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REVIEW

The Outlook for Population Growth

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Projections of population size, growth rates, and age distribution, although extending to distant horizons, shape policies today for the economy, environment, and government programs such as public pensions and health care. The projections can lead to costly policy adjustments, which in turn can cause political and economic turmoil. The United Nations projects global population to grow from about 7 billion today to 9.3 billion in 2050 and 10.1 billion in 2100, while the Old Age Dependency Ratio doubles by 2050 and triples by 2100. How are such population projections made, and how certain can we be about the trends they foresee?

The growth rate of the global population increased slowly from 1700 to 1950, then accelerated rapidly until the mid-1960s, peaking at just over 2% per year before descending to 1.1% per year in 2010. Between 1800 and 2011, population size increased sevenfold, coinciding with an economic expansion. There are two grand perspectives that systematically link population growth and economic growth. According to Malthus, population growth responds to a wage or income signal that depends negatively on the size of the population in relation to the economy and its resource base, keeping living standards near an equilibrium level that is maintained through negative feedback (*1*). Technological revolutions raise incomes and call forth a corresponding increase in population. According to Boserup, population growth is the engine that drives progress by inducing technological innovation and hastening adoption of existing technologies (*2*). Combined, these theories suggest an upward spiral of population and technology with both negative and positive feedback. Such a process must ultimately be limited by natural resource constraints (*3*). More recent economic theories offer important insights (*4*), but do not lend themselves to forecasts.

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How, exactly, can these perspectives be brought to bear on our understanding of current population growth, and how can their insights guide our efforts to forecast population in the 21st century? In principle, one could develop a Malthus-style projection based on an estimate of the carrying capacity of each country, given its resources, institutions, and level of technology. Such estimates and projections are rarely attempted. The practical reality is that population forecasts largely ignore economic and resource constraints, and instead focus on other forces shaping fertility and mortality, forces that are weakly linked to economic and environmental change. It is indeed hard to see how else to proceed, given our current state of understanding.

In fact, demographers have been quite successful in their population forecasts, well represented by the biennial United Nations (UN) population projections for countries, regions, and the world population (*5*). Apparently, population growth since the Industrial Revolution has mainly occurred in a kind of neutral zone in which technological progress, economic growth, and migration have enabled populations to grow while avoiding the sort of negative feedback that would substantially alter fertility or mortality. Global population will reach 7 billion in late 2011, and the UN projects it will reach 10 billion by 2100. It is possible that desertification, global warming, shortage of fresh water, extinctions of species, and other man-made degradations of the natural resource base will lead to catastrophic effects on the population and its growth and change all that. However, despite abundant evidence of environmental change, little demographic response has so far been apparent.

The Demographic Transition

Lacking practical guidance from grand dynamic theories, forecasters rely on a largely descriptive framework known as the demographic transition, which summarizes historical patterns initially observed in Europe but which have been found appropriate for less developed countries (LDCs) as well (*6*). Over the course of the demographic transition, populations move from an initial state of high mortality and high fertility to a state of low mortality and low fertility. Typically mortality begins to decline first, continuing at a gradual and steady pace, with a later and faster decline in fertility that may move from a high to a relatively low level in a span of two or three decades.

These changes in vital rates cause dramatic changes in the population size, the rate of population growth, and the age distribution. During the period in which mortality has begun to decline but fertility remains high, the population growth rate rises and the proportion of youth in the population rises as well. Once fertility begins to decline the proportion of population in the working ages rises, and continues to rise for five or six decades, until well after fertility decline ceases. Eventually the growth of the working age population slows while that of the older population accelerates. The population ages, and the old age dependency ratio or OADR (the population aged 65 and over divided by the population aged 20 to 64) rises.

In Fig. 1, fertility (measured by the total fertility rate or TFR) is on the left vertical axis and life expectancy, e_0, is on the horizontal one. The figure plots specific historical combinations of fertility and mortality and projected trajectories for Europe and more developed countries (MDCs), for India and LDCs, and for Japan.

On the European and Indian trajectories the initial movement is horizontal to the right, as life expectancy rises but fertility remains high. India continues in this way until 1970, but around 1880 fertility begins to decline in Europe and the line slants down to the right until 1950. As in India, the LDC line moves horizontally to the right from 1950 to 1970, then plunges to 2.6 in 2010 as fertility drops precipitously. The MDC post–World War II baby booms are obscured by the 1950 start date of the MDC line. The line slants downward to 1.7 in 2010. The Japan line drops more steeply, ending at 1.3 in 2010.

Population Aging in the 21st Century

A fundamental theorem in demography tells us that if age-specific fertility and mortality remain constant in a population closed to migration, the population will converge to a unique population growth rate and a unique proportional age distribution determined only by the age schedules of fertility and mortality. This steady state (or "stable population") will be independent of the initial population age distribution except for some extreme cases. The contours on Fig. 1 show combinations of TFR and e_0 for which the steady-state level of the OADR is constant. The contours are quite flat until high levels of e_0, indicating that until very high levels of life expectancy, fertility variation is the main cause of population aging. The current OADR in the United States is 0.216, which is low for a rich industrial nation, reflecting the U.S. history of relatively high fertility.

In the extreme pretransition (upper left corner) fertility is high (up to seven births per woman) and life is short (life expectancy of 20 years). The OADR is only 0.06—six elderly per 100 "working age" adults (although all adults would probably have been working in this context). In the extreme posttransition (lower right corner) fertility is very low (TFR of ~1.5 births per woman), and life is long (e_0 of ~85). The OADR would be very high at 0.73—that is, 0.73 elderly per working age person, or 12 times as high as before.

In LDCs, the OADR is now near 0.2 but will rise toward 0.4 by 2100. In MDCs, it will rise above 0.5 and in Japan 0.6. Without the UN assumption that MDC fertility will rise toward 2.1, these ratios would be even higher. Even under the UN assumptions, the actual OADRs will almost double in MDCs between now and 2050, rising from 0.26 to 0.49 (*5*).

The OADR measure assumes that labor ceases at age 65, and indeed in MDCs, people do stop working by then or even by age 60, and the same is true in some upper-income LDCs (*7*). However, the health and vitality of the elderly have improved markedly in past decades (*8*) and restructured public pensions encourage longer work, so this measure may become obsolete in the future. The UN offers forecasts for alternate definitions, including an age boundary at 70 rather than 60 or 65, and measures based on functional status rather than age have also been developed (*8*).

Having sketched the trajectories of fertility and mortality across the demographic transition, I will now discuss each in more detail.

Mortality: The Future Outlook

Ten years ago a remarkable result was reported in the pages of this journal: The record-holding country's life expectancy for females (the highest female life expectancy reported by any nation with credible data in a given year) has been increasing linearly from 1840 to 2000 at the pace of 2.4 years per decade or 24 years per century (*9*), and similarly for males. Life expectancy has risen considerably faster than this in the LDC population in the 20th century. Behind this surprisingly regular rise in longevity lie major changes in the structure of mortality. Initially the greatest mortality declines accrued to infants and children, but in recent decades they have accrued to the elderly. Previously mortality decline was driven by reductions in deaths due to infectious diseases, but in recent decades reductions in deaths from chronic diseases, such as cardiovascular disease and cancer, have been more important.

The Oeppen-Vaupel (*9*) result is consistent in spirit but not detail with forecasting models, which find regular exponential decline in age-specific mortality over long periods of time despite expectations that specific advances such as tuberculosis therapy, antibiotics, and hypertension medication would lead to discernible bursts of progress (*10*, *11*). Nonetheless, despite the rapid and regular decline in mortality in many countries, there are important and tragic exceptions, notably in the countries with high HIV/AIDS prevalence, largely in Sub-Saharan Africa, and in the former member countries of the USSR in which mortality has stagnated for decades.

These forecasting models focus on regularities in past change as a basis for trend extrapolation, drawing on well-established methods in statistical time series analysis. They do not investigate the causes of mortality decline. Yet social scientists and epidemiologists have made progress in understanding some of the forces at play. The mortality decline across the transition is due in part to economic progress, in part to improved waste dis-

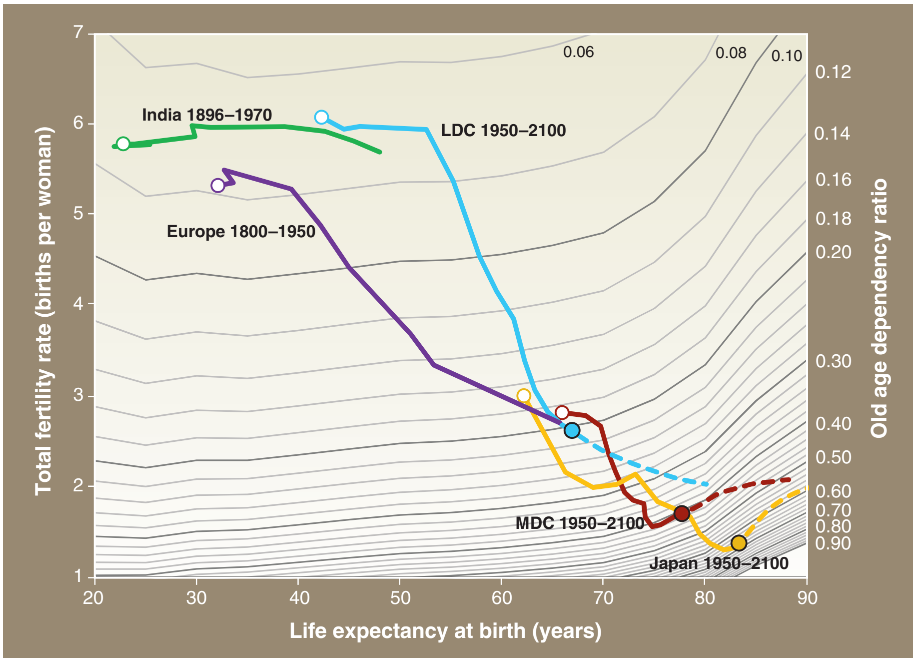

Fig. 1. Fertility (TFR) and life expectancy (e_0) decline across the demographic transition, and the old age dependency ratios (OADRs) that they generate rise. The solid colored lines show historical data, starting with an empty circle at the first available year and ending in 2010 with a colored circle. The dashed lines show projected trajectories. The purple line for Europe represents the earlier experience of the MDCs (red line). The green line for India represents the earlier experience of LDCs (blue line). The black and gray contour lines show the combinations of fertility and mortality for which the OADR is constant in a steady-state (stable) population. Historical data from 1950 to 2010 and forecasts from 2010 to 2100 are from the UN. (*5*). Prior to 1950, data for India are taken from (*31*). Data for Europe prior to 1950 are based on estimates in tables 6.2 to 6.5 in (*32*) for the period 1800 to 1900, and (*33*) for the period 1900 to 1950. The OADR contours are derived from (*34*) using the Model West Female life table with a mean age of childbearing at 29.

See interactive figure at **www.scim.ag/qzMAEp** posal and water supply, in part to public health interventions, and in part to curative medicine. Early-life and fetal conditions are increasingly recognized as important for health and mortality later in life, including in old age, with adult height a convenient summary measure of childhood conditions. The timing and extent of smoking uptake influence later trends in mortality by age and sex and are important factors explaining international mortality differences among the rich industrial nations (*12*). Although many worry about the mortality consequences of rising obesity, its influence on future trends in mortality is not yet clear (*12*, *13*). With the help of population surveys, HIV/AIDS prevalence is now better measured in the countries of Sub-Saharan Africa where it is highest, and it is now recognized that the number of new HIV infections peaked in the late 1990s and by 2009 had declined by 20%, although it remains a huge influence on health and mortality in many countries (*14*, *15*).

Looking to the future, most demographers expect that mortality will continue to decline and life expectancy will continue to rise with no limit yet in sight. Mortality is declining as rapidly in those countries like Japan and Sweden where it is already lowest as it is in lagging countries like the United States, suggesting that life expectancy is not yet approaching a biological limit. Studies of mortality in a number of model organisms suggest a surprising plasticity of life span (*16*).

Fertility: The Future Outlook

Sociologists and economists have developed and tested behavioral theories of fertility, but these have not proved useful for forecasting. Fertility in LDCs is difficult to forecast because unlike mortality, it begins its decline abruptly in a given country, declines rapidly, and then levels off, and the year of initiation of decline, the pace of the decline, and the level at which it ends are all difficult to foresee. Furthermore, the most widely used measure of fertility, the total fertility rate or TFR, is subject to "tempo" distortion when the age at which women in a population give birth changes. If women increasingly delay the start of childbearing so that the mean age at giving birth in the population rises each year, the TFR is distorted downward in relation to the number of births that women will actually bear over their reproductive years (*17*). The mean age of childbearing has in fact been rising in most MDCs, and in many LDCs as well, sometimes at a pace sufficient to depress the TFR by a few tenths of a child. Perhaps partly because of this, the TFR has fallen well below the replacement level of 2.1 births per woman in most rich nations and also in many developing nations in East Asia and elsewhere. It is also possible that many governments will eventually respond to low fertility and the aging and declining populations to which it leads by enacting strong pronatalist policies. How will couples respond? To further complicate the matter, there is evidence of recent upturns in fertility (*18*) and an emerging pattern in which the richest countries have higher fertility (*19*). The UN projections assume that fertility will slowly converge toward replacement level (2.1 births per woman) by 2100.

International Migration

Although fertility and mortality have both declined over the demographic transition, globalization has led to increasing international migration and to growing stocks of foreign-born population in many countries (*20*). Although international migration can have no direct effect on population growth at the global level, it does affect population growth in many MDCs, where low fertility would otherwise lead to population decline. Indeed, immigration is sometimes encouraged as a means to reduce population aging. Net immigration is more difficult to forecast than either fertility or mortality, because it is sensitive to differences in economic growth, political and military upheavals, and policy changes. But recent research bases projections on more persistent features of pairs of countries between which migration occurs (*21*).

Demographic Data

The starting point for population projections or forecasts (I will use these terms interchangeably) is the demographic data from surveys, registration systems, and administrative records. The census, a periodic (usually decennial) survey of the entire population of an area, is fundamental as a static picture of the population and its characteristics at an instant in time. Vital registration systems, by contrast, compile registered births, deaths, marriages, and divorces as they occur over time. These continuous counts of demographic events provide the numerators for the calculation of birth, death, marriage, and divorce rates by age and sex. The denominators for these rates are interpolated from the decennial census counts. Errors in these rates result from errors in either the census or the registration system, but typically registration errors are more consequential. Administrative data can be combined with these other sources to yield additional estimates—for example, of immigration and emigration. Specialized surveys can provide basic demographic data in places where the census or registration systems are flawed or incomplete, and also provide more detailed information than is otherwise available. The Demographic and Health Surveys (DHS, www.measuredhs.com/) provide internationally comparable information of this sort and are widely used in many Third World countries. Demographers have developed many specialized methods for investigating the consistency of data from these various sources and adjusting the data, and for indirect estimation of vital rates.

Population Projections

Population projections are based on these demographic data in several ways. First, the baseline size of the population and its distribution by age and sex are essential, sometimes augmented by other characteristics such as region, urban or rural, or race or ethnic group. Second, fertility, mortality, and net immigration by age and sex (except for fertility, which is typically for females only) are used to project the population forward on the basis of age, time, or sex accounting equations. However, these rates are themselves changing over time, and the most challenging part of the projection process is to specify the time paths of these rates. An essential starting point is the past trend in the vital rates, which requires estimates of the vital rates for earlier periods as well as the base period. If fertility has been declining for 10 years, the analyst would probably project it to continue to decline, but with uncertainty over how long and to how low a level, and whether a rebound is expected in the more distant future. If mortality has been declining for the past century, the analyst will expect it to continue to decline, but there is uncertainty and controversy about the pace of decline and whether there is a near upper limit to human life expectancy such that life expectancy gains will decelerate as this limit is approached (*16*, *22*).

The most common approach to demographic forecasting is expert judgment based on the data available for each country, on historical patterns in countries passing through each stage of the transition, and on contemporary trends in similar countries. Ancillary information and theories about relevant processes also enter into the forecast—for example, regarding contraceptive use, trends in women's education and labor force participation, and surveys of desired fertility. The UN has traditionally used this approach, combined with more formal analysis of the shapes of trajectories of fertility decline and leveling off. When expert judgment is used to specify the input trajectories leading to the central forecast (also called the middle, medium, or intermediate forecast), the same experts usually provide upper and lower variants for the input trajectories. The forecaster then bundles together these variants—for example, combining high fertility and high net immigration with low mortality—to generate high and low forecasts. But the exact meaning and interpretation of the upper and lower variants and the high and low forecast scenarios are not clear, and they inevitably give inconsistent indications of uncertainty for the different kinds of outputs that are generated. For example, the bundling described above generates a broad range for future population size and growth rates, since both are raised by high fertility and high net immigration, and also by low mortality. But it generates a narrow range for the OADR because high fertility and net immigration reduce this ratio, whereas low mortality raises it (*23*).

Another approach, particularly for forecasting mortality but sometimes used for fertility as well, is to use statistical time series analysis to

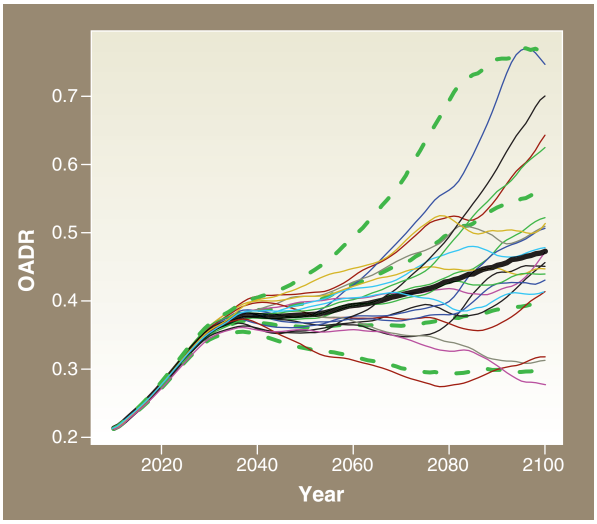

Fig. 2. Forecasts of the United States OADR, 2010 to 2100, based on the time series method and stochastic simulation. Each of the 20 thin lines shows a single stochastic sample path, calculated for each year based on the prior years and by a random variable which, together with the given model of the fertility process, generates that year's value, and similarly for mortality for which an independent random variable is drawn. The actual forecast is based on 1000 sample paths of this sort. The heavy black line is the median of these in each year, and the green dashed lines show the upper and lower 95% and 50% probability bound. The particular stochastic mortality model used in these forecasts is based on (*35*) and takes into account common features of the mortality histories of 15 low-mortality industrial nations, including 13 European populations and Japan as well as the United States. The fertility model is similar to that in (*25*).

model the general level of mortality or the individual age-specific rates as stochastic processes, and then to use these models to generate the forecasts (*10*). Sometimes covariates such as smoking behavior and economic trends are taken into account (*24*). The time series approach has been less successful for fertility, where in the MDCs baby booms and busts and changes in the age of childbearing obscure the central trend. Analysts sometimes combine expert demographic judgment about the central value while using time series analysis to estimate the uncertainty about this central value (*25*).

The Uncertainty of Population Projections

Because population projections motivate painful decisions about tax increases, benefit cuts, retirement age, and measures to offset global warming, we need careful measures of their uncertainty. While traditional projections come with High, Medium and Low variants, no probability is attached to these, nor could one be, owing to the inconsistencies mentioned above and to the incorrect treatment of the correlation of errors over time and across subcategories such as ages or countries (*23*). Some analysts construct a probability distribution for the true future value defined in terms of the expert High-Low range—for example, by assuming that the range covers 95% of a normal distribution. Stochastic simulation can then be used to construct probability distributions for forecasts (*26*).

When time series methods are used, the actual forecasts are generated by stochastic simulation of a thousand or more sample paths rather than by taking the mean forecasts for fertility and mortality as inputs into the usual projection machinery. This approach generates probability distributions for any demographic output desired. Figure 2 illustrates this approach in a forecast for the OADR in the United States, showing 20 illustrative sample paths out of the thousand that were used to calculate the probability distribution. The paths fluctuate, may cross the median line, and may spend time outside the 95% probability range. The 95% probability range indicates that uncertainty is very small through 2030, at which time the children born after 2010 (which is an uncertain number) begin to reach 20 years of age and enter the denominator of the OADR. This uncertain number of children becomes an uncertain number of parents, who bear children at an uncertain rate, which is why the probability fan opens out so rapidly. After 2035 the median forecast stops rising and flattens out as the smaller generations born after the baby boom begin to enter old age and the more numerous baby boom generations gradually die.

More subtly, this approach can provide probability intervals for outcomes that depend on a whole demographic trajectory and not just on the dependency ratio in a single year. For example, the balance in the U.S. Social Security Trust Fund depends on the whole history of tax payments into the fund and benefits paid out of it, with interest on the balance, up to the year of the observed outcome (*27*, *28*). The Social Security Trustees calculate probability distributions for the size of the Trust Fund and its date of exhaustion with this approach.

A final method is particularly useful and appealing: analyzing the performance of earlier forecasts to assess their accuracy empirically as a basis for constructing probability distributions for the forecasts (*29*). This approach requires that there have been no major changes in methods or data quality, so that the success of forecasts in the past can be taken as a guide to their success in the future. The National Research Council (NRC) (*20*) implemented this approach for the UN projections. Special issues arise in constructing consistent probability intervals for individual countries, for regions, and for the world, because account must be taken of the positive or negative correlations among the country forecast errors within regions and across regions. Because error correlation is typically positive but less than 1.0, country

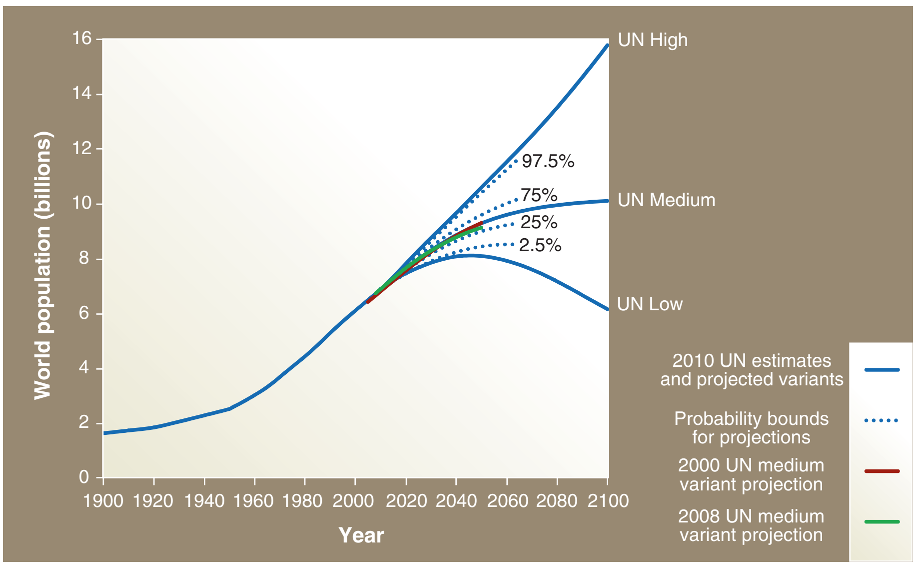

Fig. 3. United Nations (2011) estimates and projections of world population with High, Medium, and Low variants (solid blue lines) and with probability intervals. Mortality is the same in all variants, but fertility is higher or lower by 0.5 births per woman in the variants. The dotted blue lines represent 95% and 50% probability intervals based on the ex post analysis of UN projections done between 1973, 1980, 1984, and 1994 as reported in National Research Council (*20*) and its appendices. The red line is the Medium UN projection in the 2000 Revision, and the green line is the Medium projection in the 2008 revision, both to 2050. The population from 1900 to 1940 is from (*36*).

errors tend to cancel under aggregation, and the proportional error bounds for the world population are far narrower than for individual countries. The NRC study (*20*) found that the average absolute country error was 21%, whereas the average global error was only 3%. When the High, Medium, and Low scenario approach is used, there is no cancellation of error under aggregation, so the probability coverage at different levels of aggregation cannot be handled consistently. An ongoing research collaboration between the UN Population Division and a team led by Raftery is developing new and very promising statistical methods for handling uncertainty in future forecasts (*30*).

The United Nations Projections and Their Uncertainty

The NRC (*20*) laboriously analyzed past errors in national, regional, and global UN projections done in 1973, 1980, 1984, and 1994, and constructed probability distributions for the UN population forecasts in the 1998 revision. For horizons of 5 to 10 years, the largest source of error in population size forecasts was the base population estimate. For horizons of 10 to 25 years, the largest source of error was migration. Beyond 25 years, it was fertility. Mortality never accounted for more than a sliver of the total error, but it is particularly important for forecasts of the older population.

It was not possible to update that complex analysis for this article, but as an approximation I have simply applied the proportional probability intervals in the NRC study (*20*) for each length of forecast. The result is shown in Fig. 3, along with the High and Low trajectories given in the 2010 revision. For the first time a formal statistical procedure was used to forecast fertility in this revision (*30*), although expert judgment was used to set the long run mean level at 2.1 in 2100. For this reason, the ex post analysis of earlier forecast performance is less relevant. Although the model used to forecast fertility was probabilistic, it was used only to generate the Medium forecast. The High and Low forecasts were generated by raising or lowering the target fertility level in 2100 by 0.5 births per woman.

Because the projections assume that fertility will tend toward replacement level by 2100, it is not surprising that the proportional annual population growth rate is projected to decline over the whole 21st century, approaching zero by 2100. Population size is projected to be 9.3 billion in 2050, about 160 million bigger than the 2008 Revision projected for 2050, with a Low to High range of 8.1 to 10.6 billion. Population size is projected to reach 10.1 billion by 2100, with a range of 6 to 16 billion. The 95% probability bounds calculated from the NRC (*20*) are also plotted for the first 55 years of the forecast (the forecast length for which they were calculated in that report). The upper 97.5% probability boundary corresponds quite closely to the UN High scenario, but the lower 2.5% boundary is higher than the Low scenario. The Low projection suggests that population might decline in the second half of the century. However, the NRC analysis (*20*) found only a one in a thousand chance that population would decline from 2030 to 2050, contrary to the Low scenario in those UN projections.

When the new UN forecasts were released in May 2011, many commentators interpreted them as a notable upward revision of the previous forecasts in 2008 for which the figure plots the Medium projection as a green line. Evidently, the revision is numerically very small relative to the levels forecast and relative to the uncertainty surrounding the forecast. Nonetheless, two reasons behind the revision are important: The prevalence of HIV/AIDS in Third World populations has been revised downward on the basis of population surveys as opposed to clinic data, and fertility decline in Sub-Saharan Africa has proceeded more slowly than previously expected. The figure also plots as a red line the 2000 Revision of the UN projection, and the 2010 projection is virtually identical.

One might quibble with this or that assumption, but the UN projections have had an impressive record of success in the past, particularly at the global level, and I expect that to continue in the future. To a remarkable degree, the UN has sought out expert advice and experimented with cutting-edge forecasting techniques, while maintaining consistency in projections. But in forecasting, errors are inevitable, and sound decision-making requires that the likelihood of errors be taken into account. In this respect, there is much room for improvement in the UN projections and indeed in all projections by government statistical offices.

So what do we know about the outlook for population growth and change? Population aging is virtually certain, a necessary by-product of the demographic transition. Its timing is clear for countries in which fertility has declined, even if its magnitude may be somewhat uncertain. Societies must face the costly policy adjustments that population change entails. Continuing world population growth through mid-century seems nearly certain as well. But nearly all population forecasts, including those by the UN, implicitly assume that population growth will occur in a neutral zone without negative economic or environmental feedback. Will the rising trajectory that is projected in fact remain within this neutral zone? That will depend in part on the success of policy measures to reduce the environmental impact of economic and demographic growth.

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