27. Caswell, H. *Matrix Population Models: Construction, Analysis, and Interpretation* (Sinauer Associates, Sunderland, Massachusetts, 2001).
28. Sabelis, M. W. How to analyze prey preference when prey density varies? A new method to discriminate between effects of gut fullness and prey type composition. *Oecologia* **82,** 289–298 (1990).
29. Sabelis, M. W. & Nagelkerke, C. J. Sex allocation strategies of pseudoarrhenotokous phytoseiid mites. *Neth. J. Zool.* **37,** 117–136 (1987).

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The end of world population growth

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There has been enormous concern about the consequences of human population growth for the environment and for social and economic development. But this growth is likely to come to an end in the foreseeable future. Improving on earlier methods of probabilistic forecasting[1], here we show that there is around an 85 per cent chance that the world's population will stop growing before the end of the century. There is a 60 per cent probability that the world's population will not exceed 10 billion people before 2100, and around a 15 per cent probability that the world's population at the end of the century will be lower than it is today. For different regions, the date and size of the peak population will vary considerably.

Figure 1 shows the probability that the world population size would reach a peak at or before any given year. It indicates that there is around a 20 per cent chance that the peak population would be reached by 2050, around a 55 per cent chance that it would be reached by 2075, and around an 85 per cent chance that it would be reached by the end of the century.

There is around a 75 per cent chance that the peak population of the European portion of the former USSR has already been reached in 2000, an 88 per cent probability that it will be reached by 2025, and over a 95 per cent chance by the end of the century. For the China region, the probability of reaching a peak within the next two decades is still low owing to its relatively young age structure. By 2040 the probability becomes greater than half. In sub-Saharan Africa, despite the prevalence of HIV, there is a low probability of peaking before the middle of the century. The probability reaches 25 per cent by 2070, 50 per cent by 2085, and almost 75 per cent by 2100, owing to assumed reductions in fertility.

Figure 2 shows the distribution of simulated world population sizes over time. The median value of our projections reaches a peak around 2070 at 9.0 billion people and then slowly decreases. In 2100,

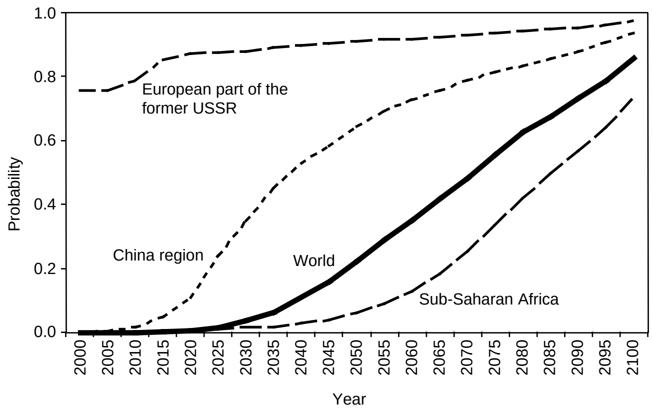

Figure 1 Forecasted probability that population will start to decline at or before the indicated date.

the median value of our projections is 8.4 billion people with the 80 per cent prediction interval bounded by 5.6 and 12.1 billion. The medium scenario of the most recent United Nations long-range projection[2] is inserted in Fig. 2 as a white line. It is almost identical to our median until the middle of the century, but is higher thereafter owing to the United Nations assumption of universal replacement-level fertility, that is two surviving children per woman.

Table 1 shows the median population sizes and associated 80 per cent prediction intervals for the world and its 13 regions, indicating major regional differences in the paths of population growth. While over the next two decades the medians are already declining in eastern Europe and the European portion of the former Soviet Union, the populations of north Africa and sub-Saharan Africa are likely to double, even when we take into account the uncertainty about future HIV trends.

The China region and the South Asia region, which have approximately the same population size in 2000, are likely to follow very different trends. Owing to an earlier fertility decline, the China region is likely to have around 700 million fewer people than the South Asia region by the middle of the century. This absolute difference in population size is likely to be maintained over the entire second half of the century and illustrates the strong impact of the timing of fertility decline on eventual population size[3].

Our findings concerning the timing of the end of world population growth are robust to plausible changes in parameter assumptions. A detailed sensitivity analysis is provided as Supplementary Information. The forecasts of the World Bank, the US Census Bureau, and the medium variant of the United Nations[2,4,5] are based on independent assumptions; the median trajectory of our world forecasts is almost identical to these up until 2045. Of these three forecasts, only the UN long-range projections provide scenarios of the world's population to the end of the century. If we define the end of population growth slightly less literally, and take it to correspond with annual population growth of one-tenth of one per cent or less, the United Nations medium projection also shows the end of population growth during the second half of the century. Their medium scenario predicts that world population growth will first fall below one-tenth of one per cent at around 2075.

A stabilized or shrinking population will be a much older population. At the global level the proportion above age 60 is likely to increase from its current level of 10 per cent to around 22 per cent in 2050. This is higher than it is in western Europe today. By the end of the century it will increase to around 34 per cent, and extensive population ageing will occur in all world regions. The most extreme levels will be reached in the Pacific OECD (mostly Japan), where half of the population is likely to be age 60 and above by the end of the century, with the 80 per cent uncertainty interval

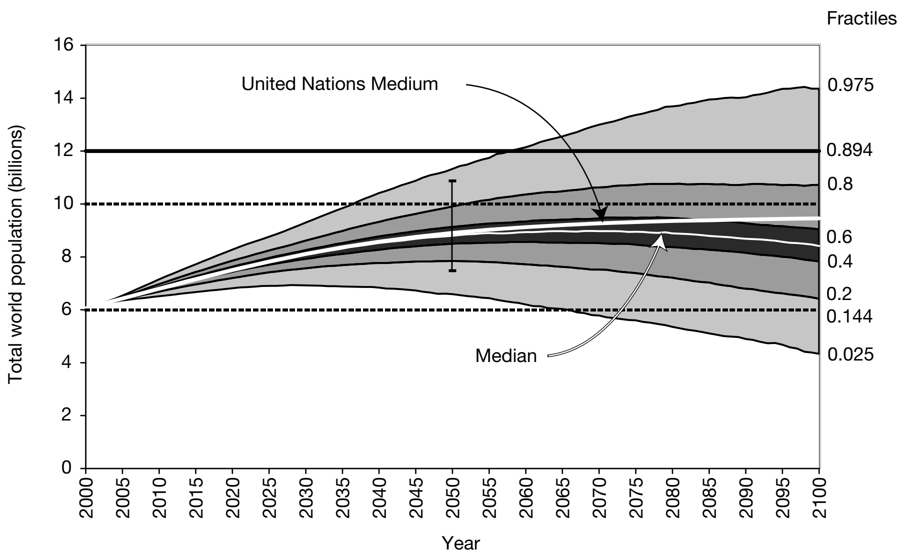

Figure 2 Forecasted distributions of world population sizes (fractiles). For comparison, the United Nations medium scenario (white line), and 95 per cent interval as given by the NRC[11] on the basis of an ex post error analysis (vertical line in 2050) are also given.

reaching from 35 to 61 per cent. Even sub-Saharan Africa in 100 years is likely to be more aged than Europe today. The trend of our median proportion over age 60 is almost identical to that of the UN long-range projections[2] up to 2050, but shows significantly stronger ageing thereafter. This confirms recent criticism that conventional projections tend to underestimate ageing[6,7]. The extent of and regional differences in the speed of population ageing—the inevitable consequence of population stabilization and decline—will pose major social and economic challenges.

However, population numbers are only one aspect of human impact, and in some of the world's most vulnerable regions, significant population growth is still to be expected. Nevertheless, the prospect of an end to world population growth is welcome news for efforts towards sustainable development. □

Methods

The method of probabilistic population projection that was applied here (see Box 1) is a further development of our earlier approach[1,8,9] that allows short-term fluctuations in the vital rates[6,10] and refers to the ex post error analysis of past projections[11]. We produced a set of 2000 simulations by single years of age for 13 world regions[12] starting in 2000. Information on baseline conditions has been derived from the United Nations[2] and US Census Bureau[4] estimates, and the sensitivity of our results to possible baseline errors is discussed in the Supplementary Information. World population sizes at five-year intervals for all 2000 simulations are also listed there.

The substantive assumptions about future trends in the three components of fertility, mortality and migration, and their associated uncertainty ranges are based on revisions and updates of our earlier work[12] and the extensive analyses summarized in the recent US National Research Council (NRC) report[11].

Fertility

The key determinant of the timing of the peak in population size is the assumed speed of fertility decline in the parts of the world that still have higher fertility. On this issue there is

Table 1 Forecasted population sizes and proportions over age 60

	Median world and regional population sizes (millions)					Proportion of population over age 60		
Year	2000	2025	2050	2075	2100	2000	2050	2100
World total	6,055	7,827 (7,219–8,459)	8,797 (7,347–10,443)	8,951 (6,636–11,652)	8,414 (5,577–12,123)	0.10	0.22 (0.18–0.27)	0.34 (0.25–0.44)
North Africa	173	257 (228–285)	311 (249–378)	336 (238–443)	333 (215–484)	0.06	0.19 (0.15–0.25)	0.32 (0.23–0.44)
Sub-Saharan Africa	611	976 (856–1,100)	1,319 (1,010–1,701)	1,522 (1,021–2,194)	1,500 (878–2,450)	0.05	0.07 (0.05–0.09)	0.20 (0.14–0.27)
North America	314	379 (351–410)	422 (358–498)	441 (343–565)	454 (313–631)	0.16	0.30 (0.23–0.37)	0.40 (0.28–0.52)
Latin America	515	709 (643–775)	840 (679–1,005)	904 (647–1,202)	934 (585–1,383)	0.08	0.22 (0.17–0.28)	0.33 (0.23–0.45)
Central Asia	56	81 (73–90)	100 (80–121)	107 (76–145)	106 (66–159)	0.08	0.20 (0.15–0.25)	0.34 (0.24–0.46)
Middle East	172	285 (252–318)	368 (301–445)	413 (296–544)	413 (259–597)	0.06	0.18 (0.14–0.23)	0.35 (0.24–0.47)
South Asia	1,367	1,940 (1,735–2,154)	2,249 (1,795–2,776)	2,242 (1,528–3,085)	1,958 (1,186–3,035)	0.07	0.18 (0.14–0.24)	0.35 (0.25–0.48)
China region	1,408	1,608 (1,494–1,714)	1,580 (1,305–1,849)	1,422 (1,003–1,884)	1,250 (765–1,870)	0.10	0.30 (0.24–0.37)	0.39 (0.27–0.53)
Pacific Asia	476	625 (569–682)	702 (575–842)	702 (509–937)	654 (410–949)	0.08	0.23 (0.18–0.29)	0.36 (0.26–0.49)
Pacific OECD	150	155 (144–165)	148 (125–174)	135 (100–175)	123 (79–173)	0.22	0.39 (0.32–0.47)	0.49 (0.35–0.61)
Western Europe	456	478 (445–508)	470 (399–549)	433 (321–562)	392 (257–568)	0.20	0.35 (0.29–0.43)	0.45 (0.32–0.58)
Eastern Europe	121	117 (109–125)	104 (86–124)	87 (61–118)	74 (44–115)	0.18	0.38 (0.30–0.46)	0.42 (0.28–0.57)
European part of the former USSR	236	218 (203–234)	187 (154–225)	159 (110–216)	141 (85–218)	0.19	0.35 (0.27–0.44)	0.36 (0.23–0.50)

80 per cent prediction intervals are shown in parentheses.

Box 1

Different approaches to probabilistic population projections

The cohort component method of projection is taken as a standard; thus, the differences between alternative approaches discussed in this box refer only to the modelling of future fertility, mortality and migration rates. Here we can distinguish between the specific process chosen for representing the time series of rates, and the basis for the specific assumptions made about the future range of uncertainty.

Model

In the literature there are essentially two methods of specifying the series of vital rates: (1) processes with annual fluctuations[10,13,14,15]; and (2) piece-wise linear scenarios[1,8,16]. Whereas method (2) has the advantage of conforming to the current practice of scenario definition in statistical offices around the world (including the UN)[2], method (1) can produce realistic annual fluctuations given that the possible levels are bounded. We have chosen the following moving-average model with annual fluctuations, in order to avoid the argument that our model underestimates variance[10].

Let v be a vital rate to be forecasted for periods 1 through T and v_t the forecasted value at time t. $v_t = \bar{v}_t + \epsilon_t$, where the mean of v_t, $\bar{v}_t$, and its standard deviation at time t, $\sigma(\epsilon_t)$, are determined according to the assumptions in the text. Let $\{x_{2-n}, \ldots, x_T\}$ be the values of $T + n - 1$ independent draws from a standard normal distribution and n be the number of periods in the moving average. Then $\epsilon_t = [\sigma(\epsilon_t)/\sqrt{n}]\cdot\Sigma_{i=t-n+1}^{t} x_i$. A more detailed description of the model is given in the Supplementary Information.

Assumptions

The literature suggests three approaches for deriving assumptions about the future range of uncertainty of the components: (1) to compute a measure of the future error from the ex post analysis of past projections[17,18,19]; (2) to apply time series models[10,13]; and (3) to have well informed experts make assumptions based on explicitly stated substantive arguments[9]. These three approaches are not mutually exclusive, and approaches (1) and (2) also include expert judgement.

Here we use a synthesis of the three approaches. Our process specification uses a time series model. We have explicitly considered existing national-level parameter estimates[13,14] given that, at the level of world regions, empirical estimation is impossible owing to lack of data. The ex post analysis of past errors enters our study in two ways: the substantive assumptions made on fertility and mortality changes are informed by the analysis of past errors in those components[11,18], and our results at the regional level have been compared to the results of an ex post error analysis of global UN projections documented in the NRC report. Because we preferred to err on the side of higher variance (that is, lower probability of population growth ending this century), we followed the general rule of producing intervals that are at least as large as those in the NRC report at the level of major world regions[11]. Combining this with argument-based expert judgement[12], we saw substantive reasons for assuming a larger uncertainty in many regions as a result of new factors such as HIV/AIDS, the new situation in the former USSR and the indeterminacy of long-range post-transitional fertility levels that will affect an increasing number of countries.

The 95 per cent interval resulting from the NRC ex post error analysis is inserted in Fig. 2 as a vertical line in 2050 (the latest year given in the NRC report). It corresponds to roughly 80 per cent of our distribution, which clearly indicates that our method produces a broader uncertainty range than the ex post error approach.

a broad consensus that fertility transitions are likely to be completed in the next few decades[11]. For the eventual size of the population and the question of whether or not world population will begin a decline by the end of this century the key variable is the assumed level of post-transitional fertility. The thorough review of the literature on that subject by the NRC states that "fertility in countries that have not completed transition should eventually reach levels similar to those now observed in low fertility countries" (page 106 in ref. 11). Our fertility assumptions are consistent with this view.

The trends in the means of the regional fertility levels have been defined for the periods 2025–29 and 2080–84 with interpolations in between. The total fertility rates assumed for 2025–29 are similar to those chosen by the United Nations[2], but for 2080–84 they are assumed to range between 1.5 and 2.0, with lower levels for regions with higher population density in 2030. The variances in the total fertility rates are assumed to depend on the level of fertility. If the total fertility rate is above 3.0 there is an 80 per cent chance that fertility would be within one child of the mean. When it is below 2.0, the same probability is attached to a range within one half a child of the mean. Between the two total fertility rate levels, the variance is interpolated.

Life expectancy

We assume that life expectancy at birth will rise in all regions, except in sub-Saharan Africa, where HIV/AIDS will lower life expectancies during the early part of the century. In general, we assume that life expectancy increases by two years per decade with an 80 per cent probability that the increase is between zero and four years; but there are a number of exceptions to this rule based on specific regional conditions. These assumptions reflect the very large uncertainty that exists regarding future mortality conditions. On one hand, significant biomedical breakthroughs are likely to be made; on the other, AIDS could still become a major issue outside Africa, and new and unexpected threats to human life can emerge.

Autocorrelations

Migration is treated as a random vector on the basis of recent interregional migration patterns. The autocorrelation chosen for all components is based on a 31-year moving-average process that seemed the most plausible after we had experimented with 21-, 31-, and 41-year moving averages (see Supplementary Information), and is close to existing national level figures[10]. We assumed an interregional correlation of 0.7 for fertility and 0.9 for mortality deviations with no correlation between fertility and mortality deviations from the assumed trend, and perfect correlation between male and female life expectancy. These choices followed extensive sensitivity analyses as documented in the Supplementary Information. The main rationale behind our choice is that under post-transition conditions, correlations between deviations from assumed fertility and mortality trends are unlikely to be large, while globalization of communication is likely to bring correlated fluctuations of rates among world regions. Mortality correlations will be higher than fertility correlations, owing to the faster communication of medical technology and the faster spread of new health hazards. The sensitivity analysis documented in the Supplementary Information shows that our main conclusion, that there is around an 85 per cent chance that a peak in world population size will occur in this century, is quite robust to plausible changes in those correlations.

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1. Lutz, W., Sanderson, W. & Scherbov, S. Doubling of world population unlikely. *Nature* **387,** 803–805 (1997).
2. United Nations. *Long-Range World Population Projections: Based on the 1998 Revision* (United Nations, New York, ESA/P/WP.153, 1999).
3. O'Neill, B. C., Scherbov, S. & Lutz, W. The long-term effect of the timing of fertility decline on population size. *Pop. Dev. Rev.* **25,** 749–756 (1999).
4. US Census Bureau. *International Database* 10 May 200 edition ⟨http://www.census.gov/ipc/www/worldpop.html⟩ (US Census Bureau, 2000).
5. World Bank. *World Development Indicators* (CD-ROM) (World Bank, Washington DC, 2000).
6. Tuljapurkar, S., Li, N. & Boe, C. A universal pattern of mortality decline in the G7 countries. *Nature* **405,** 789–792 (2000).
7. Vaupel, J. W. & Lundström, H. in *The Future Population of the World. What Can We Assume Today?* (ed. Lutz, W.) rev. edn, 278–295 (Earthscan, London, 1996).
8. Lutz, W., Sanderson, W. & Scherbov, S. in *The Future Population of the World: What Can We Assume Today?* (ed. Lutz, W.) rev. edn, 397–385 (Earthscan, London, 1996).
9. Lutz, W., Sanderson, W. C. & Scherbov, S. in *Frontiers of Population Forecasting* (eds Lutz, W., Vaupel, J. W. & Ahlburg, D. A.; *Pop. Dev. Rev.* Suppl. **24,** 1998) 139–155 (Population Council, New York, 1999).
10. Lee, R. D. in *Frontiers of Population Forecasting* (eds Lutz, W., Vaupel, J. W. & Ahlburg, D. A.; *Pop. Dev. Rev.* Suppl. **24,** 1998) 156–190 (Population Council, New York, 1999).
11. Bongaarts, J. & Bulatao, R A. (eds) *Beyond Six Billion. Forecasting the World's Population* (National Academy Press, Washington DC, 2000).
12. Lutz, W. (ed.) *The Future Population of the World. What Can We Assume Today?* rev. edn (Earthscan, London,, 1996).
13. Lee, R. & Tuljapurkar, S. Stochaistic population projections for the United States: Beyond high, medium and low. *J. Am. Stat. Assoc.* **89,** 1175–1189 (1994).
14. Lee, R. D. & Carter, L. Modeling and forecasting the time series of U.S. mortality. *J. Am. Stat. Assoc.* **87,** 659–671 (1992).
15. Alho, J. M. Stochastic methods in population forecasting. *Int. J. Forecast.* **6,** 521–530 (1990).
16. Lutz, W. & Scherbov, S. An expert-based framework for probabilistic national population projections: The example of Austria. *Eur. J. Pop.* **14,** 1–17 (1998).
17. Alho, J. M. Scenarios, uncertainty and conditional forecasts of the world population. *J. R. Stat. Soc. Ser. A* **160,** 71–85 (1997).
18. Keilman, N. in *Frontiers of Population Forecasting* (eds Lutz, W., Vaupel, J. W. & Ahlburg, D. A.; *Pop. Dev. Rev.* Suppl. **24,** 1998) 15–41 (Population Council, New York, 1999).
19. Stoto, M. The accuracy of population projections. *J. Am. Stat. Assoc.* **78,** 13–20 (1983).

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