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Key Points:

- United Nations population projections are based on a logical fallacy.
- The global average fertility rate might rise even if each country's rate falls.
- Agricultural advances in the 20th century permitted world population to triple.

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Can human populations be stabilized?

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Abstract Historical examples of demographic change, in China, Italy, Nigeria, Utah, Easter Island, and elsewhere, together with simple mathematics and biological principles, show that stabilizing world population before it is limited by food supply will be more difficult than is generally appreciated. United Nations population projections are wrong because they assume, in spite of the absence of necessary feedbacks, that all nations will converge rapidly to replacement-level fertility and thereafter remain at that level. Education of women and provision of contraceptives have caused dramatic reductions in fertility, but many groups, including some that are well-educated, maintain high fertility. Small groups with persistent high fertility can grow to supplant low-fertility groups, resulting in continued growth of the total population. The global average fertility rate could rise even if each country's fertility rate is falling. In some low-fertility European countries where deaths exceed births, the population continues to grow because of immigration. Producing more than two offspring is normal for all animal species with stable populations because their populations are limited by resources or predation rather than birth control. It may therefore be appropriate to view the growth of human population as the result not of excess fertility but rather of excess food.

1. The Importance of Population in Environmental Problems

The various environmental problems facing us, including global warming, air pollution, water pollution, deforestation, and species extinction, may each be addressed by targeting relevant factors that are different for each problem (shown in Box 1 for the example of global warming). But population is a factor common to all of them, so it deserves to be singled out for special attention.

Furthermore, population size is important not only for the causes of environmental problems but also for determining the magnitude of their impacts. Consider Bangladesh, a low-lying country smaller than Washington State but with a population more than half that of the United States [*Inman*, 2009; *Schiermeier*, 2014]. The consequences of sea-level rise depend very much on the size of that country's population: whether it is 80 million (in 1975), or 160 million (in 2013), or 200 million (projected for 2050) [*Population Reference Bureau*, 2013]. The fact that small differences in fertility rate can lead to large differences in population (shown below) supports the proposal of *Motesharrei et al*. [2014] that Earth-system models should include feedbacks involving human population dynamics.

The world population has been growing for centuries, but interest in population problems has fluctuated, and has undergone periods of decline in recent decades [*Campbell et al*., 2007]. Where concern about population growth is at a low level, the reason may be a belief that the worldwide trend to smaller families means that "population will take care of itself." This paper examines current human population dynamics in the context of past and future centuries. I will argue that stabilizing the population short of the limit set by food supply will be more difficult than is generally appreciated.

2. Are Modern Times Unusual?

The world population doubled in 40 years, from 3 billion in 1960 to 6 billion in 2000. The U.S. population doubled in 56 years, from 150 million in 1950 to 300 million in 2006. In fact, the period 1960–2000 experienced the most rapid growth rate of any time in human history. If the world population had doubled every 40 years throughout history and reached 6 billion in the year 2000, we would have to conclude that humanity began in the year 720 Common Era (C.E.). This is because to grow from 2 people to 6 billion people requires 32 doublings; at 40 years per doubling that takes just 1280 years. Quoting *Cohen* [1995]:

Box 1: The Role of Population in Global Warming

The rate of emission of CO_2 to the atmosphere by fossil-fuel burning (*R*; grams per year) in a single nation or region can be expressed as the product of five factors:

$$R = P \cdot A \cdot E \cdot C \cdot f \quad (1)$$

where P = population of the region; A = affluence (per-capita gross domestic product (GDP); dollars per person per year); E = energy intensity (the energy required to make a dollar of GDP; Joules per dollar); C = "carbon content of energy" (CO_2 emitted per unit of energy consumed, grams per Joule); f = fraction of CO_2 emitted that is not sequestered.

With the exception of f, equation (1) is identical to a formula published by *Bongaarts* [1992].

The values of A, E, and C all vary widely among the world's nations. The global rate of emission is a sum over nations:

$$R = \sum_{i=1}^{N} P_i A_i E_i C_i f_i \quad (2)$$

where N is the number of nations (or regions).

On a personal level, reducing any of these factors will reduce your CO_2 emissions. To reduce P, you can practice birth control. To reduce A, you can retire early or take a low-paying job. To reduce E, you can improve your energy efficiency, and to reduce C you can switch to non-carbon energy sources. There may be dependences among these factors; for example, reducing E may increase A.

"Within the lifetime of some people now alive, world population has tripled; within the lifetime of everyone over 40 years old, it has doubled − yet never before the last half of the twentieth century had world population doubled within the life span of any human."

In that sense we are living in an unusual time. But we should not think it unusual to be alive in an unusual time. Following the arguments of *Gott* [1993], if all centuries of the past 200,000 years were equally likely for you to be alive, then the chance of living in this century would be only 0.05%. But if we instead list all 80 billion humans who have ever lived, and choose one of those humans randomly to be you, the chance is 8% that you would be alive today. For a human to be alive, this time is more probable than any other time.

The growth rate for world population peaked around 1970 at 2% per year and has since declined, as shown by the inflection point on the logarithmic plot in Figure 1. Yet we are still adding 80 million people every year. Table 1 shows that for the past 30 years, the annual increase in world population has been steady at ~80 million (i.e., steady growth rather than exponential growth) *because* the growth rate is dropping [*Keyfitz*, 1985, Sec. 1.5].

Table 2 shows the distribution of population by region; Asia is dominant, with 61% of the world's people. The Northern Hemisphere has 87% of the global population, while the Southern Hemisphere has 13%.

3. Relating Family Size to Population Growth Rate and Doubling Time

The child-bearing years for women are assumed to span the ages from 15 to 50. Some examples of *age-specific fertility rates* are shown in Figure 2, giving the number of births per thousand women per year in each age group. It peaks somewhere between the ages of 20 and 30 for all countries. The integral of these curves, divided by 1000, gives the *total fertility rate* (*TFR*), which is the total number of children an average woman would produce during her child-bearing years, using the current rates for each age-cohort. [It is questionable whether the time-integral of a rate should be called a rate, but the name "total fertility rate" is standard in the demographic literature, so I will adhere to that convention.]

The relation of *TFR* to population growth rate can be expressed by simple formulas if *TFR*, life expectancy, and generation time are all constant over several generations. [Otherwise there are transient effects which persist for one human lifespan (approximately three generations), which go by the name "population momentum."] These conditions are not satisfied by human populations, but they are helpful for designing

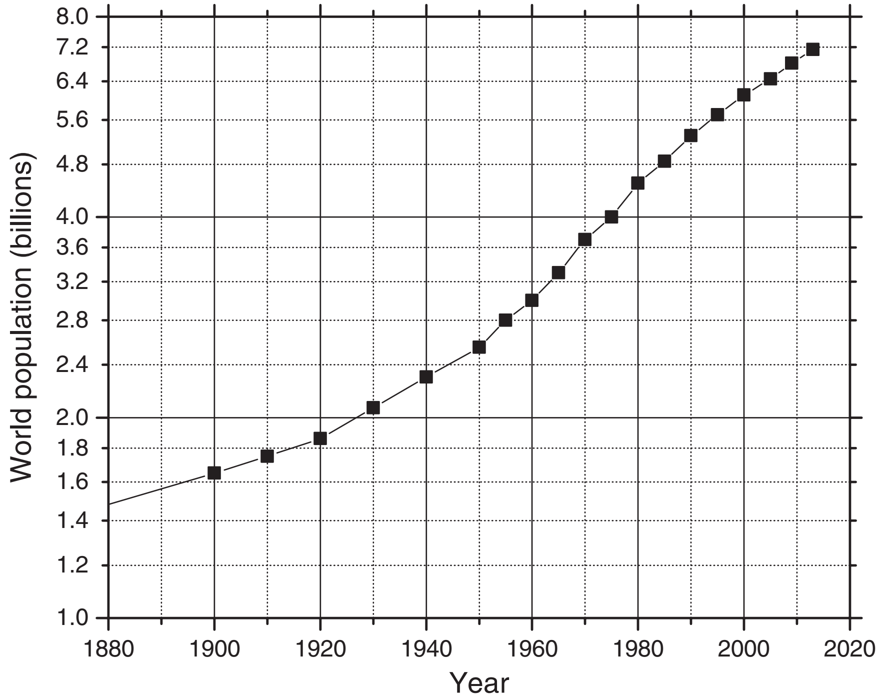

Figure 1. World population from 1880 to 2013, plotted logarithmically. Data from *Cohen* [1995] and from *Population Reference Bureau* [2013 and prior years].

Table 1. Additions to World Population in Recent Decades[a]

Year	World Population (Billions)	Growth Rate (Percent per Year)	People Added per Year (Millions)
1977	4.3	1.9	82
1994	5.6	1.5	82
2008	6.7	1.2	82

[a]From *Population Reference Bureau* [2009 and earlier years].

exercises to understand population dynamics. Some of these exercises are presented in boxes; they were developed for use in an undergraduate course in environmental science. To simplify the mathematics in our exercises, we will assume that the sex ratio of the children is 1:1, and that they do not die before reaching reproductive age. If childhood deaths are taken into account, replacement-level fertility

Table 2. Total Fertility Rates (TFRs), and Contributions to World Population, by Major Regions[a]

	TFR (Children per Woman)		Percent of World Population	
Region	1950–1955	2013	2013	2050 (Projected)
Asia[b]	5.9	2.2	61	55
Africa	6.7	4.8	15	25
Europe[c]	2.7	1.6	10	7
Latin America[d]	5.9	2.2	9	8
The United States and Canada	3.5	1.9	5	5

[a]Data from *Ashford et al*. [2004] and *Population Reference Bureau* [2013].
[b]Including adjacent islands (Indonesia, Japan, Philippines); excluding Russia.
[c]Including all of Russia.
[d]Including all Caribbean islands.

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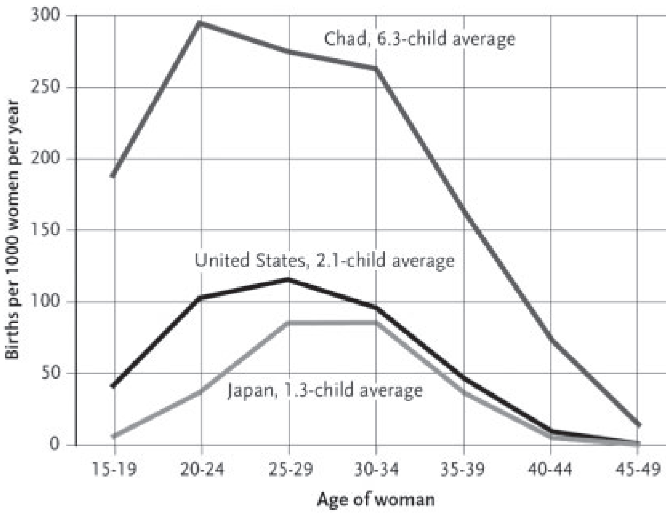

Figure 2. Age-specific fertility rates (births per 1000 women per year), for three countries in 2005. The total fertility rates (TFRs) given (1.3, 2.1, and 6.3) are the integrals of these curves, divided by 1000. From Figure 1 of *McFalls* [2007], with modification.

is somewhat greater than 2.0 children per woman. It varies among regions from 2.1 to 2.9; the world average now is 2.3 [*Espenshade et al.*, 2003]. The first exercise (Box 2) shows that slight differences in *TFR* can have surprisingly large consequences.

With the above assumptions, and for $TFR > 2$, the population doubling time t_d is given by

$$t_d = \frac{t_g \ln 2}{\ln (TFR/2)} \quad (3)$$

where t_g is the generation time (average age of the mother when her children are born). [The derivation of equation (3) is given in the Appendix.] If $TFR < 2$, the halving time t_h is given by

$$t_h = \frac{t_g \ln 2}{\ln (2/TFR)} \quad (4)$$

Some important special cases are the following:

$TFR = 4$: Population doubles in one generation.
$TFR = 3$: Population increases by 50% in one generation.
$TFR = 2$: Population is stable (birth rate equals death rate).
$TFR = 1$: Population halves in one generation.

Box 2: Test Your Intuition About Population Growth: Can Low Birth Rates Lead to Overcrowding?

Given unlimited resources, the populations of animals, plants, or bacteria are capable of growing exponentially because the number of offspring is proportional to the existing population. This exercise is designed to show that the mathematics of exponential growth is non-intuitive. [Exponential growth eventually stops because at some point the supply of an essential resource, or the spread of disease, or harvesting by predators, becomes limiting. And before limits are reached, the growth rate usually starts to decrease because the growth perturbs the environment that allowed for the growth.]

What happened on Easter Island? Easter Island is a small volcanic island in the eastern Pacific, far from any other land. It was uninhabited until about 600 C.E., when between 20 and 30 Polynesians arrived by canoe. By the year 1600, the population had grown to 6000, resulting in deforestation, famine, war, and cannibalism [*Bahn and Flenley*, 1992; *Rolett and Diamond*, 2004]. [There is some disagreement about these numbers and dates; I have chosen these values to simplify the mathematics.] We will work out what fertility rate was needed to lead to this disaster.

Question. How many children that reached reproductive age were produced by each couple, on average, during those thousand years? Assume that there were no additional immigrants, no change in life expectancy, and no change in TFR (the number of children a woman produces in her lifetime) during those thousand years, and that the generation time (average age of the mother when her children are born) was 25 years. Start with a population of 24. A fertility rate of 2.0 would have kept the population stable at 24 because each couple produces enough children to replace themselves.

Answer. The increase is a factor $6000/24 = 250 \approx 2^8$, so the population doubled eight times. Eight doublings in 1000 years means that the doubling time was 125 years, or five generations, so in one generation the population was multiplied by $2^{1/5} = 1.15$, an increase of 15%, requiring just 2.3 children per woman. [Before doing the calculation, the guesses of me and my students were way off, ranging from 3 to 8.]

TFRs for the five major regions of the world are given in Table 2. For the world average at present, $TFR = 2.5$ and $t_g = 25$ years, implying a doubling time of 78 years if the replacement-level fertility rlf is 2.0, or 200 years if $rlf = 2.3$ (see Appendix).

More familiar than equation (3) is the relation between doubling time and annual percent growth rate r:

$$t_d = \frac{100 \ln 2}{r} = \frac{69.3}{r} \tag{5}$$

Equation (3) has the advantage of directly relating doubling time to family size, which equation (5) does not do.

4. Why Family Size Has Been Shrinking Worldwide, and Why the Exceptions Are Important

The dramatic decline in *TFR* shown for Asia in Table 2 is dominated by China (Figure 3). From 1950 to 1970 China's *TFR* was steady at about six children, except during the "Great Leap Forward" in 1959–1961. From 1970 to 1979, the *TFR* dropped rapidly to 2.7, encouraged by governmental policies favoring small families [*Greenhalgh and Winckler*, 2005]. In 1980–1983, the coercive one-child policy was introduced, resulting in further reduction. According to the Chinese government, the *TFR* was down to 1.8 by the year 2000.

Some other nations have had governmental policies to reduce family size. In several of the states of India, an award is made when a girl completes tenth grade, and another award every year that she delays marriage up to age 21 (e.g., *Chamberlin* [2009]). A large reward is given for accepting permanent sterilization. In Iran, an educational campaign and provision of free contraceptives (but not abortion) to all parts of the country, described by *Weisman* [2013, Chapter 12], lowered the *TFR* from ~6 in 1989 to 1.8 in 2013, although there are now proposals to retreat from those policies [*The Economist*, 2014]. By contrast, some

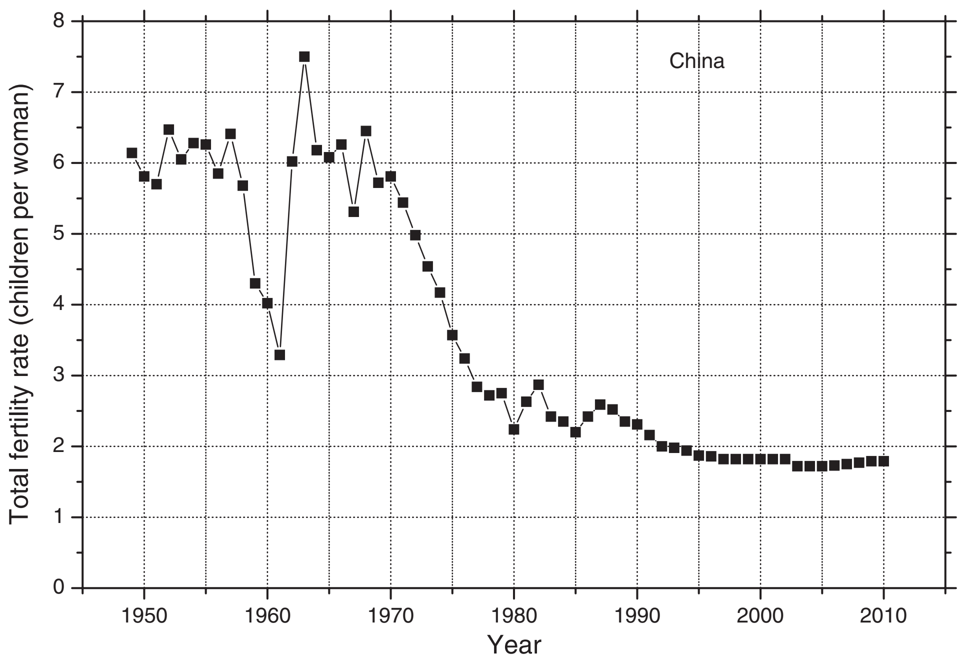

Figure 3. TFR for China from 1949 to 2010. Data from Figure 3 of *Riley* [2004], extended to 2010 with data from www.indexmundi.com, accessed 30 May 2010.

Table 3. TFR (Children per Woman) as a Function of Mother's Educational Level [*Cohen*, 2008]

	Less than Primary	Primary Completed	Secondary Completed
Niger, 1998	7.8	6.7	4.6
Guatemala, 1999	7.1	5.1	2.6
Yemen, 1997	6.9	4.6	3.1
Haiti, 2000	6.4	5.1	2.5
Kenya, 2003	6.7	4.8	3.2
Philippines, 2003	5.3	5.0	3.5

countries have pro-birth policies, such as Israel, whose government is trying to increase its *TFR* above the current value of 3.0 children [*Portugese*, 1998], which is already higher than the global average but lower than that of the neighboring Palestinian Territory.

Perhaps the most effective governmental policy concerns general education; even minimal literacy seems to have a big effect [*Cohen*, 2008]. Studies in many countries have found a strong negative correlation between *TFR* and the educational status of women; some examples are given in Table 3. Affluence is apparently not always required; fertility has dropped below replacement level in the southernmost states of India (Tamil Nadu and Kerala), where the women are poor but educated. But *Campbell et al*. [2013] pointed out that *TFR* will not decline unless the means of contraception are available, and cited evidence that "poor and uneducated women in a number of countries who said they did not want to use contraceptives have suddenly shown rapid uptake of them when this option became realistically available." Campbell et al. argued that improved education of girls may be more often an effect than a cause of lower fertility rates, which would still support the correlation shown in Table 3. They concluded that what is most important in the progress of fertility decline is "the degree to which the woman has freedom from . . . barriers to family planning".

It is important to note that female literacy does not guarantee low fertility; political and religious influences can create growing sub-groups. For example, in the United States, whose average *TFR* is 1.9, there is great diversity. The state with the highest fertility is Utah, whose women have an average of 2.6 children even though they are literate and affluent. And the Palestinian Territory, where girls get 12 years of schooling, has $TFR = 4.1$. We will see next that such exceptions, even if they represent only a small minority, are crucial to forecasting the future of population. In a comparison of many nations, the *TFR* is seen to decline with increase of the "human development index" (an index combining health, literacy, and affluence), but appears to rise again at the highest values of that index [*Myrskylä et al*., 2009].

5. Why Can the Global Average Fertility Rate Rise Even if Each Country's Fertility Rate Is Falling?

The answer to this riddle is a result of the mathematics of subpopulations [*Keyfitz*, 1985, p. 392], sometimes called "shifting shares," which means that over time the global average fertility rate becomes dominated by the groups with high fertility, as the low-fertility groups shrink. To illustrate this concept, suppose the world consisted of just two countries, whose "population pyramids" are shown in Figure 4. Nigeria has the pyramid structure characteristic of continuous high fertility, whereas Italy has undergone a transition to below-replacement-level fertility.

Table 4 shows how during half a century both Italy and Nigeria reduced their *TFR*s (from 2.3 to 1.3, and from 6.9 to 5.9), but their average increased from 4.2 to 4.5 because of the growing statistical weight of Nigeria in forming the average. If these fertility rates were to persist, eventually the Italians would die out and become irrelevant in population computations. The fact that the *TFR* of many countries is now below replacement level has been cited as an encouraging development (e.g., *Wilson* [2004]; *The Economist* [2009]), but the phenomenon of shifting shares shows that we should not be complacent (see the exercise on "renegades" in Box 3).

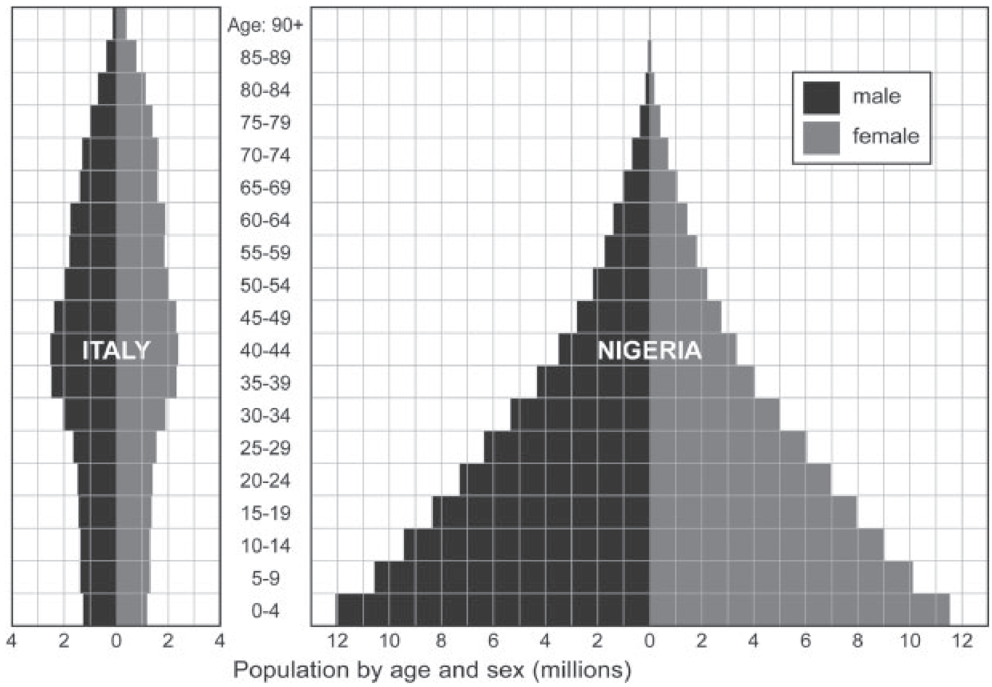

Figure 4. Population pyramids for Italy and Nigeria in 2010. The histograms give population in millions for males (left) and females (right) in 5-year cohorts. Data from *U.S. Census Bureau* [2010].

Table 4. Population (Millions) and TFR (Children per Woman) of Italy and Nigeria at Intervals of ~50 Years[b]

	Italy	Nigeria	Average
Population in 1950	47	33	
TFR in 1950	2.3	6.9	4.2
Population in 2006	59	134	
TFR in 2006	1.3	5.9	4.5
Population in 2050 (projected)	56	300	

[b]Data from *Population Reference Bureau* [2006].

Box 3: The Problem of Renegades

Suppose it is determined at an international convention that the maximum sustainable human population is the present population of 7.2 billion, and suppose that all countries agree on this and sign a treaty for zero population growth. Furthermore, suppose that compliance is spectacular: 99.9% of the Earth's people all agree to have no more than two children. But there is a small renegade ethnic group, 0.1% of the human population, which continues to have four surviving children per woman. How long will it take for the descendants of this small group to grow to 7.2 billion, equaling the rest of humanity? *Answer*: The growth required is a factor of 1000, or 2^{10}, so 10 doublings are required. For $TFR = 4$, the doubling time is one generation (25 years), so 10 doublings takes 250 years.

For a smaller renegade population, and with a fertility rate smaller than four children, the process takes longer. For example, if our renegade group is Utah, which has 2.9 million people and $TFR = 2.6$, equation (3) shows that it would take 750 years for the descendants of Utah's people to grow to 7.2 billion. Admittedly, it is questionable whether the social mechanisms responsible for the high fertility could be maintained for so long.

The champion renegades of the past were probably the European immigrants to North America. From 1800 to 1900, the U.S. population grew from 5 million to 76 million, doubling every 25 years, so that the native Americans became a small minority.

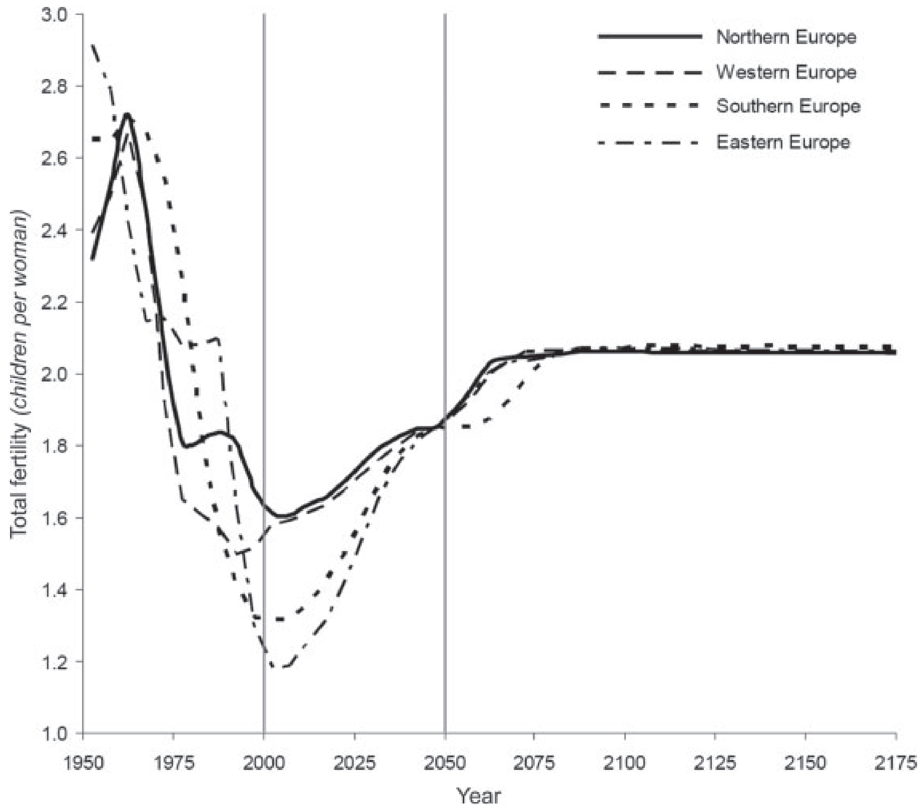

Figure 5. TFR for European regions, historically from 1950 to 2004, and as projected by the United Nations Population Division for 2004 to 2175. From *United Nations Population Division* [2004, Figure 37].

6. The United Nations Population Projections (and Why They Are Wrong)

The projections of future population made by the Population Division of the United Nations are widely used, but they have been inaccurate even for short-term predictions. For example, in 1951 the world population for 1980 was predicted to be between 3.0 and 3.6 billion, but the actual 1980 population turned out to be 4.4 billion [*Cohen*, 1995, Figure 7.6].

In spite of past failures even for just a few decades ahead, the United Nations has made projections for the next three centuries [*U.N. Population Division*, 2004]. Its 240-page report contains tables showing for each country the total fertility, the male and female life expectancies, and the population, at 50-year intervals from now to the year 2300. By way of introduction, the report shows the consequences of three assumed constant values of *TFR*: "low" (1.85), "medium" (2.1), and "high" (2.35); respectively they lead to global populations of 2.3, 9.0, and 36.4 billion people in 2300. The point is that the assumed values differ by only ±0.25 children per woman yet lead to very different consequences after three centuries (assuming that population is limited only by fertility, not by resources).

The medium value, $TFR = 2.1$, which is the replacement-level *TFR* for developed countries, appears throughout the report as an attractor to which all countries are aiming, and which they are then projected to retain indefinitely. For Europe, which was the first region to experience the "demographic transition" from high to low fertility [*Davis*, 1945], Figure 5 shows that its fertility declined further from ~2.6 in 1950 to ~1.5 in 2004, but is arbitrarily projected now to rise to 2.1 and remain there. And Figure 6 shows how two countries with extreme high and low fertility rates (Niger, 8 children; and Latvia, 1 child) are projected soon to converge in their behavior to be equal at 2.1 children.

Achieving and maintaining such stability requires strong negative feedbacks. At least two negative feedbacks on *TFR* are probably necessary, one to bring it down if $TFR > 2.1$, and one to bring it up if $TFR < 2.1$. Such feedbacks have been searched for, but they have not been found. In an article titled

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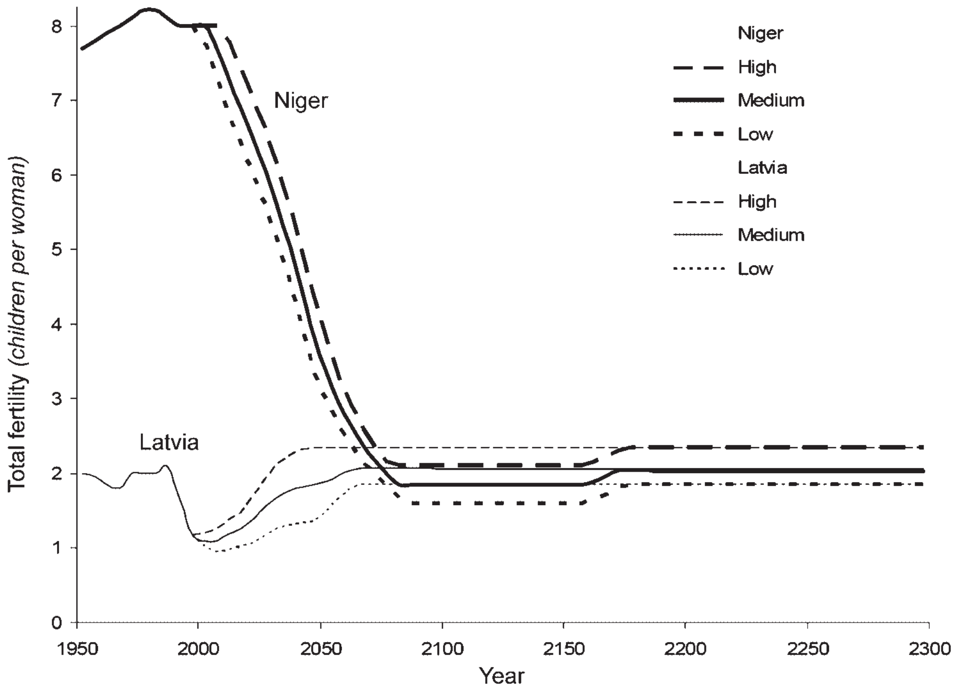

Figure 6. TFR for Niger and Latvia, historically from 1950 to 2000, and as projected by the United Nations Population Division for 2000–2300. From *United Nations Population Division* [2004, Figure 41].

"Replacement-level fertility: the implausible endpoint of the demographic transition," *Demeny* [1997] states, "Neither policy-makers nor the informed public seem to grasp the point that there is no magic force that guarantees stability of fertility behavior once replacement level is reached." Demeny reviewed the works of 11 prominent authors who have written about the demographic transition, and concluded that " … none of them provides support to the assumption that secular fertility change is constrained by a social mechanism that could be trusted to keep fertility from sinking below replacement level." The U.N. projections in Figures 5 and 6 are thus revealed to be just wishful thinking.

Another example of interesting logic is in the U.N. report's warning of what would happen by the year 2300 at *current* fertility rates: "About half the countries of Europe would lose 95 per cent or more of their population, and such countries as the Russian Federation and Italy would have only 1 per cent of their population left. Although one might entertain the possibility that fertility will never rise above current levels, the consequences appear sufficiently grotesque as to make this seem improbable." I leave it to the reader to consider whether "grotesque" really implies "improbable."

7. Migration

Even if the Russians and Italians do maintain their low birth rates and thereby achieve voluntary extinction, we cannot expect their countries to become nature preserves because immigrants from nearby high-fertility countries are likely to come in and proliferate. For example, during 2002–2006, deaths exceeded births in the German-speaking countries of Europe, yet their population grew because the natural decline was more than offset by immigration [*Lutz*, 2008]. Immigration directed from countries with higher fertility to nearby countries with lower fertility can now be seen worldwide: migrants are moving from Algeria to France, from Mozambique to South Africa, and from Central America to the United States [*Weeks*, 1999, Figure 7.6]. Because of their improved economic circumstances in the receiving country, the fertility of the immigrants may increase. For example, the TFR in Mexico is 2.2, but for U.S. residents of Mexican descent it is 3.1 [*Haub*, 2009]. Governmental policies to limit immigration are likely to fail in the long run because smugglers thrive wherever barriers are erected.

8. Why Is the Human Population Growing (and Why Is the Answer Not Obvious)?

The first time I asked students to answer this question with an essay, many simply wrote: "Because people have more than 2 children". The next year I prefaced the question with the warning that this is not an acceptable answer because the same can be said for all other animal species, and most of their populations are *not* growing. Squirrels, foxes, spiders, birds: they all produce more than two offspring in a lifetime and yet their populations are not growing. A robin does not lay just two eggs in her lifetime; she lays four eggs every year, yet the population of robins can remain stable. Why does she lay more than two eggs? It is because a fertility rate less than two means a declining population, so any species that is perpetuating its population has more than two offspring, often far more than two, allowing the limit to population to be set by something else, usually food supply or predators. [This pattern is an important component of the mechanism of evolution.] It is thus no surprise that the animal species in existence have more than two offspring. Any that had less than two already went extinct or are now going extinct.

The question "Why is the population growing" can therefore be rephrased as "What is *permitting* the population to grow?" *Smil* [1999] argued that the answer is simply agriculture, specifically the advances in its organization and the application of science to agricultural technology. Smil's essay "Detonator of the population explosion" emphasized the singular importance of artificial means of fixing nitrogen by the Haber–Bosch process, which made ghost towns of the nitrate mines in the Atacama Desert; the efficient production of urea fertilizer allowed world population to more than triple in the twentieth century. All amino acids contain nitrogen, and Smil pointed out that much of the protein in human bodies got its nitrogen from the Haber–Bosch synthesis of ammonia. More generally, high agricultural productivity has been dependent on cheap sources of energy.

Malthus [1798] argued that whereas population can increase exponentially, food supply cannot. But from 1930 to 1998, the yields per hectare in the United States actually did increase exponentially, for tomatoes, soybeans, rice, potatoes, and corn [*Warren*, 1998], challenging Malthus's assumption on the short term. The "green revolution" in low-latitude countries [*Hardin*, 2008] facilitated rapid population growth. A second green revolution using genetic engineering may cause further large increases in the food supply [*Juma*, 2011].

When asked the question "Why is the human population growing," even the experts often answer with a statement about fertility instead of agriculture. On the two-hundredth anniversary of Malthus's essay on population, a commemorative essay by *Short* [1998] made no mention of agriculture, so it prompted a series of comments [*Warren*, 1999a,1999b; *Bondi*, 1999]. Medical advances have often been cited as permitting population growth by reducing child mortality, but I would argue that they are of secondary importance because (a) the world population was already growing in the centuries before the development of scientific medicine and the germ theory of disease, (b) populations are now growing most rapidly in countries with the lowest standards of hygiene and medical care, and (c) medical advances and improved hygiene are incapable of fostering population growth unless food is available to support a larger population. Global agricultural production increased sixfold from 1900 to 2000 [*Moses*, 2009]. As *Smil* [1999] pointed out, without the agricultural advances of the twentieth century, world population could not have grown as it did from 1.7 billion in 1900 to 6 billion in 2000, no matter how high the fertility rates were.

The major eras in human population growth were discussed by *May* [1978], emphasizing the importance of agriculture. They are summarized in Table 5.

9. What Will Stop World Population Growth?

The world population is growing now because the birth rate exceeds the death rate. In the future either a decrease in the birth rate, or an increase in the death rate, or a combination of the two will stop population growth. [For a dissenting opinion, see Box 4.]

Hopefully the birth rate will decline worldwide to replacement level or below, in response to future massive increases in funding and promotion of contraception, and universal provision of abortion services in all countries. But here I consider the possibility that the goal of a stable or declining world population may

Table 5. The Major Eras in Human Population Growth, Summarized from *May* [1978], With Simplifications and Additions

Time	Population	Number of Doublings	Average Doubling Time (Years)	Growth per Generation (%)	Process Allowing Population Growth
From 200,000 B.P. to 10,000 B.P.	From the first pair to 5 million	21	10,000	0.2	Colonization of the continents by hunter-gatherers
From 10,000 B.P. to 1700 C.E.	From 5 million to 600 million	7	1400	1.3	Spread of agriculture
From 1700 to 2000	From 600 million to 6 billion	3.3	90	21	Further spread of agriculture; application of science to technology

B.P. = Before Present.

not be achieved even if such efforts are implemented, because of cultural diversity. Even if most societies do complete a transition to low fertility, the few that do not can grow to dominate numerically.

Box 4: Populating the Universe

I asked my class of 68 students to write an essay answering the question "What will stop world population growth?" Of them, 25 thought the birth rate would drop to replacement level, and 42 thought the death rate would rise to equal the birth rate. But the one remaining student argued that the population will not stop growing: "We'll colonize other planets, other solar systems, and other galaxies, and the universe is expanding!" This answer led to formulation of a third exercise: How long would it take to populate the universe with a doubling time of 78 years?

Answer: Let us be generous and say there are 10^{12} galaxies; each galaxy has 10^{12} stars and each star is orbited by one earth. To populate all the earths with 7.2 billion each, the human population would have to grow by the factor 10^{24}, or 2^{80}. Eighty doublings, at 78 years per doubling, requires 6240 years.

If populations will be limited by death rate rising to equal the birth rate, what might cause the increase in deaths? Disease is one possible cause. The bubonic plague did cause the world population to decline temporarily in the fourteenth century [*Cohen*, 1995, Figure 5.3]. But even the most deadly viruses, such as Ebola, kill no more than 90% of those infected. If the Ebola virus were to mutate to become easily transmitted so that it killed seven eighths of the world population, the remaining one eighth with a genetic resistance to Ebola would have to double three times to reach the pre-disease population size. For a doubling time of ~80 years, that is just 240 years. The continual emergence of new pathogens might result in an oscillating population size.

Like disease, wars have had temporary effects, but in the past they neither limited population nor even slowed its growth by much. The population of Rwanda grew from 2 million in 1950 to 7.8 million in 1993. The massacres of 1994 killed more than 1 million people, but within 5 years Rwanda's population had already exceeded its prewar value, according to the World Population Data Sheets. The war caused an increase in the birth rate, termed "revenge fertility" [*The Economist*, 1997].

If disease and war are unlikely to stop population growth, what will do it? The remaining strong constraint that can limit human population is the one Malthus identified, namely food supply. Food supply is fundamentally a constraint on population size rather than a negative feedback on fertility rate. (Whether chronic malnutrition reduces fertility is a subject of debate [*Frisch*, 1978, 1982; *Bongaarts*, 1980, 1982].) Even if the fertility rate is maintained far in excess of 2, the population cannot grow if food is limiting; instead the additional babies will starve. The food supply may be enhanced in the coming decades by genetic engineering and other agricultural innovations [*Marris*, 2008; *Lele*, 2010; *Butler and Guillou*, 2010], but it may be limited by water shortage [*Bohannon*, 2010; *The Economist*, 2010], climate change [*Battisti* *and Naylor*, 2009], pollution, and energy shortage. The efficiency of agriculture may also be diminished by breakdown of social infrastructure (this is how war might indirectly limit population).

What is the maximum population that could be sustained? *Smil* [1994] estimated that with the agricultural technology of 1990 the world population could grow by 60% over its 1990 value of 5.3 billion (i.e., to 8.4 billion) without any increase in the area of farmland, by instituting increased field efficiency, reduced waste, and less-fatty diets. *Bongaarts* [1996] estimated that only about one third of the potentially arable area in the developing world is now cultivated. Among developing countries, the number of people per hectare of arable land in 1989 varied from 19 in Egypt to 0.07 in the Central African Republic, suggesting that significant increases in population could be accommodated. Bongaarts argued that a tripling of world food production could be accomplished from 1989 to 2050, even without considering the increases that may be possible with genetic engineering. On the other hand, others speculate that we are close to the maximum sustainable population now, or are already in overshoot, because high-yield agriculture is dependent on energy sources that may become prohibitively expensive [*Kunstler*, 2005]. A recent projection of regional populations based on fertility forecasts, indicating a world population of 11 ± 1.3 billion for the year 2100 [*Gerland et al*., 2014], was accompanied by a proviso that it did not consider possible constraints that may be imposed by resource shortages.

10. Was Seven Billion Inevitable?

A question that is rarely asked, but which is worthy of consideration, is whether it was inevitable that the world population would eventually at some time reach today's 7 billion, with its numerous environmental consequences. Despite the statements of prominent thinkers that no benefit would come from increasing the population beyond its current value (*Cohen* [1995] quotes John Stuart Mill from 1848, when the world population was just 1.2 billion), it has continued to grow. Are there any plausible policies that could conceivably have been put in place a century or two ago to limit the ultimate population to 2 or 3 billion? And would such policies survive beyond the typical lifetime of governments before overthrow by revolutions?

11. Summary

1. The world's population doubled in 40 years, 1960–2000. The U.S. population doubled in 56 years, 1950–2006.
2. For the last 40 years, the annual increase in world population has been steady at about 80 million, because the growth rate (percent per year) has been dropping.
3. Over time, the global average fertility rate becomes dominated by groups with high fertility, as the low-fertility groups shrink, as was shown for what happened in Italy and Nigeria.
4. The fertility of Europeans is well below two children per woman; the European populations may be replaced by immigrants from nearby countries with high fertility. The projected decline for Europe's share of global population in Table 2 may be invalidated by immigration.
5. The U.N. projections to the year 2300 are not based on sound logic and are essentially useless.
6. There is nothing unusual about having more than two offspring; it is normal for all animal species. From this perspective, the human population is then seen to be growing not because people are having more than two children but because there is excess food available. As a consequence of the excess food, world population has been growing for the last 10,000 years, since the beginnings of agriculture.
7. Education of women and provision of contraceptive services are likely to reduce fertility and slow population growth in many countries, but may not stop it worldwide; in that case the death rate will rise to meet the birth rate, most likely because of food shortage.

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Appendix A: Derivation of Equation (3)

Let n_d be the number of *generations* required to double the population, t_d the number of *years* required to double the population, t_g the generation time in years, *TFR* the total fertility rate, *rlf* the replacement-level fertility, p_0 the initial population, and $p(n)$ the population after n generations.

$p(n) = p_0(TFR/rlf)^n$ and $p(n_d) = 2p_0$, so $p(n_d)/p_0 = 2$ and $\left(TFR/rlf\right)^{n_d} = 2$.

Then $n_d = \frac{\ln 2}{\ln\left(TFR/rlf\right)}$. The doubling time is $t_d = t_g n_d = \frac{t_g \ln 2}{\ln\left(TFR/rlf\right)}$.

The derivation of Eq. (4) proceeds similarly, but with $n_h \equiv$ number of generations to *halve* the population, so that $p(n_h) = p_0/2$.

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