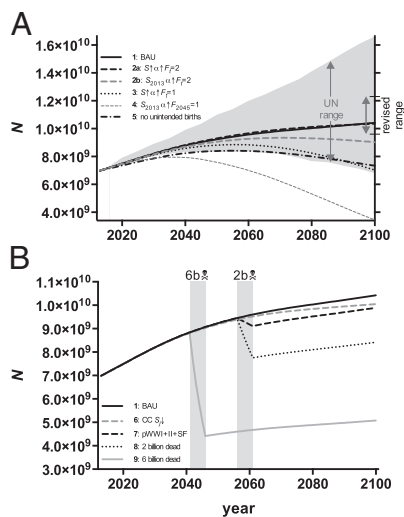
Fig. 1. Scenario-based projections of world population from 2013 to 2100. (*A*) Scenario 1: BAU population growth (constant 2013 age-specific vital rates); Scenario 2a: reducing mortality (*M*), increasing age at primiparity (α), declining fertility to two children per female ($F_t = 2$) by 2100; Scenario 2b: same as Scenario 2a, but without reduced mortality; Scenario 3: same as Scenario 2a, but $F_t = 1$; Scenario 4: same as Scenario 3, but without reduced mortality and $F_t = 1$ by 2045 and thereafter constant to 2100; Scenario 5: avoiding all unintended pregnancies resulting in annual births. High and low projections by the United Nations (12) are shown as a grayed area, and the revised range for 2100 (13) is also indicated. (*B*) Scenario 6: elevated childhood mortality (M_j) from climate change (CC); Scenario 7: mass mortality event over a 5-y period starting 2056, equal to the proportion of combined number of deaths from World War I, World War II, and Spanish flu scaled to the mid-21st century population; Scenario 8: 2 billion people killed because of a global pandemic or war spread over 5 y, starting midway (i.e., 2056) through the projection interval; Scenario 9: 6 billion people killed because of a global pandemic or war spread over 5 y and initiated one-third of the way through the projection interval (i.e., 2041). The mass mortality windows are indicated as gray bars.

mortality would double following the final year of the catastrophe (e.g., to emulate lingering effects such as food shortages, disrupted social interactions and disease epidemics), but then decline linearly to 2013 values by 2100.

For all scenario-based projections, we calculated the yearly total population size (males and females), and the proportion of the population <15-y-old or >65-y-old. The sum of this proportion (i.e., the proportion in the 15- to 65-y classes) relative to the remainder represents the "dependency ratio," which is a metric of the population generally considered to be dependent on the productivity of used society (28). To test the sensitivity of the choice of the upper-age boundary on the overall ratio (e.g., 65 y), we repeated the calculation for the upper "dependant" age of 75 y.

Subregional Scenarios. We alternatively projected each of the WHO subregions separately using their subregion-specific mortalities and US Census Bureau fertilities and population vectors, without assuming any changes over time to the component vital rates or migration between regions. Indeed, interregional migration remains one of the most difficult parameters to predict for the human population (32). For comparison, we also repeated the subregional projections assuming the same linear change in vital rates as per Scenario 2a for the global projections. For each region, we overlaid the extent of the latest 35 Conservation International Biodiversity Hotspots (37, 38) (shapefile available from databasin.org) to determine which Hotspots were associated with the most rapid projected expansion of the human population over the coming century, and the areas of highest human population density in 2100.

Results

Projection Scenarios. The population projections for the BAU (Scenario 1) and realistic changes in vital rates (Scenario 2a) produced similar 2050 [9.23 and 9.30 billion, respectively; difference (Δ) = 68 million] and end-of-century populations (10.42 and 10.35 billion, respectively; Δ = 70 million) (Fig. 1*A*). The more draconian fertility reduction to a global one child per

woman by 2100 (Scenario 3) resulted in a peak population size of 8.9 billion in 2056, followed by a decline to ~7 billion by 2100 (i.e., a return to the 2013 population size) (Fig. 1*A*). Enforcing a one child per female policy worldwide by 2045 and without improving survival (Scenario 4) resulted in a peak population size of 7.95 billion in 2037, 7.59 billion by 2050, and a rapid reduction to 3.45 billion by 2100. Avoiding the approximate 16% of annual births resulting from unintended pregnancies (Scenario 5) reduced the projected population in 2050 to 8.39 billion (compared to, for example, 9.30 billion in Scenario 2a; Δ = 901 million), and in 2100 to 7.3 billion (compared to, for example, 10.4 billion in Scenario 2a; Δ = 3014 million) (Fig. 1*A*).

The most striking aspect of the "hypothetical catastrophe" scenarios was just how little effect even these severe mass mortality events had on the final population size projected for 2100 (Fig. 1*B*). The climate change (childhood mortality increase) (Scenario 5), future proportional "World Wars" mortality event (Scenario 6), and BAU (Scenario 1) projections all produced between 9.9 and 10.4 billion people by 2100 (Fig. 1*B*). The catastrophic mass mortality of 2 billion dead within 5 y half-way through the projection interval (Scenario 7) resulted in a population size of 8.4 billion by 2100, whereas the 6 billion-dead scenario (Scenario 8) implemented one-third of the way through the projection still led to a population of 5.1 billion by 2100 (Fig. 1*B*).

Projecting Scenario 3 (worldwide one-child policy by 2100, assuming no further reduction in total fertility thereafter) to 2300, the world population would fall to half of its 2013 size by 2130, and one-quarter by 2158 (Fig. 2). This result is equivalent to an instantaneous rate of population change (*r*) of −0.0276 once the age-specific vital rates of the matrix stabilize (i.e., after we imposed invariant vital rates at 2100 and onwards).

Another notable aspect of the noncatastrophe projections (Scenarios 1 and 3) was the relative stability of the dependency ratio during the projection interval (Fig. 3). The ratio varied from 0.54 to a maximum of 0.67 (Scenario 3) by 2100, with the latter equating to ~1.5 (1/0.67) working adults per dependant. Increasing the older dependency age to 75 only stabilized the dependency ratio further (Scenario 1: 0.38–0.44; Scenario 3: 0.33–0.44) (Fig. S1).

Subregions. Region 4 (Americas B) overlaps the highest number of Biodiversity Hotspots (9), although it is projected to have the fourth lowest population density by 2100 (44.8 persons km^{-2}) (Table S2). The regions with the next-highest number of Hotspots are Regions 2 (Africa E) and 14 (Western Pacific B) (eight each) (Fig. 4 and Table S1). Although Region 14 had the largest human population in 2013, Region 2 had the second-highest projected rate of increase of all regions (Fig. 4). Furthermore, two Hotspots in Region 2 (Eastern Afromontane, Horn of Africa) are also found in Regions 6 and 7 (Eastern Mediterranean), with the sixth- and third-highest rates of increase, respectively (Table S2). Both African regions (Regions 1 and 2) are also projected to have the second- (Region 1: 246.4 persons km^{-2}) and third-highest (Region 2: 241.3 persons km^{-2}) population
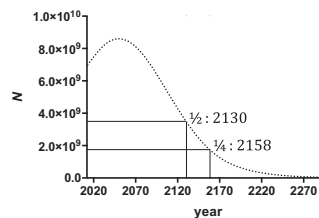

Fig. 2. Long-term outlook. Scenario-based projection of world population from 2013 to 2300 based on constant 2013 age-specific vital rates but declining fertility to one child per female ($F_t = 1$) by 2100 (fertility held constant thereafter). Population reduces to one-half of its 2013 size by 2130, and one-quarter by 2158.
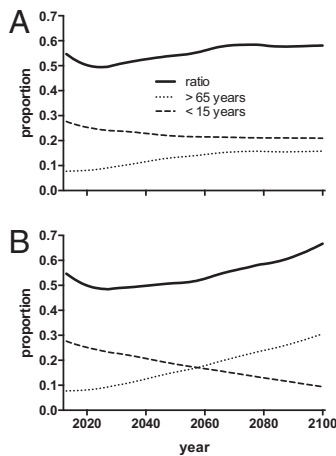
Fig. 3. Size of dependent population. Proportion of people <15 y or >65 y per time step, and their ratio to the (most productive) remainder of the population (dependency ratio) for (*A*) Scenario 1 (BAU), and (*B*) Scenario 3 (decreasing mortality, increasing age at primiparity, decreasing fertility to one child per female). See *Methods* for detailed scenario descriptions.

densities by 2100 (Fig. 4 and Table S1). The Biodiversity Hotspots of Region 12 (Southeast Asia D: Himalaya, Indo-Burma, Western Ghats, and Sri Lanka) are also a particular concern because the region currently has the second-largest population size and is projected to double by the end of this century, producing the highest projected human population density of any subregion (656 persons km^{-2}) (Fig. 4 and Table S1). If we alternatively assumed linear declines in fertility and mortality, and increasing age at primiparity (i.e., Scenario 2a conditions), the subregional rankings according to projected rate of increase were nearly identical (except for the relative ranking of the last two regions) (Table S3). For these projections, the final mean population densities were between 16% and 37% lower (Table S3) than those predicted assuming constant vital rates (Fig. 4 and Table S2).

Discussion

Although not denying the urgency with which the aggregate impacts of humanity must be mitigated on a planetary scale (3), our models clearly demonstrate that the current momentum (28) of the global human population precludes any demographic "quick fixes." That is, even if the human collective were to pull as hard as possible on the total fertility policy lever (via a range of economic, medical, and social interventions), the result would be ineffective in mitigating the immediately looming global sustainability crises (including anthropogenic climate disruption), for which we need to have major solutions well under way by 2050 and essentially solved by 2100 (3, 46, 47). However, this conclusion excludes the possibility that global society could avoid all unintended births or that the global average fertility rate could decline to one child per female by 2100. Had humanity acted more to constrain fertility before this enormous demographic momentum had developed (e.g., immediately following World War II), the prospect of reducing our future impacts would have been more easily achievable.

That said, the projections assuming all unintended pregnancies resulting in births were avoided each year resulted in a global human population size in 2100 that was over 3 billion people smaller than one assuming no similar reduction in birth rates (compare, for example, Scenarios 5 and 2a). Similarly, a global move toward one child per female by 2100 or, more radically, by 2045, indicated that there could be theoretically billions fewer people by the end of the century. More realistically, if worldwide average fertility could be reduced to two children per female by 2020 (compared with 2.37 today), there would be 777 million fewer

people to feed planet-wide by 2050 (compared with the BAU; scenario not shown in *Results*). Although these scenarios would be challenging to achieve, our model comparisons reveal that effective family planning and reproduction education worldwide (48) have great potential to reduce the size of the human population and alleviate pressure on resource availability over the long term, in addition to generating other social advantages, such as fewer abortions, miscarriages, and lower maternal mortality (3).

This finding is particularly encouraging considering that even the population reduction attributed to China's controversial one-child policy might have been assisted by an already declining fertility rate (49), much as the world's second most-populous country, India, has demonstrated over the last several decades (50). Perhaps with a more planned (rather than forced) approach to family planning, substantial reductions in future population size are plausible. Better family planning could be achieved not only by providing greater access to contraception, but through education, health improvements directed at infant mortality rates, and outreach that would assuage some of the negative social and cultural stigmas attached to their use (33). A greater commitment from high-income countries to fund such programs, especially in the developing world, is a key component of any future successes (51).

Our aim was not to forecast a precise trajectory or size of the human population over the coming century, but to demonstrate what is possible when assuming various underlying dynamics, so as to understand where to direct policy most effectively. Although all projections lacked a stochastic component (notwithstanding the prescribed trends in vital rates and mass mortality catastrophes imposed), such year-to-year variation is typically smoothed when population sizes are large, as is the case for humans. Catastrophic deaths arising from pandemics or major wars could, of course, lead to a wide range of future population sizes. Our choice of the number of people dying in the catastrophe scenarios illustrated here were therefore necessarily arbitrary, but we selected a range of values up to what we consider to be extreme (e.g., 6 billion deaths over 5 y) to demonstrate that even future events that rival or plausibly exceed past societal cataclysms cannot guarantee small future population sizes without additional measures, such as fertility control. Furthermore, we did not incorporate any density feedback to emulate the effects of a planet-wide human carrying capacity on vital rates (3), apart from scenarios imitating possible demographic consequences of reduced food supply or resource-driven war or disease, because such relationships are strongly technology-dependent and extremely difficult and politically sensitive to forecast (26, 52). Furthermore, regional comparisons should be considered only as indicative because we did not explicitly model interregional migration, and the projected rates of change and final densities are dependent on whether vital rates are assumed to be constant or change according to recent trends. Local population densities do not necessarily correlate perfectly with regional consumption given world disparity in wealth distribution, environmental leakage, and foreign land grabbing (18). Despite these simplifications, our results are indicative of the relative influence of particular sociological events on human population trajectories over the next century.

Globally, human population density has been shown to predict the number of threatened species among nations (53–55), and at a national scale, there is a clear historical relationship between human population size and threats to biodiversity (56, 57). However, because of the spatial congruence between human population size and species richness, a lack of data on extinctions, and variability across methods, there is only a weak correlation globally between human density and observed species extinctions (58). Nonetheless, the pressures are clear, with half of world protected areas losing their biodiversity (59) because of high human stressors—including population growth rates and locally or foreign-driven consumption (60)—at their edges.
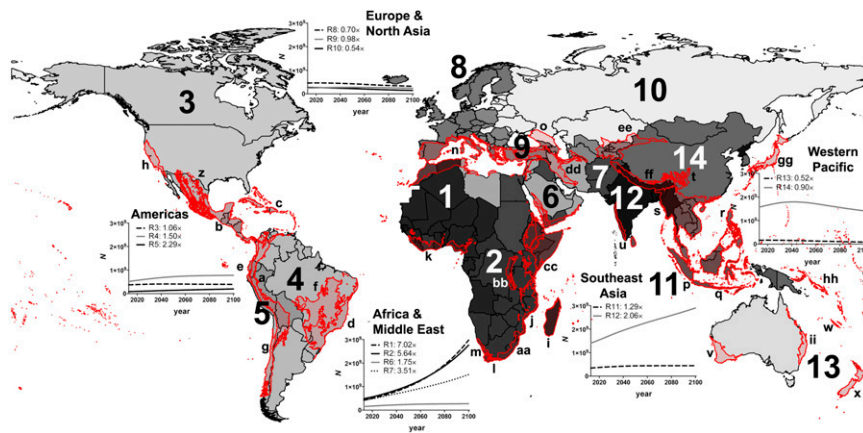
Fig. 4. Regional variation and impacts. Human population projections under the BAU levels of population growth (2013 matrix; Scenario 1) for 14 subregions (R1–R14; see below for country composition). Regional shading indicates relative mean population density projected for 2100: white shading = 0 persons km^{-2} to darker shading = 656.6 persons km^{-2}. Values next to each region line (legends) indicate the ratio of the projected 2100 population (N_{2100}) to the 2013 start population (N_{2013}). Red hatched overlay indicates position of global Biodiversity Hotspots (a–ii: see below for full Hotspot list). Full Hotspot listing per region and associated projected values are also provided in Table S2. Subregion country composition (boldface indicates region number on the map): Africa D, **Region 1**: Angola (AGO), Benin (BEN), Burkina Faso (BFA), Cameroon (CMR), Cape Verde (CPV), Algeria (DZA), Gabon (GAB), Ghana (GHA), Guinea (GIN), Gambia (GMB), Guinea-Bissau (GNB), Equatorial Guinea (GNQ), Liberia (LBR), Madagascar (MDG), Mali (MLI), Mauritania (MRT), Mauritius (MUS), Niger (NER), Nigeria (NGA), Senegal (SEN), Sierra Leone (SLE), Sao Tome and Principe (STP), Seychelles (SYC), Chad (TCD), Togo (TGO); Africa E, **Region 2**: Burundi (BDI), Botswana (BWA), Central African Republic (CAF), Côte d'Ivoire (CIV), The Democratic Republic of the Congo (COD), Congo (COG), Eritrea (ERI), Ethiopia (ETH), Kenya (KEN), Lesotho (LSO), Mozambique (MOZ), Malawi (MWI), Namibia (NAM), Rwanda (RWA), Swaziland (SWZ), United Republic of Tanzania (TZA), Uganda (UGA), South Africa (ZAF), Zambia (ZMB), Zimbabwe (ZWE); Americas A, **Region 3**: Canada (CAN), Cuba (CUB), United States (USA); Americas B, **Region 4**: Argentina (ARG), Antigua and Barbuda (ATG), Bahamas (BHS), Belize (BLZ), Brazil (BRA), Barbados (BRB), Chile (CHL), Colombia (COL), Costa Rica (CRI), Dominica (DMA), Dominican Republic (DOM), Grenada (GRD), Guyana (GUY), Honduras (HND), Jamaica (JAM), Saint Kitts and Nevis (KNA), Saint Lucia (LCA), Mexico (MEX), Panama (PAN), Paraguay (PRY), El Salvador (SLV), Suriname (SUR), Trinidad and Tobago (TTO), Uruguay (URY), Saint Vincent and the Grenadines (VCT), Venezuela (VEN); Americas D, **Region 5**: Bolivia (BOL), Ecuador (ECU), Guatemala (GTM), Haiti (HTI), Nicaragua (NIC), Peru (PER); Eastern Mediterranean B, **Region 6**: United Arab Emirates (ARE), Bahrain (BHR), Cyprus (CYP), Islamic Republic of Iran (IRN), Jordan (JOR), Kuwait (KWT), Lebanon (LBN), Libyan Arab Jamahiriya (LBY), Oman (OMN), Qatar (QAT), Saudi Arabia (SAU), Syrian Arab Republic (SYR), Tunisia (TUN); Eastern Mediterranean D, **Region 7**: Afghanistan (AFG), Djibouti (DJI), Egypt (EGY), Iraq (IRQ), Morocco (MAR), Pakistan (PAK), Somalia (SOM), Sudan (SDN), Yemen (YEM); Europe A, **Region 8**: Andorra (AND), Austria (AUT), Belgium (BEL), Switzerland (CHE), Czech Republic (CZE), Germany (DEU), Denmark (DNK), Spain (ESP), Finland (FIN), France (FRA), United Kingdom (GBR), Greece (GRC), Croatia (HRV), Ireland (IRL), Iceland (ISL), Israel (ISR), Italy (ITA), Luxembourg (LUX), Monaco (MCO), Malta (MLT), The Netherlands (NLD), Norway (NOR), Portugal (PRT), San Marino (SMR), Slovenia (SVN), Sweden (SWE); Europe B, **Region 9**: Albania (ALB), Armenia (ARM), Azerbaijan (AZE), Bulgaria (BGR), Bosnia and Herzegovina (BIH), Georgia (GEO), Kyrgyzstan (KGZ), The Former Yugoslav Republic of Macedonia (MKD), Montenegro (MNE), Poland (POL), Romania (ROU), Serbia (SRB), Slovakia (SVK), Tajikistan (TJK), Turkmenistan (TKM), Turkey (TUR), Uzbekistan (UZB); Europe C, **Region 10**: Belarus (BLR), Estonia (EST), Hungary (HUN), Kazakhstan (KAZ), Lithuania (LTU), Latvia (LVA), Moldova (MDA), Russian Federation (RUS), Ukraine (UKR); Southeast Asia B, **Region 11**: Indonesia (IDN), Sri Lanka (LKA), Thailand (THA), East Timor (TLS); Southeast Asia D, **Region 12**: Bangladesh (BGD), Bhutan (BTN), India (IND), Maldives (MDV), Myanmar (MMR), Nepal (NPL), Democratic People's Republic of Korea (PRK); Western Pacific A, **Region 13**: Australia (AUS), Brunei Darussalam (BRN), Japan (JPN), New Zealand (NZL), Singapore (SGP); Western Pacific B, **Region 14**: China (CHN), Cook Islands (COK), Fiji (FJI), Federated States of Micronesia (FSM), Cambodia (KHM), Kiribati (KIR), Republic of Korea (KOR), Lao People's Democratic Republic (LAO), Marshall Islands (MHL), Mongolia (MNG), Malaysia (MYS), Niue (NIU), Nauru (NRU), Philippines (PHL), Palau (PLW), Papua New Guinea (PNG), Solomon Islands (SLB), Tonga (TON), Tuvalu (TUV), Vietnam (VNM), Vanuatu (VUT), Samoa (WSM). **Biodiversity Hotspots:** a, Tropical Andes; b, Mesoamerica; c, Caribbean Islands; d, Atlantic Forest; e, Tumbes-Chocó-Magdalena; f, Cerrado; g, Chilean Winter Rainfall-Valdivian Forests; h, California Floristic Province; I, Madagascar and the Indian Ocean Islands; j, Coastal Forests of Eastern Africa; k, Guinean Forests of West Africa; l, Cape Floristic Region; m, Succulent Karoo; n, Mediterranean Basin; o, Caucasus; p, Sundaland; q, Wallacea; r, Philippines; s, Indo-Burma, India and Myanmar; t, Mountains of Southwest China; u, Western Ghats and Sri Lanka; v, Southwest Australia; w, New Caledonia; x, New Zealand; y, Polynesia-Micronesia; z, Madrean Pine-Oak Woodlands; aa, Maputaland-Pondoland-Albany; bb, Eastern Afromontane; cc, Horn of Africa; dd, Irano-Anatolian; ee, Mountains of Central Asia; ff, Eastern Himalaya, Nepal; gg, Japan; hh, East Melanesian Islands; ii, Forests of East Australia.

The socio-political argument for encouraging high fertility rates to offset aging populations (61) that would otherwise put a strain on the productive (working) component of the population is demonstrably weak. This is because focusing solely on the growing aged component of a population ignores the concomitant reduction in the proportion of young dependants as the affluence level and fertility rates of women shift to older primiparity and fewer children. Thus, our projections show that even an aging population maintains an approximately constant number of dependants per working-age person, even under scenarios or in regions of relatively rapid projected decline (e.g., Regions 8, 10, and 13) (Fig. 4).

The broader question of what constitutes an optimum human population size (and how long it would take) is fraught with uncertainty, being so highly dependent on technological and sociological advances (9, 62). It has been suggested that a total world population between 1 and 2 billion might ensure that all individuals lived prosperous lives, assuming limited change in per capita consumption and land/materials use (1, 62). According to

our basic fertility-reduction model (to one child per female by 2100), and excluding mass mortality events, achieving such a goal would take a minimum of 140 y (2 billion by 2153) (Fig. 1B), but realistically much longer given decreasing mortality rates and the intractability and questionable morality of enforcing a worldwide one-child policy as fertility control. A considerably larger optimal human population size is also feasible if society embraces technological improvements (including sustainable energy) that allow for decoupling of impacts and near-closed-system recycling, and so can vastly reduce consumption rates of primary resources (63, 64).

Conclusion

There are clearly many environmental and societal benefits to ongoing fertility reduction in the human population (3, 48, 58), but here we show that it is a solution long in the making from which our great-great-great-great grandchildren might ultimately benefit, rather than people living today. It therefore cannot be argued to be the elephant in the room for immediate environmental

sustainability and climate policy. A corollary of this finding is that society's efforts toward sustainability would be directed more productively toward adapting to the large and increasing human population by rapidly reducing our footprint as much as possible through technological (63, 64) and social innovation (3, 65), devising cleverer ways to conserve remaining species and ecosystems, encouraging per capita reductions in consumption of irreplaceable goods (58), and treating population as a long-term planning goal.

It is therefore inevitable that the virtually locked-in increase in the global human population during the 21st century—regardless of trends in per capita consumption rates—risks increasing the threat to the environment posed by humans because of growing aggregate and accumulated demands. Apart from efforts to accelerate (rather than reverse) ongoing declines in fertility, ameliorated especially by effective family planning, female empowerment, better education, and political and religious endorsement of sustainability in the

developing world (48), the only other immediate control on regional population trends could take the form of (politically and morally contentious) country-specific immigration policies. Accepting the difficulty of this, the question of how many more species we lose, ecosystem services we degrade, and natural capital we destroy will therefore depend mostly—at least over the coming century—on how much we can limit the damage through timely and efficient technological and social advances. However, this is not an excuse for neglecting ethical measures for fertility reduction now; it could avoid millions of deaths by midcentury and possibly keep the planet more habitable for *Homo sapiens* in the next.

1. Pimentel D, Harman R, Pacenza M, Pecarsky J, Pimentel M (1994) Natural resources and an optimum human population. *Popul Environ* 15(5):347–369.
2. Daily GC, Ehrlich PR (1992) Population, sustainability, and Earth's carrying capacity. *Bioscience* 42(10):761–771.
3. Ehrlich PR, Kareiva PM, Daily GC (2012) Securing natural capital and expanding equity to rescale civilization. *Nature* 486(7401):68–73.
4. O'Neill BC, et al. (2012) Demographic change and carbon dioxide emissions. *Lancet* 380(9837):157–164.
5. Murtaugh PA, Schlax MG (2009) Reproduction and the carbon legacies of individuals. *Glob Environ Change* 19(1):14–20.
6. Potts M (2009) Where next? *Philos Trans R Soc Lond B Biol Sci* 364(1532):3115–3124.
7. Butler CD (2012) Infectious disease emergence and global change: Thinking systemically in a shrinking world. *Infect Dis Poverty* 1(1):5.
8. Sen A (1983) *Poverty and Famines: An Essay on Entitlement and Deprivation* (Oxford Univ Press, Oxford, UK).
9. Cohen JE (1998) How many people can the earth support?. *New York Rev* October 8:29–31.
10. Simon JL, Steinmann G (1991) Population growth, farmland, and the long-run standard of living. *J Popul Econ* 4(1):37–51.
11. Johnson DG (2000) Population, food, and knowledge. *Am Econ Rev* 90(1):1–14.
12. United Nations (2013) *World Population Prospects: The 2012 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.227* (United Nations, Department of Economic and Social Affairs, Population Division, New York).
13. Gerland P, et al. (2014) World population stabilization unlikely this century. *Science*, 10.1126/science.1257469.
14. Westing AH (2010) All the many humans ever: An update. *Bioscience* 60(10):777.
15. Brook BW, Sodhi NS, Bradshaw CJA (2008) Synergies among extinction drivers under global change. *Trends Ecol Evol* 23(8):453–460.
16. Laurance WF, Sayer J, Cassman KG (2014) Agricultural expansion and its impacts on tropical nature. *Trends Ecol Evol* 29(2):107–116.
17. Ehrlich PR, Holdren J (1971) Impact of population growth. *Science* 171(3977):1212–1217.
18. Bradshaw CJA, Giam X, Sodhi NS (2010) Evaluating the relative environmental impact of countries. *PLoS ONE* 5(5):e10440.
19. The Royal Society (2012) *People and the Planet. The Royal Society Science Policy Centre Report 01/12* (The Royal Society, London).
20. Krausmann F, Erb K-H, Gingrich S, Lauk C, Haberl H (2008) Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol Econ* 65(3):471–487.
21. Butler CD (1997) The consumption bomb. *Med Confl Surviv* 13(3):209–218.
22. Davidson DJ, Andrews J (2013) Ecology. Not all about consumption. *Science* 339(6125):1286–1287.
23. Davidson DJ, Andrews J, Pauly D (2014) The effort factor: Evaluating the increasing marginal impact of resource extraction over time. *Glob Environ Change* 25:63–68.
24. DeLong JP, Burger O, Hamilton MJ (2013) The UN medium population projection is an unstable equilibrium. *Front Ecol Environ* 11(2):65–66.
25. Bailey AJ (2011) Population geographies and climate change. *Prog Hum Geogr* 35(5):686–695.
26. McMichael AJ (1995) Contemplating a one child world. *BMJ* 311(7021):1651–1652.
27. Lee R (2003) The demographic transition: Three centuries of fundamental change. *J Econ Perspect* 17(4):167–190.
28. Bongaarts J (2009) Human population growth and the demographic transition. *Philos Trans R Soc Lond B Biol Sci* 364(1532):2985–2990.
29. Bongaarts J, Watkins SC (1996) Social interactions and contemporary fertility transitions. *Popul Dev Rev* 22(4):639–682.
30. Myrskylä M, Kohler H-P, Billari FC (2009) Advances in development reverse fertility declines. *Nature* 460(7256):741–743.
31. Ebenstein A (2010) The "missing girls" of China and the unintended consequences of the One Child Policy. *J Hum Resour* 45(1):87–115.
32. Cohen JE (2003) Human population: The next half century. *Science* 302(5648):1172–1175.
33. Bongaarts J, Sinding S (2011) Population policy in transition in the developing world. *Science* 333(6042):574–576.
34. Šlaus I, Jacobs G (2011) Human capital and sustainability. *Sustainability* 3(1):97–154.
35. Stephenson J, Newman K, Mayhew S (2010) Population dynamics and climate change: What are the links? *J Public Health (Oxf)* 32(2):150–156.

36. Das Gupta M, Bongaarts J, Cleland J (2011) *Population, Poverty, and Sustainable Development: A Review of the Evidence* (World Bank, New York).
37. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–858.
38. Mittermeier RA, et al. (2004) *Hotspots Revisited: Earth's Biologically Richest and Most Endangered Ecoregions* (CEMEX, Mexico City, Mexico), 390 pp.
39. Cincotta RP, Wisnewski J, Engelman R (2000) Human population in the biodiversity hotspots. *Nature* 404(6781):990–992.
40. Williams J (2013) Humans and biodiversity: Population and demographic trends in the hotspots. *Popul Environ* 34(4):510–523.
41. Jha S, Bawa KS (2006) Population growth, human development, and deforestation in biodiversity hotspots. *Conserv Biol* 20(3):906–912.
42. Lauer JA, et al. (2003) PopMod: A longitudinal population model with two interacting disease states. *Cost Eff Resour Alloc* 1(1):6.
43. R Core Team (2014) *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria).
44. Singh S, Sedgh G, Hussain R (2010) Unintended pregnancy: Worldwide levels, trends, and outcomes. *Stud Fam Plann* 41(4):241–250.
45. Smith P, et al. (2007) Agriculture. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Cambridge Univ Press, Cambridge, UK).
46. IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. IPCC WGII AR5 Technical Summary* (Intergovernmental Panel on Climate Change, Geneva, Switzerland).
47. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Synthesis* (Island Press, Washington, DC).
48. Bongaarts J, Sinding SW (2009) A response to critics of family planning programs. *Int Perspect Sex Reprod Health* 35(1):39–44.
49. Feng W, Cai Y, Gu B (2013) Population, policy, and politics: How will history judge China's one-child policy? *Popul Dev Rev* 38(Suppl 1):115–129.
50. Drèze J, Murthi M (2001) Fertility, education, and development: Evidence from India. *Popul Dev Rev* 27(1):33–63.
51. Cleland J, et al. (2006) Family planning: The unfinished agenda. *Lancet* 368(9549):1810–1827.
52. Brook BW, Ellis EC, Perring MP, Mackay AW, Blomqvist L (2013) Does the terrestrial biosphere have planetary tipping points? *Trends Ecol Evol* 28(7):396–401.
53. Kerr JT, Currie DJ (1995) Effects of human activity on global extinction risk. *Conserv Biol* 9(6):1528–1538.
54. McKinney ML (2001) Role of human population size in raising bird and mammal threat among nations. *Anim Conserv* 4(1):45–57.
55. McKee JK, Sciulli PW, Fooce CD, Waite TA (2004) Forecasting global biodiversity threats associated with human population growth. *Biol Conserv* 115(1):161–164.
56. Thompson K, Jones A (1999) Human population density and prediction of local plant extinction in Britain. *Conserv Biol* 13(1):185–189.
57. Kirkland GL, Jr, Ostfeld RS (1999) Factors influencing variation among states in the number of federally listed mammals in the United States. *J Mammal* 80(3):711–719.
58. Luck GW (2007) A review of the relationships between human population density and biodiversity. *Biol Rev Camb Philos Soc* 82(4):607–645.
59. Laurance WF, et al. (2012) Averting biodiversity collapse in tropical forest protected areas. *Nature* 489(7415):290–294.
60. Wittemyer G, Elsen P, Bean WT, Burton ACO, Brashares JS (2008) Accelerated human population growth at protected area edges. *Science* 321(5885):123–126.
61. Bloom DE, Canning D, Fink G (2010) Implications of population ageing for economic growth. *Oxf Rev Econ Policy* 26(4):583–612.
62. Daily GC, Ehrlich AH, Ehrlich PR (1994) Optimum human population size. *Popul Environ* 15(6):469–475.
63. Pereira T (2009) Sustainability: An integral engineering design approach. *Renew Sustain Energy Rev* 13(5):1133–1137.
64. Brook BW, Bradshaw CJA (2014) Key role for nuclear energy in global biodiversity conservation. *Conserv Biol*, in press.
65. Ehrlich PR, Ornstein RE (2010) *Humanity on a Tightrope: Thoughts on Empathy, Family, and Big Changes for a Viable Future* (Rowman & Littlefield, New York, NY).

POPULATION BIOLOGY

Supporting Information

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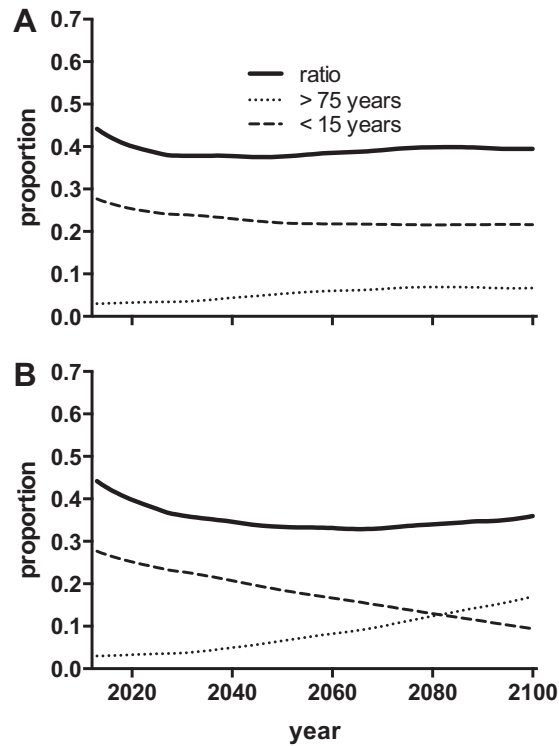

Fig. S1. Testing sensitivity of scenario assumptions: Proportion of people <15 y or >75 y per time step, and their ratio to the remainder of the population (dependency ratio) for (*A*) Scenario 1 (BAU), and (*B*) Scenario 3 (decreasing mortality, increasing age at primiparity, decreasing fertility to one child per female). See main text for detailed scenario descriptions.

Table S1. Summary of initial parameter values and temporal changes for the 10 scenarios considered

Scenario	Fertility (m) (children per female)	Primiparity	Mean juvenile mortality ($\overline{M}_{0-5}$)	Mean adult mortality ($\overline{M}_{6-100}$)	Catastrophic deaths
1	2.37 (constant)	unchanged	0.0131 (constant)	0.0490 (constant)	0
2a	2.37 (2013) → 2.00 (2100)	50% $m_{15-24} \rightarrow m_{25-49}$*	0.0131 (2013) → 0.0066 (2100)	0.0490 (2013) → 0.0245 (2100)	0
2b	2.37 (2013) → 2.00 (2100)	50% $m_{15-24} \rightarrow m_{25-49}$	0.0131 (constant)	0.0490 (constant)	0
3	2.37 (2013) → 1.00 (2100)	50% $m_{15-24} \rightarrow m_{25-49}$	0.0131 (2013) → 0.0066 (2100)	0.0490 (2013) → 0.0245 (2100)	0
4	2.37 (2013) → 1.00 (2045, constant to 2100)	50% $m_{15-24} \rightarrow m_{25-49}$	0.0131 (constant)	0.0490 (constant)	0
5	2.37–15.8% births per year† (constant)	Unchanged	0.0131 (constant)	0.0490 (constant)	0
6	2.37 (constant)	Unchanged	0.0131 (2013) → 0.0262 (2100)	0.0490 (constant)	0
7	2.37 (constant)	Unchanged	0.0131 (constant)	0.0490 (constant)	500 million deaths 2056–2061
8	2.37 (constant)	Unchanged	0.0131 (constant)	0.0490 (constant)	2 billion deaths 2056–2060
9	2.37 (constant)	Unchanged	0.0131 (constant)	0.0490 (constant)	6 billion deaths 2041–2045

An arrow (→) indicates the parameter value changes (linearly) to the new value indicated by the year given.

*For example, 50% of the fertility resulting from 15- to 24-y-olds shifts to that of 25- to 49-y-olds.

†For example, each year, 15.8% of births deemed "unwanted" are subtracted from total fertility.

Table S2. BAU population growth and its implications for Biodiversity Hotspots

Subregion	N_{2013} (millions)	N_{2100}/N_{2013}	$\overline{D}_{2100}$ (ppl km^{-2})	Biodiversity Hotspots
1-Africa D	425	7.02	246.4	Guinean Forests of West Africa
				Mediterranean Basin
2-Africa E	491	5.64	241.3	Cape Floristic Region
				Succulent Karoo
				Maputaland-Pondoland-Albany
				Madagascar & Indian Ocean Islands
				Coastal Forests of Eastern Africa
				Eastern Afromontane
				Horn of Africa
				Guinean Forests of West Africa
7-Eastern Mediterranean D	432	3.51	215.4	Eastern Afromontane
				Horn of Africa
				Mediterranean Basin
				Irano-Anatolian
5-Americas D	87	2.29	67.7	Tropical Andes
				Tumbes-Choco-Magdalena
				Caribbean Islands
				Mesoamerica
12-Southeast Asia D	1405	2.06	656.6	Himalaya
				Indo-Burma
				Western Ghats and Sri Lanka
6-Eastern Mediterranean B	158	1.75	44.7	Eastern Afromontane
				Horn of Africa
				Mediterranean Basin
				Irano-Anatolian
4-Americas B	518	1.50	44.8	Chilean Winter Rainfall and Valdivian Forests
				Atlantic Forest
				Cerrado
				Tropical Andes
				Tumbes-Choco-Magdalena
				Caribbean Islands
				Mesoamerica
				California Floristic Province
				Madrean Pine-Oak Woodlands
11-Southeast Asia B	346	1.29	177.1	Indo-Burma
				Sundaland
				Wallacea
3-Americas A	373	1.06	20.0	Caribbean Islands
				California Floristic Province
9-Europe B	241	0.98	75.1	Mediterranean Basin
				Irano-Anatolian
				Caucasus
				Mountains of Central Asia
14-Western Pacific B	1571	0.90	107.5	Mountains of Central Asia
				Himalaya
				Mountains of Southwest China
				Indo-Burma
				Sundaland
				Philippines
				East Melanesian Islands
				Polynesia-Micronesia
8-Europe A	460	0.70	82.7	Mediterranean Basin
10-Europe C	270	0.54	7.0	Caucasus
				Mountains of Central Asia
13-Western Pacific A	166	0.52	10.4	Southwest Australia
				Forests of East Australia
				New Caledonia
				New Zealand
				Japan

Current human population size and structure (N_{2013}), ratio of population change based on our midrange BAU demographic projections (N_{2100}/N_{2013}), mean population density (people km^{-2}) in 2100 across all countries per region ($\overline{D}_{2100}$) and the Biodiversity Hotspots contained within each of 14 WHO-defined population subregions. Regions are ordered (descending) by N_{2100}/N_{2013}. Subregion country composition (see legend to Fig. 4 for country code expansion): Africa D (Region 1: AGO, BEN, BFA, CMR, CPV, DZA, GAB, GHA, GIN, GMB, GNB, GNQ, LBR, MDG, MLI, MRT, MUS, NER, NGA, SEN, SLE, STP, SYC, TCD, TGO), Africa E (Region 2: BDI, BWA, CAF, CIV, COD, COG, ERI, ETH, KEN, LSO, MOZ, MWI, NAM, RWA, SWZ, TZA, UGA, ZAF, ZMB, ZWE), Americas A (Region 3: CAN, CUB, USA), Americas B (Region 4: ARG, ATG, BHS, BLZ, BRA, BRB, CHL, COL, CRI, DMA, DOM, GRD, GUY, HND, JAM, KNA, LCA, MEX, PAN, PRY, SLV, SUR, TTO, URY, VCT, VEN), Americas D (Region 5: BOL, ECU, GTM, HTI, NIC, PER), Eastern Mediterranean B (Region 6: ARE, BHR, CYP, IRN, JOR, KWT, LBN, LBY, OMN, QAT, SAU, SYR, TUN), Eastern Mediterranean D (Region 7: AFG, DJI, EGY, IRQ, MAR, PAK, SOM, SDN, YEM), Europe A (Region 8: AND, AUT, BEL, CHE, CZE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, HRV, IRL, ISL, ISR, ITA, LUX, MCO, MLT, NLD, NOR, PRT, SMR, SVN, SWE), Europe B (Region 9: ALB, ARM, AZE, BGR, BIH, GEO, KGZ, MKD, MNE, POL, ROU, SRB, SVK, TJK, TKM, TUR, UZB), Europe C (Region 10: BLR, EST, HUN, KAZ, LTU, LVA, MDA, RUS, U.K.R), Southeast Asia B (Region 11: IDN, LKA, THA, TLS), Southeast Asia D (Region 12: BGD, BTN, IND, MDV, MMR, NPL, PRK), Western Pacific A (Region 13: AUS, BRN, JPN, NZL, SGP), Western Pacific B (Region 14: CHN, COK, FJI, FSM, KHM, KIR, KOR, LAO, MHL, MNG, MYS, NIU, NRU, PHL, PLW, PNG, SLB, TON, TUV, VNM, VUT, WSM).

Table S3. Effects of declining fertility and mortality by region

Subregion	N_{2013} (millions)	N_{2100}/N_{2013}	$\overline{D}_{2100}$ (ppl km^{-2})
1-Africa D	425	4.45	156.1
2-Africa E	491	3.61	154.7
7-Eastern Mediterranean D	432	2.31	141.8
5-Americas D	87	1.56	46.1
12-Southeast Asia D	1405	1.41	448.5
6-Eastern Mediterranean B	158	1.24	31.7
4-Americas B	518	1.08	32.2
11-Southeast Asia B	346	0.96	132.1
3-Americas A	373	0.77	14.7
9-Europe B	241	0.74	56.4
14-Western Pacific B	1571	0.68	81.5
8-Europe A	460	0.54	64.3
13-Western Pacific A	166	0.44	8.7
10-Europe C	270	0.42	5.4

Shown are the current human population size and structure (N_{2013}), ratio of population change based on our midrange demographic projections (N_{2100}/N_{2013}), mean population density (people km^{-2}) in 2100 across all countries per region ($\overline{D}_{2100}$). This scenario assumes a linear trend to halving the initial (2013) fertilities and mortalities (juvenile and nonjuvenile), and increasing age at primiparity (following Scenario 2 conditions) by 2100. Regions are ordered (descending) by N_{2100}/N_{2013}. Subregion country composition (see Fig. 4 for expansion of country abbreviations): Africa D (Region 1: AGO, BEN, BFA, CMR, CPV, DZA, GAB, GHA, GIN, GMB, GNB, GNQ, LBR, MDG, MLI, MRT, MUS, NER, NGA, SEN, SLE, STP, SYC, TCD, TGO), Africa E (Region 2: BDI, BWA, CAF, CIV, COD, COG, ERI, ETH, KEN, LSO, MOZ, MWI, NAM, RWA, SWZ, TZA, UGA, ZAF, ZMB, ZWE), Americas A (Region 3: CAN, CUB, USA), Americas B (Region 4: ARG, ATG, BHS, BLZ, BRA, BRB, CHL, COL, CRI, DMA, DOM, GRD, GUY, HND, JAM, KNA, LCA, MEX, PAN, PRY, SLV, SUR, TTO, URY, VCT, VEN), Americas D (Region 5: BOL, ECU, GTM, HTI, NIC, PER), Eastern Mediterranean B (Region 6: ARE, BHR, CYP, IRN, JOR, KWT, LBN, LBY, OMN, QAT, SAU, SYR, TUN), Eastern Mediterranean D (Region 7: AFG, DJI, EGY, IRQ, MAR, PAK, SOM, SDN, YEM), Europe A (Region 8: AND, AUT, BEL, CHE, CZE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, HRV, IRL, ISL, ISR, ITA, LUX, MCO, MLT, NLD, NOR, PRT, SMR, SVN, SWE), Europe B (Region 9: ALB, ARM, AZE, BGR, BIH, GEO, KGZ, MKD, MNE, POL, ROU, SRB, SVK, TJK, TKM, TUR, UZB), Europe C (Region 10: BLR, EST, HUN, KAZ, LTU, LVA, MDA, RUS, U.K.R), Southeast Asia B (Region 11: IDN, LKA, THA, TLS), Southeast Asia D (Region 12: BGD, BTN, IND, MDV, MMR, NPL, PRK), Western Pacific A (Region 13: AUS, BRN, JPN, NZL, SGP), Western Pacific B (Region 14: CHN, COK, FJI, FSM, KHM, KIR, KOR, LAO, MHL, MNG, MYS, NIU, NRU, PHL, PLW, PNG, SLB, TON, TUV, VNM, VUT, WSM).

Other Supporting Information Files

Dataset S1 (PDF)
Dataset S2 (PDF)

```
## Human demographic matrix projections
## Corey J. A. Bradshaw & Brook W. Brook
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## The University of Adelaide, Adelaide, Australia
## Sep 2014

## Remove everything
rm(list = ls())

## libraries
library(boot)

## matrix operators source fille (supplied separately)
source("/Applications/RStudio.app/Contents/Resources/R/matrixOperators.r")

## set working directory
#setwd("~/xxx/xxx/") # user to update

###############################################
## WHO-CHOICE 0-100 per 1-yr age structure
## import 2013 data
## US Census Bureau 2013 world life table
dat.world13 <- read.table("world2013lifetable.csv", header=T, sep=",") # available at http://dx.doi.org/10.4227/05/53869A9434A46

# import data
dat.afrD <- read.table("afrD.csv", header=T, sep=",")
dat.afrE <- read.table("afrE.csv", header=T, sep=",")
dat.AmA <- read.table("AmA.csv", header=T, sep=",")
dat.AmB <- read.table("AmB.csv", header=T, sep=",")
dat.AmD <- read.table("AmD.csv", header=T, sep=",")
dat.eMedB <- read.table("eMedB.csv", header=T, sep=",")
dat.eMedD <- read.table("eMedD.csv", header=T, sep=",")
dat.EurA <- read.table("EurA.csv", header=T, sep=",")
dat.EurB <- read.table("EurB.csv", header=T, sep=",")
dat.EurC <- read.table("EurC.csv", header=T, sep=",")
dat.SEAB <- read.table("SEAB.csv", header=T, sep=",")
dat.SEAD <- read.table("SEAD.csv", header=T, sep=",")
dat.wPacA <- read.table("wPacA.csv", header=T, sep=",")
dat.wPacB <- read.table("wPacB.csv", header=T, sep=",")

## combined age structure
mal05.N <- dat.afrD$mal.N + dat.afrE$mal.N + dat.AmA$mal.N + dat.AmB$mal.N + dat.AmD$mal.N + dat.eMedB$mal.N + dat.eMedD$mal.N + dat.EurA$mal.N +
dat.EurB$mal.N + dat.EurC$mal.N + dat.SEAB$mal.N + dat.SEAD$mal.N + dat.wPacA$mal.N + dat.wPacB$mal.N
fem05.N <- dat.afrD$fem.N + dat.afrE$fem.N + dat.AmA$fem.N + dat.AmB$fem.N + dat.AmD$fem.N + dat.eMedB$fem.N + dat.eMedD$fem.N + dat.EurA$fem.N +
dat.EurB$fem.N + dat.EurC$fem.N + dat.SEAB$fem.N + dat.SEAD$fem.N + dat.wPacA$fem.N + dat.wPacB$fem.N

## 2005 pop estimate
tot.pop05 <- sum(as.numeric(mal05.N+fem05.N))

## scale to 2013 pop estimate
tot.pop13 <- sum(as.numeric(dat.world13$N))
mal13.N <- round((tot.pop13/tot.pop05) * mal05.N, 0)
fem13.N <- round((tot.pop13/tot.pop05) * fem05.N, 0)

## N-weighted mortality rates
a.ages <- length(mal13.N)
```

```
mal.mort.mat <-
as.matrix(data.frame(dat.afrD$mal.M,dat.afrE$mal.M,dat.AmA$mal.M,dat.AmB$mal.M,dat.AmD$mal.M,dat.eMedB$mal.M,dat.eMedD$mal.M,dat.EurA$mal.M,dat.E
urB$mal.M,dat.EurC$mal.M,dat.SEAB$mal.M,dat.SEAD$mal.M,dat.wPacA$mal.M,dat.wPacB$mal.M))
lab.vec <- c("afrD","afrE","AmA","AmB","AmD","eMedB","eMedD","EurA","EurB","EurC","SEAB","SEAD","wPacA","wPacB")
colnames(mal.mort.mat) <- lab.vec
rownames(mal.mort.mat) <- 0:100
fem.mort.mat <-
as.matrix(data.frame(dat.afrD$fem.M,dat.afrE$fem.M,dat.AmA$fem.M,dat.AmB$fem.M,dat.AmD$fem.M,dat.eMedB$fem.M,dat.eMedD$fem.M,dat.EurA$fem.M,dat.E
urB$fem.M,dat.EurC$fem.M,dat.SEAB$fem.M,dat.SEAD$fem.M,dat.wPacA$fem.M,dat.wPacB$fem.M))
lab.vec <- c("afrD","afrE","AmA","AmB","AmD","eMedB","eMedD","EurA","EurB","EurC","SEAB","SEAD","wPacA","wPacB")
colnames(fem.mort.mat) <- lab.vec
rownames(fem.mort.mat) <- 0:100


mal.N.mat <-
as.matrix(data.frame(dat.afrD$mal.N,dat.afrE$mal.N,dat.AmA$mal.N,dat.AmB$mal.N,dat.AmD$mal.N,dat.eMedB$mal.N,dat.eMedD$mal.N,dat.EurA$mal.N,dat.E
urB$mal.N,dat.EurC$mal.N,dat.SEAB$mal.N,dat.SEAD$mal.N,dat.wPacA$mal.N,dat.wPacB$mal.N))
colnames(mal.N.mat) <- lab.vec
rownames(mal.N.mat) <- rownames(mal.mort.mat)
fem.N.mat <-
as.matrix(data.frame(dat.afrD$fem.N,dat.afrE$fem.N,dat.AmA$fem.N,dat.AmB$fem.N,dat.AmD$fem.N,dat.eMedB$fem.N,dat.eMedD$fem.N,dat.EurA$fem.N,dat.E
urB$fem.N,dat.EurC$fem.N,dat.SEAB$fem.N,dat.SEAD$fem.N,dat.wPacA$fem.N,dat.wPacB$fem.N))
colnames(fem.N.mat) <- lab.vec
rownames(fem.N.mat) <- rownames(fem.mort.mat)


mal.wM <- fem.wM <- rep(0,a.ages)

for (a in 1:a.ages) {
  mal.wM[a] <- weighted.mean(mal.mort.mat[a,],mal.N.mat[a,])
  fem.wM[a] <- weighted.mean(fem.mort.mat[a,],fem.N.mat[a,])
}

lng.age.vec <- seq(0,100,1)

## construct matrix
stagesWHO <- a.ages
popmatWHO <- matrix(0,nrow=stagesWHO,ncol=stagesWHO)
colnames(popmatWHO) <- lng.age.vec[1:stagesWHO]
rownames(popmatWHO) <- lng.age.vec[1:stagesWHO]

## populate matrix
popmatWHO[1,1:length(dat.world13$m.f)] <- dat.world13$m.f
surv.vec2 <- 1-fem.wM
diag(popmatWHO[2:stagesWHO,]) <- surv.vec2[-stagesWHO]
#popmatWHO[2,1] <- surv.vec[1] ## infant mortality from dat.world13
popmatWHO[stagesWHO,stagesWHO] <- surv.vec2[stagesWHO]
popmatWHO.orig <- popmatWHO ## save original matrix

## matrix properties
max.lambda(popmatWHO) ## 1-yr lambda
max.r(popmatWHO) # rate of population change, 1-yr
stable.stage.dist(popmatWHO) ## stable stage distribution
R.val(popmatWHO,stagesWHO) # reproductive value
G.val(popmatWHO,stagesWHO) # mean generation length

## initial population vector
initWHO.vec <- fem13.N
```

```
################
## project
## set time limit for projection in 1-yr increments
yr.now <- 2013 # update if more data available post-2010
#*********************
yr.end <- 2100 # set projection end date
#*********************
t <- (yr.end - yr.now)


## linear fertility trends
int.vec <- 1:t

tot.F <- sum(popmatWHO.orig[1,])
popmatWHO <- popmatWHO.orig


#****************************************************
## Choose scenarios
## Fertility change
F.scen0 <- tot.F ## no fertility change
F.scen1 <- 1 # worldwide 1-child policy
F.scen2 <- 2.00 #
#***********************
end.fert <- 2100
F.scen.choose <- F.scen0
#***********************


## fertilty-change vector
F.scen.ch <- ifelse(F.scen.choose == tot.F, F.scen.choose, F.scen.choose/2)
F.mult <- rep(F.scen.ch/tot.F, t)
ft <- (end.fert - yr.now)
F.mult.vec <- pmax(F.mult, (tot.F - (tot.F - F.scen.ch)*int.vec/ft)/tot.F)

#*****************************************************************************
## Unwanted pregancy aversion
preg.aversion <- 0 # 1 if avoid number of unwanted pregancies; 0 if not avoid
# 2008: 208 million pregnancies; 86 million unintended
# 33 million unplanned births; 41 million abortions; 11 million miscarriages
prop.unwanted <- 33/208 # worldwide proportion of potentially avoidable births
#*****************************************************************************


#*****************************************************************************
## Stepped fertility reduction (as per reviewer 1's recommended scenario)
## 1 child/female by 2045
stepped <- 0 # 1 if this stepped function invoked
fts <- (2045 - yr.now); ints.vec <- 1:fts; Fs.targ <- 1.0*0.5; mults <- Fs.targ/tot.F; F.mults <- rep(mults, fts)
step.fert.mult <- pmax(F.mults, (tot.F - (tot.F - Fs.targ)*ints.vec/fts)/tot.F)
step.fert.mult.vec <- c(step.fert.mult,rep(step.fert.mult[length(step.fert.mult)], ft-fts))
#*****************************************************************************


#*****************************************************************************
## Stepped fertility reduction 2nd scenario
## 2.0 child/female by 2020
stepped2 <- 0 # 1 if this stepped function invoked
fts2 <- (2020 - yr.now); ints2.vec <- 1:fts2; Fs.targ2 <- 2.0*0.5; mults2 <- Fs.targ2/tot.F; F.mults2 <- rep(mults2, fts2)
step.fert.mult2 <- pmax(F.mults2, (tot.F - (tot.F - Fs.targ2)*ints2.vec/fts2)/tot.F)
step.fert.mult2.vec <- c(step.fert.mult2,rep(step.fert.mult2[length(step.fert.mult2)], ft-fts2))
#*****************************************************************************
```

```
## Age at primiparity changes (alpha)
A.scen0 <- 1
A.scen1 <- 0.5 # amount of fertility redistributed from 14:24 to 25:49
#***********************
end.alpha <- 2100
A.scen.choose <- A.scen0
#***********************


## Non-juvenile (6:oldest) survival change (S)
D.scen0 <- 1 ## no survival change
D.scen1 <- 0.50 # 50 % reduction in stage-specific death rate
#***********************
end.death <- 2100
D.scen.choose <- D.scen0
#***********************
## need to create using UN life-expectancy projections (back-calculated to death rates)

## Juvenile survival change (0-5 yrs)
J.scen0 <- 1 ## no survival change
J.scen1 <- 0.50 # 50 % reduction in juvenile death rate
J.scen2 <- 1.50 # 50 % increase in juvenile death rates (e.g., famine from CC)
#***********************
end.juvd <- 2100
J.scen.choose <- J.scen0
#***********************


## add a catastrophic mortality event
# spread over 5 years
# implemented mid-projection
# equal likelihood of taking any age (/2 for females only)
no.toll <- 0
firstsecwars.toll <- 1.31e+8/2 #131,000,000
firstsecwars.prop.toll <- (firstsecwars.toll*2/2500000000*tot.pop13)/2 # deaths proportional to 2.5 b alive at end WWII
twobillion.toll <- 2e+9/2 #2,000,000,000 dead
sixbillion.toll <- 6e+9/2 #6,000,000,000 dead
#***********************
Cat.scen <- no.toll
#***********************


## change to fertility/survival if war/pandemic invoked
war.fert.mult <- 2 # fertility doubles following war/pandemic (subsequently increases linearly until 2013 values thereafter)
war.surv.mult <- 2 # mortality doubles following war (subsequently increases linearly until 2013 values thereafter)


yr.vec <- seq(yr.now,yr.end)

if (Cat.scen != sixbillion.toll) {
  eyr.cat <- yr.vec[round(t/2)+5] # year + 1 end of catastrophe
}
if (Cat.scen == sixbillion.toll) {
  eyr.cat <- yr.vec[round(t/3)+5] # year + 1 end of catastrophe
}

ws.dt <- (end.death - eyr.cat)
mid.int.vec <- 1:ws.dt
war.surv.mult.vc <- rev(pmin(war.surv.mult, 1 - (1 - war.surv.mult)*mid.int.vec/ws.dt))
# add 1s to first part of vector for no change prior to war/disease catastrophe
```

```
add.surv.mult <- rep(1,t-ws.dt)
war.surv.mult.vec <- c(add.surv.mult,war.surv.mult.vc)
war.surv.mult.vec

war.F.mult.vc <- rev(pmin(war.fert.mult, 1 - (1 - war.fert.mult)*mid.int.vec/ws.dt))
add.fert.mult <- rep(1,t-ws.dt)
war.fert.mult.vec <- c(add.fert.mult,war.F.mult.vc)
war.fert.mult.vec

## changes in female age at primparity (alpha)
## done via redistribution of fertility in 15:24 breeding classes amongst remaining (25:49)
A.mult <- rep(0, t)
at <- (end.alpha - yr.now)
A.mult.vec <- A.scen.choose^(1/t)
A.mult.vec

## changes in survival
## expressed in death rate (1 - S)
D.mult <- rep(1, t)
dt <- (end.death - yr.now)
D.mult.vec <- pmax(D.scen.choose, 1 - (1 - D.scen.choose)*int.vec/dt)
D.mult.vec

## changes in juvenile survival (expressed in mortality changes)
J.mult <- rep(1, t)
jt <- (end.juvd - yr.now)
if (J.scen.choose <= 1) {
  J.mult.vec <- pmax(J.scen.choose, 1 - (1 - J.scen.choose)*int.vec/jt)}
if (J.scen.choose > 1) {
  J.mult.vec <- 1 - (1 - J.scen.choose)*int.vec/jt}
J.mult.vec

## set population storage matrix
n.matWHO <- matrix(0,nrow=stagesWHO,ncol=(t+1))
n.matWHO[,1] <- initWHO.vec

## fertility storage vector
fertWHO.tot <- fertWHO.15.24 <- rep(0,t)

## set up projection loop
for (i in 1:t) {
  fertWHO.tot[i] <- sum(popmatWHO[1,])
  fertWHO.15.24[i] <- sum(popmatWHO[1,16:25])
  n.matWHO[,i+1] <- popmatWHO %*% n.matWHO[,i]

  ## invoke catastrophic mortality over 5-year window
  if (Cat.scen != sixbillion.toll) {
    if (i == round(t/2,0)) {
      if (Cat.scen == firstsecwars.prop.toll) {
        Cat.scen <- firstsecwars.toll*2/2500000000*sum(n.matWHO[,i])
      }
      prop.death <- Cat.scen/5/sum(n.matWHO[,i+1])
      n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death) ## five-year (Cat.scen/5) catastrophic mortality event
    }
    if (i == round(t/2,0)+1) {
      n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
    }
```

```
  if (i == round(t/2,0)+2) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
  if (i == round(t/2,0)+3) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
  if (i == round(t/2,0)+4) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
}

if (Cat.scen == sixbillion.toll) {
  if (i == round(t/3,0)) {
    prop.death <- Cat.scen/5/sum(n.matWHO[,i+1])
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death) ## five-year (Cat.scen/5) catastrophic mortality event
  }
  if (i == round(t/3,0)+1) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
  if (i == round(t/3,0)+2) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
  if (i == round(t/3,0)+3) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
  if (i == round(t/3,0)+4) {
    n.matWHO[,i+1] <- n.matWHO[,i+1] - (n.matWHO[,i+1]*prop.death)
  }
}

## unwanted pregnancies averted
if (preg.aversion == 1) {
  n.matWHO[1,i+1] <- n.matWHO[1,i+1] * (1-prop.unwanted) # n * 1-proportion unwanted
}

## stepped fertility decline
if (stepped == 1) {
  F.mult.vec <- step.fert.mult.vec
}

## stepped fertility decline (2nd scenario)
if (stepped2 == 1) {
  F.mult.vec <- step.fert.mult2.vec
}

## change fertility/survival following catastrophic mortality event
if (Cat.scen > 0) {
  popmatWHO[1,] <- popmatWHO.orig[1,]*war.fert.mult.vec[i]
  diag(popmatWHO[7:stagesWHO,6:stagesWHO]) <- 1 - ((1 - diag(popmatWHO.orig[7:stagesWHO,6:stagesWHO]))*war.surv.mult.vec[i])
  popmatWHO[stagesWHO,stagesWHO] <- 1 - ((1 - popmatWHO.orig[stagesWHO,stagesWHO])*war.surv.mult.vec[i])
  diag(popmatWHO[2:6,1:5]) <- 1 - ((1 - diag(popmatWHO.orig[2:6,1:5]))*war.surv.mult.vec[i])
}

popmatWHO[1,] <- popmatWHO.orig[1,]*F.mult.vec[i]
diag(popmatWHO[7:stagesWHO,6:stagesWHO]) <- 1 - ((1 - diag(popmatWHO.orig[7:stagesWHO,6:stagesWHO]))*D.mult.vec[i])
popmatWHO[stagesWHO,stagesWHO] <- 1 - ((1 - popmatWHO.orig[stagesWHO,stagesWHO])*D.mult.vec[i])
diag(popmatWHO[2:6,1:5]) <- 1 - ((1 - diag(popmatWHO.orig[2:6,1:5]))*J.mult.vec[i])
```

```
  A.allocWHO <- sum(popmatWHO[1,16:25])*(1-A.mult.vec)
  F1524WHO.wt <- popmatWHO[1,16:25]/sum(popmatWHO[1,16:25])
  popmatWHO[1,16:25] <- popmatWHO[1,16:25] - F1524WHO.wt*A.allocWHO
  FRWHO.wt <- popmatWHO[1,26:50]/sum(popmatWHO[1,26:50])
  popmatWHO[1,26:50] <- popmatWHO[1,26:50] + FRWHO.wt*A.allocWHO
  ## revisit the mult.vecs - might be able to do faster as for A.alloc
}

## final population size
totWHO.sex.ratio <- 1/(sum(mal13.N)/(sum(fem13.N) + sum(mal13.N)))
fin.popWHO <- totWHO.sex.ratio*(sum(n.matWHO[,(t+1)]))
fin.popWHO

## end max lambda
max.lambda(popmatWHO) # 1-yr lambda

# max population size reached over projection interval
n.maxWHO <-  totWHO.sex.ratio*max(colSums(n.matWHO))
n.maxWHO

## x change (initial - final)
times.deltaWHO <- round(fin.popWHO/(totWHO.sex.ratio*sum(initWHO.vec)), 2)
times.deltaWHO

## year projection vector
yrs <- seq(yr.now,yr.end,1)

## > 65 (or 75, for sensitivity test) proportion (of total population) (choose 65 or 75 upper threshold - comment/uncomment accordingly)
#over65WHO <- colSums(n.matWHO[67:stagesWHO,])/colSums(n.matWHO)
over65WHO <- colSums(n.matWHO[77:stagesWHO,])/colSums(n.matWHO)

## < 15 proportion (of total pop)
under15WHO <- colSums(n.matWHO[1:15,])/colSums(n.matWHO)

## dependency ratio
# number of people < 15 and > 65 relative to rest (choose 65 or 75 upper threshold - comment/uncomment accordingly)
#dep.ratioWHO <- (colSums(n.matWHO[1:15,]) + colSums(n.matWHO[67:stagesWHO,])) / colSums(n.matWHO[16:66,])
dep.ratioWHO <- (colSums(n.matWHO[1:15,]) + colSums(n.matWHO[77:stagesWHO,])) / colSums(n.matWHO[16:76,])

## plots
par(mfrow=c(2,2),yaxt="s")
plot(yrs,as.vector(colSums(n.matWHO)*totWHO.sex.ratio),type="l",xlab="year",ylab="N",ylim=c(0,1.02*n.maxWHO),xlim=c(yr.now,yr.end))
abline(h=sum(n.matWHO[,1]*totWHO.sex.ratio),lty=2)
maxN.sub <- which(colSums(n.matWHO)==max(colSums(n.matWHO)))
abline(v=yrs[maxN.sub],lty=2)
title(main=paste("final N = ",round(fin.popWHO/1e9, 4), " b","; max N = ",round(n.maxWHO/1e9, 4), " b",sep=""),
      sub = paste("delta = ", times.deltaWHO, "x", sep=""))
plot(yrs,as.vector(over65WHO),type="l",xlab="year",ylab="proportion",ylim=c(0,1))
lines(yrs,as.vector(under15WHO),lty=2)
title(main=paste("prop <15 (dashed) & >65 (solid) yrs", sep=""))
plot(yrs,as.vector(dep.ratioWHO),type="l",xlab="year",ylab="dependency ratio",ylim=c(0,1))
title(main=paste("dependency ratio: initial = ", round(dep.ratioWHO[1],4), "; final = ", round(dep.ratioWHO[t+1],4), sep=""))
barplot(n.matWHO[-stagesWHO,t+1],names.arg=rownames(popmatWHO[-stagesWHO]),beside=T,xlab="age class",ylab="final N",axes=T,horiz=F,axis.lty=1)
par(mfrow=c(1,1))
```

```r
# Matrix operators for population models
# Corey J. A. Bradshaw
# The University of Adelaide, Adelaide, Australia
# corey.bradshaw@adelaide.edu.au
# September 2014
# place in R 'Resources/R/' folder


## maximum lambda function
max.lambda <- function(x) Re((eigen(x)$values)[1]) ## where 'x' is a Leslie matrix


## Maximum r function
max.r <- function(x) log(Re((eigen(x)$values)[1])) ## where 'x' is a Leslie matrix


## Stable stage distribution
stable.stage.dist <- function(x) ((x %*% (Re((eigen(x)$vectors)[,1])))/(sum((x %*% (Re((eigen(x)$vectors)[,1]))))))[,1]


## Generation length function
R.val <- function(X,age.max) ## reproductive value (R0) where X = Leslie matrix; age.max = maximum age of females
{
            ## define the transition matrix
            T <- X[1:age.max,1:age.max]
            T[1,1:(age.max)] <- 0

            ## define the fertility matrix
            F <- X[1:age.max,1:age.max]
            diag(F[2:age.max,1:(age.max-1)]) <- 0

            ## define the identity matrix
            I <- matrix(data<-0,nrow<-age.max,ncol<-age.max)
            diag(I) <- 1

            ## define the fundamental matrix
            library(MASS)
            N.fund <- ginv(I-T)

            ## define the reproductive matrix
            R <- F %*% N.fund

            ## define R0 (number of female offspring produced per female during lifetime)
            R0 <- Re((eigen(R)$values)[1])

            ## output
            print("number of female offspring produced per female during its lifetime")
            print("_____")
            print(R0)

}


## Mean generation time function
G.val <- function (X,age.max) ## where X is a Leslie Matrix
{
            G <- (log(R.val(X,age.max)))/(log(Re((eigen(X)$values)[1])))
            print("mean generation time")
            print("_____")
            print(G)
}
```