a decrease in frequency (indicating possibly either muscle limitations or active control to decrease inertial forces), whereas the robot speed decrease was largely determined by a decrease in spacing between tracks, as shown in fig. S6D. This decrease in effective step length was related to slipping of the robot at the highest θ. Comparative study of the anchoring mechanics is useful to learn about which lower-level mechanisms in the control hierarchy are critical, both to generate template dynamics as well as to understand neuromechanical control targets for the anchors.


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## SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/346/6206/224/suppl/DC1
Materials and Methods
Figs. S1 to S6
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Movies S1 to S5


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ECONOMIC DEMOGRAPHY

# Is low fertility really a problem? Population aging, dependency, and consumption


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**Longer lives and fertility far below the replacement level of 2.1 births per woman are leading to rapid population aging in many countries. Many observers are concerned that aging will adversely affect public finances and standards of living. Analysis of newly available National Transfer Accounts data for 40 countries shows that fertility well above replacement would typically be most beneficial for government budgets. However, fertility near replacement would be most beneficial for standards of living when the analysis includes the effects of age structure on families as well as governments. And fertility below replacement would maximize per capita consumption when the cost of providing capital for a growing labor force is taken into account. Although low fertility will indeed challenge government programs and very low fertility undermines living standards, we find that moderately low fertility and population decline favor the broader material standard of living.**


Economic behavior, abilities, and needs vary strongly over the human life cycle. During childhood and old age, we consume more than we produce through our labor. The gap is made up in part by relying on accumulated assets. It is also made up through intergenerational transfers, both public and private, that shift resources from some generations to others with no expectation of direct repayment. Private transfers occur when parents rear their children and when older people assist their adult children or receive assistance from them. Public transfers include public education, publicly funded health care, public pensions, and the taxes to pay for these programs. Because of these economic interdependencies across age, fertility rates that are falling or already low will drive rapid population aging in economies around the world. Forty-eight percent of the world's people live in countries where the total fertility rate (TFR) was below replacement, about 2.1 births per woman for 2005 to 2010. The TFR is 1.5 births per woman in Europe and 1.4 births per woman in Japan (*1*). With fertility this low, population growth will give way to population decline, and population aging will be rapid. The median age of the Southern European population, for example, is projected to reach 50 years of age by 2040 as compared to 41 in 2010 and 27 in 1950 (*1*). In 2013, governments in 102 countries reported that population aging was a "major concern," and 54 countries had enacted policies intended to raise fertility (*2*).

This is a remarkable reversal from decades of concern about the economic and environmental consequences of high fertility and rapid population growth (*3*). Should we now be alarmed about low fertility, population decline, and population aging? Should governments encourage their citizens to bear more children to balance the dramatic future increase in the number and proportion of elderly?

Identifying an optimal population policy is likely to be impossible for several reasons. First, children yield direct satisfaction and impose


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costs on parents that are difficult or impossible to measure. Second, the environmental consequences of continuing population growth are exceedingly complex and difficult to value or weigh against other costs and benefits of low fertility. Third, assessing the welfare consequences of differences in fertility requires comparing the welfare of those not yet born to those who will never be born.

Our goal is more modest: to examine how low fertility and population aging will influence the material standard of living. The analysis shows that relatively high fertility and young populations are favorable to public finances in rich countries because they have comprehensive systems of support for the elderly. A broader analysis that incorporates private intergenerational transfers and the capital costs of equipping each new generation shows that low fertility, older populations, and gradual population decline favor the material standard of living.

The implications of low fertility and population aging depend on the age patterns of labor income, consumption, and intergenerational transfers (*4*–*8*). However, estimates of economic life cycles and intergenerational transfers have not previously been available. The results presented here have their basis in estimates constructed by research teams in 40 countries following a common methodology: National Transfer Accounts (NTA) (*9*–*11*). NTA uses existing surveys, administrative data, and the United Nations System of National Accounts (SNA) to estimate the values of goods and services produced and consumed at each age and the intergenerational flows across ages through public and private transfers and assets. NTA incorporates the age dimension into SNA, thereby facilitating analysis of the macroeconomic implications of population change.

Estimated labor income by age includes wages, salaries, and fringe benefits as well as an estimate of the value of labor of those who are self-employed or unpaid family workers, all averaged across the entire population at each age. Consumption includes private expenditures and goods and services produced by governments (e.g., education and health care) imputed to different ages and averaged across all individuals at a given age.

NTA age profiles for the United States and Thailand illustrate the data used in the analysis (Fig. 1). In the United States, elderly consume far more than young adults and labor income falls off rapidly at older ages (Fig. 1A). Public transfer inflows to the elderly are generous, funded largely through public transfer outflows from the working ages (Fig. 1B). Familial transfers are important to some elderly, but on average the elderly give more than they receive at almost every age (Fig. 1C). In Thailand, elderly and young adults consume at similar levels. The elderly have somewhat higher labor income than in the United States (Fig. 1D). The public system for the elderly is very modest, with public transfer outflows from the elderly as great as public transfer inflows (Fig. 1E). Familial support is very important for the elderly, with private transfer inflows higher than private transfer outflows (Fig. 1F).

The differences in shapes of labor income and consumption by age, and in public and private transfers made and received, lead to differences in the impacts of population age distributions in the forty countries studied here. These differences are incorporated into two summary measures, the fiscal support ratio (FSR) and the support ratio (SR). Definitions are given below, but heuristically the FSR is the ratio of taxpayers to beneficiaries and the SR is the ratio of earners to consumers. Age profiles, FSR, and SR for all countries and complete definitions of variables are provided in the supplementary materials (*9*) (Table 1).

The FSR summarizes the influence of population age distribution on government budgets. The FSR is defined as the number of effective taxpayers, calculated by weighting the population in each age group by the average taxes paid by that age group in the base year, divided by the number of effective beneficiaries, calculated by weighting the population in each age group by per capita benefits received. A higher FSR is favorable for public finances allowing higher benefits at each age, lower taxes at each age, a smaller budget deficit, or some combination of the three. A population concentrated in high taxpaying ages leads to a high FSR. A population with many children, who pay little in taxes and receive education benefits, leads to a low FSR. Likewise, a population at older ages has a low FSR in rich countries, because they emphasize pensions and health care spending on the elderly.

The SR summarizes the effect of the population age distribution on income and outlays per person combining both the public and the private sectors. The SR is defined as the number of effective workers, the population weighted by per capita labor income at each age, divided by the number of effective consumers, the population weighted by per capita consumption at each age. A higher SR indicates proportionally higher resources available per person allowing for higher consumption, higher saving and investment, or some combination of the two. A population concentrated at ages where labor income is high and consumption is low leads to a high SR. A population concentrated at ages where labor income is low and consumption is high leads to a low SR.

The FSR and the SR provide distinctive perspectives because intergenerational transfers through the public and private sectors are very different. Especially in rich countries, public transfers are predominantly to the elderly, whereas private transfers go mostly to children. As a consequence, the age structure that favors public finances is much younger than the age structure that favors the combined finances of public and private sectors. Both a young, high-fertility, rapidly growing population and an old, low-fertility, rapidly declining population reduce the FSR and the SR. The central issue addressed here is what demographic conditions would be most favorable to public finances and standards of living in the long run.

The age structure of a population in the long run is determined by fertility, mortality, and migration.

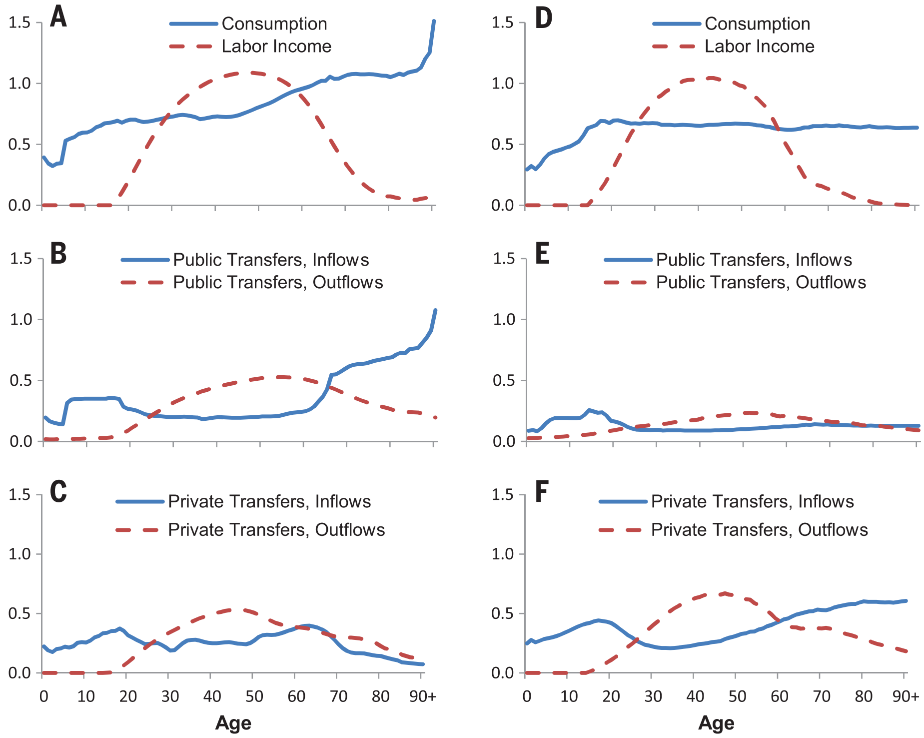


**Fig. 1. Age profiles of economic flows.** Per capita age profiles of consumption, labor income, and public and private transfers for the United States (2009) (**A** to **C**) and Thailand (2004) (**D** to **F**). Profiles are expressed relative to the mean labor income of persons 30 to 49 in each country.

Our analysis emphasizes fertility because it is an important determinant of age structure and because so many governments are encouraging higher fertility as a result of their concerns about population aging. Mortality decline also leads to older populations, but the effects are gradual, and no government has ever proposed slowing mortality decline to avoid population aging. Immigration is often suggested to help reduce the population aging that results from low fertility. Immigration does lead to a younger population in the short term, but it has a muted effect in the long term. Immigrants are relatively young on average when they arrive, but over time their age distribution tends to become similar to or older than the age distribution of the receiving population. This occurs because the immigrant populations age and because immigrant fertility rates typically converge toward the fertility rates of the receiving population (*12–14*). A summary of the literature concluded that "a steady stream of migrants almost always makes a population younger in the short-term but older in the long-term" (*13*). Net immigration also raises the population growth rate, which imposes capital costs, discussed below, that must be balanced against possible benefits from age structure.

Thus, we consider the effect of fertility given the level of mortality in a population closed to migration. Given mortality and in the absence of migration, the population growth rate is determined by fertility. What level of fertility and population growth rate would maximize the FSR and SR in the long run?

Given the NTA age profiles, we can easily find this level of fertility or growth rate by systematic numerical search. To gain analytic insight, we can also differentiate the log of the support ratio (ln *SR*) with respect to the population growth rate ($n$), finding that $\partial \ln SR/\partial n = A_c - A_{y_l}$ (see supplementary materials). Here, $A_c$ is the average age of consuming in the population, and $A_{y_l}$ is the average age of earning. The differentiation is across long-run age distributions with differing growth rates (steady-state age distributions or stable-population age distributions). When $A_c > A_{y_l}$ then earning occurs at a younger age than consumption, on average, so a younger population, achieved through higher fertility and more rapid population growth, would raise effective workers more than effective consumers, thereby raising the SR, and conversely. At the maximum long-run SR, these average ages are equal, and the derivative equals zero (*5*).

The SR is an intuitive and widely used indicator, but it has a serious limitation. Although higher fertility might push the SR higher, this could come at a cost: the increased saving and investment that would be required to provide capital for the growing labor force (*5–8*, *15–17*). This "capital cost" of higher fertility and additional population growth depends on the behavioral responses of households and firms and on public policies that influence saving and investment, for example, the extent of unfunded public pensions and health care. To deal with the uncertainty about future public policy, we consider two scenarios that in our view encompass the possible responses.

In one approach, the low capital cost case, we assume that the ratio of capital to output is constant and unaffected by changing demography. In the face of fertility decline, policies are implemented as needed to reduce saving rates to achieve this outcome. This case would be optimal for one variant of a well-known economic growth model (*9*, *18*, *19*). Between 1980 and 2004, the capital-output ratio was very stable for many Organization for Economic Co-operation and Development (OECD) countries, including the United States, with about three dollars of capital for each dollar of output produced (*20*). We use the average value of 3.0 to represent the low-capital-cost case.

For the second case, the high capital cost case, we rely on the most widely used model of economic growth, the neoclassical model. We will use an important, special case of this model in which policies are used to achieve the saving rate that leads to the economic growth path with the highest possible consumption per capita, called "golden rule" growth by economists. Under these conditions, capital per worker rises when fertility falls, as has been true in Japan, many OECD countries, and recently many other high-income countries (*21*). Under the high-capital-cost scenario, the capital-output ratio rises to higher levels than currently found in any country. The increase in capital because of low fertility is consistent with the view recently advanced by Piketty (*22*).

Again, the fertility rate that maximizes per capita consumption incorporating capital costs can be found by numerical search. For either of the cases, we can also differentiate across steady states, finding that the first order condition for maximum consumption is $d[\ln(\text{lifetime consumption})]/dn = A_c - A_{y_l} - K/C$, where $K$ is capital and $C$ is consumption. The SR effect is captured by $A_c - A_{y_l}$, whereas $-K/C$ captures the capital costs of higher fertility or more rapid population growth (*9*).

Table 2 reports the key results for 40 countries comparing each country's current fertility (column B) with the fertility rate that maximizes the FSR (column C), the SR (column D), and per capita consumption for the low- and high-capital-cost scenarios (columns E and F). Very low fertility does not adversely affect public finances in lower-income countries because public programs for the elderly are quite limited and the elderly do pay taxes. For every high- and upper-middle-income country except South Africa and Thailand, current fertility is below the fertility level that maximizes the FSR—3.0 and 2.9 births per woman, respectively, for upper-middle- and high-income countries. We expect that public transfer programs will become more generous in countries that have not yet embraced them, so that higher TFRs will maximize their FSRs in the future. At the same time, future pension and health care reform in rich industrial nations and many Latin American countries may well reduce the TFRs that maximize their FSRs.

The TFR that would maximize the support ratio (column D) is 1.8 births per woman in lower-income countries, 2.0 in upper-middle-income countries, and 2.3 in high-income countries. These values are lower than the FSR-maximizing values

**Table 1. Key aging variables, definition, method of calculation, summary statistics, and sources.** WPP is World Population Prospects 2012 Revision; NTA is from www.ntaccounts.org (accessed 10 July 2013). The range and mean values, except those for the TFR, are the stable values that would result if current age-specific fertility and mortality rates persist. See supplementary materials for detailed method of calculation.

| Variable | Definition and sources | Range (mean) |
|---|---|---|
| FSR | Number of effective taxpayers per effective beneficiary determined by the population age distribution (WPP) and the age profiles of per capita taxes paid and benefits received for all in-kind and cash transfer programs, including education, health care, and pensions (NTA). All values expressed relative to the FSR for 2010. | 0.70 to 1.09 (0.88) |
| $A_C$ | Average age at which goods and services are being consumed. This is determined by the age distribution of the population (WPP) and the age profile of per capita consumption (NTA). | 28.0 to 56.9 (44.5) |
| $A_{y_l}$ | Average age at which goods and services are being produced by workers. This is determined by the age distribution of the population (WPP) and the age profile of per capita labor income (NTA). | 35.2 to 47.4 (42.8) |
| SR | Number of effective producers per effective consumer determined by the population age distribution (WPP) and the age profiles of per capita consumption and labor income (NTA). | 0.36 to 0.67 (0.49) |
| TFR | Number of births per woman over the reproductive span, given current age-specific birth rates (WPP). | 1.1 to 5.6 (2.2) |

because families bear most of the costs of childrearing while governments, except in lower-income countries, are typically burdened more by the elderly. Still, one-third of the upper-middle-income countries and all high-income countries except Uruguay currently have fertility below the level that maximizes the support ratio. For high income countries, 2.3 births per woman would be "best," on average, as compared with a current value of 1.6 births per woman. Judged in this limited way, high-income countries would benefit from higher fertility.

The fertility rates that would maximize consumption, taking capital cost into account, are reported in columns E (low-capital-cost scenario) and F (high-capital-cost scenario). Using either of these measures, current fertility is higher than the consumption-maximizing level in every lower-income country except Vietnam and every upper-middle-income country except China, Hungary, and Thailand. In these four countries, fertility is too low with use of the low-capital-cost scenario and too high with use of the high-capital-cost scenario. However, we emphatically are not suggesting that these lower-income countries should be aiming for fertility as low as shown in Table 2. Development will likely lead to consumption and public support age profiles similar to those of richer countries.

The picture is mixed for the higher-income countries. Consider the nine countries with TFRs above 1.6 births per woman in 2005 to 2010 (Australia, Canada, Chile, Finland, France, Sweden, United Kingdom, United States, and Uruguay). In these countries, the TFR exceeds or is very close to the consumption-maximizing fertility level. Under any plausible assumption about the capital costs of higher fertility, these nine countries did not have fertility rates that were too low. For seven countries with TFRs ranging from 1.2 to 1.5 for 2005 to 2010 (Austria, Germany, Japan, Slovenia, South Korea, Spain, and Taiwan), higher fertility rates would result in higher consumption under any plausible scenario. For only one high-income country, Italy, is a definitive conclusion not possible.

Very low fertility results in lower living standards. Given current mortality rates, no immigration, and age profiles of high-income countries, an $n = -2\%$ per year ($TFR \simeq 1.1$) would reduce per capita consumption by 4% relative to consumption for $n = 0$ and TFR at replacement. Low fertility produces a smaller decline in consumption in lower- and upper-middle-income countries because elder consumption is not as high and because these countries have higher mortality rates (Fig. 2A). Given Japanese mortality rates, lost consumption would be greater for all income groups but especially for high-income countries—a 7.6% decline compared with consumption at replacement fertility (Fig. 2B). These costs of low fertility would be smaller for the high-capital-cost scenario.

The effects of having low fertility in 2005 to 2010 unfold gradually as the lower stable SR is reached. Among the high-income countries with TFRs of 1.6 or higher, the stable SRs are about 10% less than the 2010 SRs. For high-income countries with TFRs below 1.6, the stable SR is 80% of its 2010 level. For these, South Korea excluded, between 50 and 75% of the decline toward the stable SR would occur by 2030 (*9*)

Based on Japan, with the oldest population in the world, the effects of low fertility highlighted in this study are already beginning to emerge (*9*). Because of low fertility and long life, the population is aging rapidly, and the SR fell at 0.6% annually during the last decade, whereas the FSR fell even faster at 0.9%. However, slower and now negative labor force growth has led to

**Table 2. Current TFRs and TFRs that maximize alternative objectives.** Current TFRs are most recent estimates from the United Nations Population Division (*1*) and refer to the period of 2005 to 2010. All other values calculated by using methods described in detail in the supplementary materials. Income group based on World Bank classification for 2014 (http://data.worldbank.org/about/country-and-lending-groups); lower income includes low-income and lower-middle-income countries. Results were calculated by using the age profiles of economic flows estimated for each country, a depreciation rate of 5% per year, and exogenous labor-augmenting technological growth of 2% per year. na, not available.

| Country/income group | TFR 2005–2010 (B) | TFR that maximizes each outcome | | | |
|---|---|---|---|---|---|
| | | FSR (C) | SR (D) | Consumption, low-capital-cost scenario (E) | Consumption, high-capital-cost scenario (F) |
| *All countries* | 2.44 | 2.56 | 2.05 | 1.54 | 1.24 |
| *Lower income* | 4.03 | 1.08 | 1.75 | 1.21 | 0.91 |
| Cambodia | 3.08 | na | 3.66 | 2.67 | 2.19 |
| Ethiopia | 5.26 | na | 1.40 | 0.91 | 0.62 |
| Ghana | 4.22 | na | 1.01 | 0.67 | 0.46 |
| India | 2.66 | 1.80 | 1.93 | 1.40 | 1.06 |
| Indonesia | 2.50 | 0.88 | 1.28 | 0.84 | 0.53 |
| Kenya | 4.80 | 1.12 | 2.07 | 1.54 | 1.26 |
| Mozambique | 5.57 | 1.30 | 1.61 | 1.12 | 0.89 |
| Nigeria | 6.00 | na | 0.96 | 0.54 | 0.29 |
| Philippines | 3.27 | 1.13 | 1.43 | 1.00 | 0.73 |
| Senegal | 5.11 | 0.25 | 1.32 | 0.67 | 0.28 |
| Vietnam | 1.89 | na | 2.60 | 1.99 | 1.67 |
| *Upper-middle income* | 2.09 | 2.96 | 2.01 | 1.51 | 1.20 |
| Argentina | 2.25 | 3.25 | 2.00 | 1.54 | 1.26 |
| Brazil | 1.90 | 5.45 | 2.29 | 1.82 | 1.50 |
| China | 1.63 | 2.64 | 2.17 | 1.65 | 1.34 |
| Colombia | 2.45 | 3.77 | 2.04 | 1.49 | 1.13 |
| Costa Rica | 1.92 | 3.85 | 2.31 | 1.77 | 1.42 |
| Hungary | 1.33 | 2.58 | 1.89 | 1.47 | 1.21 |
| Jamaica | 2.40 | na | 2.19 | 1.63 | 1.30 |
| Mexico | 2.37 | 2.83 | 1.98 | 1.47 | 1.14 |
| Peru | 2.60 | 3.45 | 2.17 | 1.61 | 1.26 |
| South Africa | 2.55 | 0.97 | 1.40 | 1.02 | 0.82 |
| Thailand | 1.49 | 0.79 | 2.00 | 1.55 | 1.28 |
| Turkey | 2.16 | na | 1.63 | 1.08 | 0.71 |
| *High income* | 1.65 | 2.94 | 2.27 | 1.78 | 1.48 |
| Australia | 1.89 | na | 2.70 | 2.06 | 1.70 |
| Austria | 1.40 | 3.74 | 2.44 | 1.90 | 1.58 |
| Canada | 1.63 | na | 1.96 | 1.55 | 1.26 |
| Chile | 1.90 | 3.63 | 2.20 | 1.69 | 1.36 |
| Finland | 1.84 | 2.92 | 2.30 | 1.83 | 1.54 |
| France | 1.97 | na | 2.41 | 1.92 | 1.61 |
| Germany | 1.36 | 3.33 | 2.55 | 2.00 | 1.65 |
| Italy | 1.38 | na | 2.11 | 1.65 | 1.34 |
| Japan | 1.34 | 2.70 | 2.33 | 1.88 | 1.57 |
| Slovenia | 1.44 | 3.25 | 2.21 | 1.78 | 1.52 |
| South Korea | 1.23 | 2.07 | 2.04 | 1.55 | 1.25 |
| Spain | 1.41 | 3.29 | 2.20 | 1.73 | 1.43 |
| Sweden | 1.89 | 3.07 | 2.15 | 1.76 | 1.49 |
| Taiwan | 1.26 | 1.85 | 2.15 | 1.70 | 1.43 |
| United Kingdom | 1.88 | 3.00 | 2.63 | 2.03 | 1.68 |
| United States | 2.06 | 2.16 | 2.33 | 1.84 | 1.50 |
| Uruguay | 2.12 | 3.22 | 1.90 | 1.47 | 1.19 |

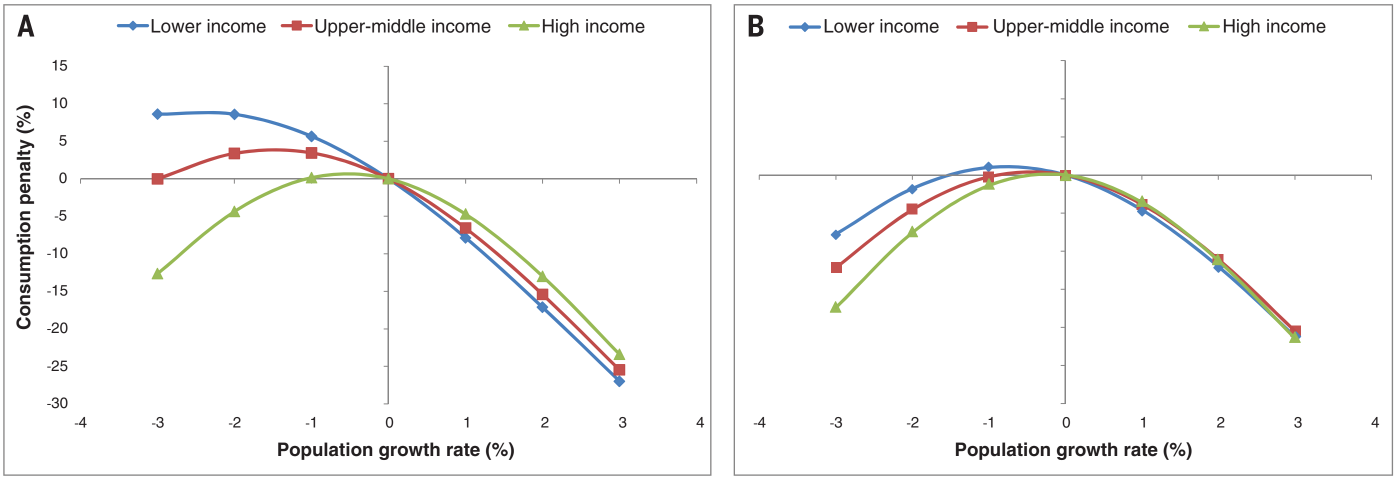


**Fig. 2. Effect of population growth on consumption per equivalent adult as a percentage of consumption level for zero population growth.** These data have their basis in the low-capital-cost case assuming that the saving rate adjusts to keep the capital-output ratio constant at 3.0 given own-country mortality rates (**A**) and 2009 Japanese mortality rates (**B**). Values are simple averages for countries in three groups: lower income, upper middle income, and high income. See Table 2 for countries in each group. Data sources are as follows: NTA (ntaccounts.org) for consumption and labor income profiles; United Nations Population Division (*1*) for age-specific mortality rates, except for age-specific survival rates for Japan in 2009, which were taken from the Human Mortality Database (www.mortality.org; accessed 16 October 2013).

reduced capital costs of equipping the new workers. Even with lower saving rates from 2000 to 2007 (the start of the global recession), the capital output ratio has risen, and, remarkably, consumption per capita also rose at more than 2% annually. It seems possible through developments in robotics that capital will be able to substitute for labor in elder care. It remains true, however, that a TFR of 1.34 (the average for 2005 to 2010) will impose considerable strain on public finances. Public debt is very high in Japan, making higher taxes and lower benefits a near certainty. But Japan is not experiencing economic decline, and standards of living continue to increase at favorable rates for an advanced economy—faster than long-term productivity growth.

Many factors will influence the economic effects of low fertility that are not part of the formal model used in the analysis. However, these additional considerations reinforce the basic conclusion that low fertility is not a serious economic challenge. The effect of low fertility on the number of workers and taxpayers has been offset by greater human capital investment, enhancing the productivity of workers (*23*). Targeted immigration policy might be helpful, although we are somewhat skeptical on this point (*9*). International capital flows, trade, and technological innovation may mitigate some adverse effects of population aging. Behavioral responses are likely: Changes in patterns of work and consumption are already occurring. Governments are scaling back systems that are not sustainable given any likely demographic scenario.

Fiscal pressures on public programs resulting from population aging are real and important. If the subreplacement fertility levels found in many countries persist, larger adjustments in public programs and retirement age will be required. The United States is exceptional with a TFR close to the level best for public finances. In a number of countries, particularly those with very low fertility, standards of living would be moderately higher if fertility increased. Fertility as low as 1.6 births per woman and possibly even lower should not in itself be a matter of concern. Fertility below replacement and modest population decline favor higher material standards of living.

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**SUPPLEMENTARY MATERIALS**

www.sciencemag.org/content/346/6206/229/suppl/DC1
Materials and Methods
Tables S1 and S2
References (*24–34*)

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WORLD POPULATION

# World population stabilization unlikely this century

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**The United Nations (UN) recently released population projections based on data until 2012 and a Bayesian probabilistic methodology. Analysis of these data reveals that, contrary to previous literature, the world population is unlikely to stop growing this century. There is an 80% probability that world population, now 7.2 billion people, will increase to between 9.6 billion and 12.3 billion in 2100. This uncertainty is much smaller than the range from the traditional UN high and low variants. Much of the increase is expected to happen in Africa, in part due to higher fertility rates and a recent slowdown in the pace of fertility decline. Also, the ratio of working-age people to older people is likely to decline substantially in all countries, even those that currently have young populations.**

The United Nations (UN) is the leading agency that projects world population into the future on a regular basis (*1*). Every 2 years the UN publishes revised data of the populations of all countries by age and sex—as well as fertility, mortality, and migration rates—in a biennial publication called the *World Population Prospects* (*2*). In July 2014, probabilistic projections were released for individual countries to 2100. Unlike previous projections, these estimates allow us to quantify our confidence in projected future trends using established methods of statistical inference. These projections are based on recent data, including the results of the 2010 round of censuses and recent surveys until 2012, as well as the most recent data on incidence, prevalence, and treatment for the countries most affected by the HIV/AIDS epidemic (*3*), which had not been included previously.

Our analysis of these data shows that world population can be expected to increase from the current 7.2 billion people to 9.6 billion in 2050 and 10.9 billion in 2100 (Fig. 1A). These projections indicate that there is little prospect of an end to world population growth this century without unprecedented fertility declines in most parts of sub-Saharan Africa still experiencing fast population growth.

Traditionally, the UN has also provided high- and low-projection scenarios (shown in Fig. 1A), obtained by adding or subtracting half a child from the total fertility rate [(TFR) in children per woman] on which the main (or medium) projection is based, for each country and all future time periods. These scenarios have been criticized as having no probabilistic basis and leading to inconsistencies (*4*, *5*). For example, though it is plausible that fertility could exceed the main projection by half a child in a given country and year, it is unlikely that this would be the case for all countries and all years in the future, as assumed in the high projection.

In a methodological innovation aimed at overcoming this limitation, we derived new probabilistic projections based on probabilistic Bayesian hierarchical models for major components of demographic change—namely, fertility (*6–8*) and life expectancy (*9*, *10*). These models incorporated available data and take advantage of data from other countries when making projections for a given country. They also incorporated external information through Bayesian prior distributions, including an upper bound of 1.3 years per decade on the asymptotic rate of increase of life expectancy, based on historic data on life expectancy in leading countries (*11*) and on changes in the maximum age at death (*12*). The models included the assumption that the TFR for a country will ultimately fluctuate around a country-specific long-term average that is estimated from the data; these long-term averages are between 1.5 and 2 children per woman for most countries with high probability (*7*).

Probabilistic population projections were then obtained by inputting the output from the statistical models to the standard cohort component projection method (*4*, *13*). Aggregates were based on individual country projections and take into account the correlations between countries' fertility future trajectories (*8*). The models yielded probabilistic projections and, thus, probabilistic limits for future quantities of interest, responding to calls for probabilistic population forecasting (*5*). (See the supplementary materials and http://esa.un.org/unpd/ppp/ for summary tables, plots, assumptions, and methodology.) Here we summarize the overall trends and discuss their implications for world population in the future. The probabilistic projections of world population (Fig. 1A) provide a general statement of the confidence we can have in the projections. For example, there is a 95%

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**Is low fertility really a problem? Population aging, dependency, and consumption**
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Editor's Summary

**Adjusting to fewer kids and more elderly**

In many countries, populations are aging as retirees live longer, and the rates of population growth have declined as fewer babies are born. These demographic changes have evoked alarmist predictions that future retirement pensions will need to be curtailed, constraining future generations' purchasing power. Lee *et al.* point out that compensatory factors, such as more women working more years, along with a better educated workforce, may mitigate these demographic impacts (see the Perspective by Smeeding).

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