THE ROYAL SOCIETY

Published online 23 August 2002

Determinants of human population growth

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The 20th century has seen unprecedented growth of the human population on this planet. While at the beginning of the century the Earth had an estimated 1.6 billion inhabitants, this number grew to 6.1 billion by the end of the century, and further significant growth is a near certainty. This paper tries to summarize what factors lie behind this extraordinary expansion of the human population and what population growth we can expect for the future. It discusses the concept of demographic transition and the preconditions for a lasting secular fertility decline. Recent fertility declines in all parts of the world now make it likely that human population growth will come to an end over the course of this century, but in parts of the developing world significant population growth is still to be expected over the coming decades. The slowing of population growth through declining birth rates, together with still increasing life expectancy, will result in a strong ageing of population age structure. Finally, this paper presents a global level systematic analysis of the relationship between population density on the one hand, and growth and fertility rates on the other. This analysis indicates that in addition to the well-studied social and economic determinants, population density also presents a significant factor for the levels and trends of human birth rates.

Keywords: world population growth; demographic transition; human fertility; population density

1. FACTORS DRIVING PREVIOUS POPULATION GROWTH

The broad outlines of the history of global population growth are by now familiar. At the dawn of the agricultural revolution (8000 years before present), total population was about 250 000 (Cook 1962). It took all of human history (until 1800) for global population to reach one billion—roughly today's population of Europe and North America combined. It took 130 years (until 1930) to reach two billion. It took only 60 more years (1960) to reach three billion. The fourth billion was reached between 1960 and 1975, the five billion mark was passed in 1987 and the six billion mark was reached in 1999.

Less well appreciated are the facts that both the annual growth rate and the annual absolute increment of world population have passed their peaks and are expected to continue to decline. The growth rate peaked at 2.1% per year in the late 1960s and fell to 1.35% by 2000 (see table 1), and the annual absolute increment to population peaked at about 87 million per year in the late 1980s and was about 81 million at the end of the 20th century. This does not mean, of course, that little further population growth is to be expected; most mid-range population projections foresee future population rising to 8–10 billion by the end of the 21st century.

As shown in table 1, the TFR (average number of children per woman under a period perspective) declined modestly in most parts of the world from 1950–1955 to 1970–1975, then declined over the following 25 years with a rapidity that was unimaginable in the 1960s. This second period of decline was especially pronounced in Asia, where TFR fell by more than two children per woman (a statistic that is, however, heavily influenced by a dramatic fertility decline in China during the 1970s). One exception has been Africa, where fertility rates remained well above six children per woman on average through the late 1980s; since then, the beginnings of a fertility decline have become apparent. Meanwhile, regions such as Europe and North America that had already achieved very low fertility by 1970–1975 saw these rates persist or fall further.

During the 1950s and 1960s, reductions in mortality resulting from the spread of modern hygiene and medicine were even more significant than fertility declines. During the period 1950–1955 (the first period for which estimates are available), life expectancy was lowest in Africa (38 years) and Asia (41 years), while it had already improved significantly in Latin America (51 years). Over the following 20 years life expectancy increased impressively in all parts of the world. In Asia, by far the most populous continent of the world, it increased by 15 years over this short period. In Africa, it improved by 8 years, although this increase was below the world average. Improvements continued over the next 25 years to 1995–2000, but at a somewhat slower speed, with Asia, Latin America and Africa (even with AIDS) seeing substantial improvements.

These trends in fertility and mortality resulted in different patterns of population growth in different parts of the world. In fact, the dominant feature of the global demographic landscape has been the contrast between the well-off populations of Europe, North America and Japan and

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One contribution of 15 to a Discussion Meeting Issue 'Population growth rate: determining factors and role in population regulation'.

Table 1. Demographic trends in the world since 1950 by main regions. (From United Nations 2001.)

region	total population size (millions)			growth rate (%)			life expectancy (both sexes, in years)			total fertility rate		
	1950	1970	2000	1950–1955	1970–1975	1995–2000	1950–1955	1970–1975	1995–2000	1950–1955	1970–1975	1995–2000
world	2519	3691	6057	1.79	1.93	1.35	47	58	65	5.0	4.5	2.8
MDCs	814	1008	1191	1.20	0.78	0.30	66	71	75	2.8	2.1	1.6
LDCs	1706	2683	4865	2.06	2.35	1.62	41	55	63	6.2	5.4	3.1
Africa	221	356	794	2.17	2.61	2.41	38	46	51	6.7	6.7	5.3
Asia	1399	2142	3672	1.93	2.25	1.41	41	56	66	5.9	5.1	2.7
Europe	548	657	727	0.99	0.59	−0.04	63	67	69	2.7	2.2	1.4
Latin America and Caribbean	167	285	518	2.65	2.45	1.56	51	61	69	5.9	5.0	2.7
North America	172	231	314	1.70	0.97	1.04	69	72	77	3.5	2.0	2.0
Oceania	13	19	31	2.18	2.08	1.37	61	66	74	3.9	3.2	2.4

the poorer populations of Asia, Africa, the Middle East and Latin America. The population of the MDCs is relatively small (about 1.2 billion in 2000) and expanding very slowly (0.3% per year) following a 46% increase since 1950 (see table 1). That of the LDCs is large (*ca*. 4.9 billion in 2000) and expanding rapidly (1.6% per year) after increasing by a factor of 2.9 since 1950. As a consequence, the share of today's industrialized countries in the world population decreased from 32% in 1950 to 20% in 2000 and is likely to decrease much more in the future. In addition, despite the rapid changes in most LDCs, inhabitants of MDCs on average live significantly longer (life expectancy at birth for both sexes combined is *ca*. 75 years, versus 63 years in LDCs) and have fewer children (TFR is 1.6, versus 3.1 in LDCs).

The widely varying historical experiences of the different regions of the world have also left a strong imprint on the age structure of their populations. In Africa, age distribution is typical of a rapidly growing population, showing larger and larger cohorts in the young age groups. There are more than twice as many children under age 5 than adults aged 20–25, four times more than those aged 40–45 and 10 times more than the elderly aged 65–70. In Western Europe the pattern is completely different: the number of women aged 60–65 approximately equals the number of children under age 5, while the largest age groups are those between 30 and 40. The age pyramid is narrower at the bottom due to the very low levels of fertility since the 1970s; at the same time, declining mortality rates have widened the top by increasing the size of older age cohorts.

The narrowing of population pyramids at the bottom (from low fertility) and widening at the top (due to extended longevity) is called 'population ageing'. The two components are referred to as ageing 'from the bottom' and 'from the top'. Population ageing is an enormously important social phenomenon, especially in relation to the uncertain future of pension and health care systems. Ageing will continue in MDCs and has already started in LDCs. Just as the speed of mortality improvements accentuated the implications of demographic transition for population growth rates, the speed of LDC fertility decline will accentuate the ageing phenomenon. Both trends are part of the secular change called demographic transition.

The demographic transition began in MDCs in the late 18th century and spread to LDCs in the last half of the 20th (Notestein 1945; Davis 1954, 1991; Coale 1973). The conventional 'theory' of demographic transition predicts that, as living standards rise and health conditions improve, first mortality rates decline and then, somewhat later, fertility rates decline. Demographic transition 'theory' has evolved as a generalization of the typical sequence of events in what are now MDCs, where mortality rates declined comparatively gradually beginning in the late 1700s and then more rapidly in the late 1800s and where, after a lag of 75 to 100 years, fertility rates declined as well. Different societies experienced transition in different ways and today, various regions of the world are following distinctive paths (Tabah 1989). Nonetheless, the broad result was, and is, a gradual transition from a small, slowly growing population with high mortality and high fertility to a large, slowly growing population with low mortality and low fertility rates. During the transition

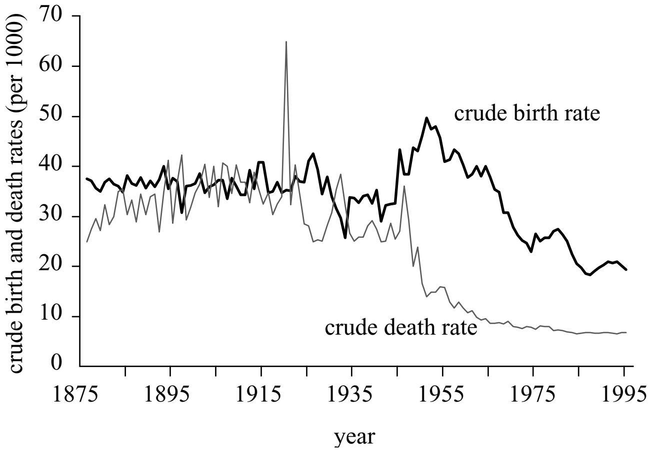

Figure 1. Birth and death rates in Mauritius since 1871. Grey line, crude death rate; black line, crude birth rate. (Source: Mauritius Central Statistical Office.)

itself, population growth accelerates because the decline in death rates precedes the decline in birth rates.

On a theoretical level there are two different ways to explain demographic transition. One views the fertility decline as a direct response to the mortality decline. This so-called 'homeostasis argument' stresses that societies tend to find an equilibrium between births and deaths. When death rates decline due to progress in medicine and better living conditions, the equilibrium is disturbed and the population grows unless birth rates adjust to the new mortality conditions and also start to decline. The fact that fertility tends to decline many years after mortality may be explained by a perception lag. The other view assumes that modernization of society acts as a joint driving force of declining mortality and fertility. Fertility decline lags mortality decline, according to this view, because fertility is more strongly embedded in the system of cultural norms and therefore changes more slowly than mortality relevant behaviour. The historical record of Europe—where fertility sometimes declined simultaneously with mortality and population growth was generally much lower than in today's high fertility countries (Coale & Treadway 1979; Coale & Watkins 1986)—gives more support to the second explanation. But the two arguments are not necessarily mutually exclusive.

Figure 1 illustrates the demographic transition in Mauritius, a developing country that has good records for birth and death rates for more than a century. Up to around World War II, birth and death rates show a pattern of strong annual fluctuations, due mostly to diseases and changing weather conditions, which are typical for 'premodern' societies. Whenever birth rates are consistently above death rates, the population grows, as was the case in Mauritius during the late 19th century. After World War II, death rates on Mauritius declined precipitously due to malaria eradication and the introduction of European medical technology. Birth rates, on the other hand, remained high or even increased somewhat due to the better health status of women (a typical phenomenon in the early phase of demographic transition). By 1950 this had resulted in a population growth rate of more than 3% per year, one of the highest at that time. Later, birth rates declined, with the bulk of the transition occurring during the late 1960s and early 1970s when TFR declined from more than six to less than three children per woman within only 7 years, probably the world's most rapid national fertility decline. It happened on a strictly voluntary basis and was a result of high female educational status together with successful family planning programmes (Lutz 1994). Because of the still very young age structure of the Mauritian population, current birth rates are still higher than death rates and the population is growing by *ca*. 1% per year despite fertility around replacement level (i.e. two surviving children or TFR somewhat above 2.0, depending on mortality conditions).

Empirically observed trends in all parts of the world have overwhelmingly confirmed the relevance of the concept of demographic transition to LDCs (Tabah 1989; Cleland 1996; Westoff 1996; United Nations 2001). With the exception of pockets where religious or cultural beliefs are strongly pro-natalist, fertility decline is well advanced in all regions except sub-Saharan Africa, and even in that region many signs of a fertility transition can be perceived. In South East Asia and many countries in Latin America, fertility rates are on par with those in MDCs only several decades ago, and in several countries such as China, Taiwan and Korea, fertility is at sub-replacement levels.

The biggest difference between the demographic transition process in what are now MDCs and LDCs has been the speed of mortality decline. Mortality decline in Europe, North America and Japan came about over the course of two centuries as a result of reduced variability in the food supply, better housing, improved sanitation and, finally, progress in preventive and curative medicine. Mortality decline in LDCs, by contrast, occurred very quickly as a result of the application of Western medical and public health technology to infectious, parasitic and diarrhoeal diseases since World War II. Life expectancy in Europe rose gradually from about 35 years in 1800 to about 50 years in 1900, 66.5 years at the end of World War II and 74.4 years in 1995. In LDCs, it shot up from 40.9 years at the end of World War II to 63 years in 2000. The increase that took MDCs about one and a half centuries to achieve came to pass in LDCs in less than half a century. As a result of the speed of the mortality decline, populations in LDCs are growing three times faster today than did the populations of the present MDCs at the comparable stage of their own demographic transition.

Studies of the factors influencing changes in fertility must begin with the proximate determinants of fertility: (i) age at marriage (or beginning of sexual activity); (ii) prevalence and effectiveness of contraception; (iii) prevalence of induced abortion; and (iv) duration of postpartum infecundability, especially due to breast feeding (Bongaarts & Potter 1983). Fertility decline must come through changes in one or more of these four proximate determinants.

The adoption of contraception has been the principal source of fertility decline in LDCs. However, how couples adopt contraceptive practices is a function of many influences. The spread of contraceptive practice is a diffusion process consisting of stages of awareness, information, evaluation, trial and adoption. All of these stages consist of actions undertaken in social networks, leading to path dependence and the persistence of heterogeneity between sub-populations (Kohler 1997). Coale (1973) lists three 'preconditions' required for fertility decline. First, fertility must be regarded as being within the realm of conscious choice. Often, this marks a fundamental change in the way individuals view their lives and their families (Lockwood 1997; Van de Walle 1992); for example, people may change from having a fatalistic attitude toward fertility to making procreation an object of their life-course planning. Yet, in most demographic transitions, fertility regulation was already practised during the pre-transition phase, albeit more for spacing than for limiting the final number of children (Mason 1997). Therefore, second, there must be objective advantages to lower fertility. Third, acceptable means of fertility reduction must be at hand. These three preconditions for a lasting fertility decline suggest three parallel strategies to foster the transition from high to low fertility.

(i) Emphasize universal basic education to bring fertility increasingly into the realm of conscious choice. Modern mass media may also exert an important influence. These strategies are also likely to bring about attitudinal and cultural change.
(ii) Pursue changes in socioeconomic variables, mostly neoclassical economic costs and benefits arising from variables such as child labour, female participation in the modern-sector labour force, support in old age, etc. Changes in the 'value' of children also impact on couples' desired family size.
(iii) Invest in reproductive health and the availability of family planning services, including maternal and child health programmes that reduce infant mortality. Help women match their desired and actual number of children by focusing on the unmet need for family planning.

This framework suggests that if two of the three preconditions are already met, the introduction of the third may trigger a rapid fertility decline. In the previously described case of the rapid Mauritian fertility decline, the young female population was already literate and large families were increasingly perceived as an economic burden. The strong and strictly voluntary family planning campaign that strengthened the negative perception of high fertility and provided efficient family planning services that were even supported by the influential Roman Catholic church (supporting only the 'natural' ones) then triggered the precipitous fertility decline. In some other countries huge investments in family planning were virtually without effect because one of the other two preconditions was not met.

2. EXPECTED FUTURE POPULATION GROWTH

The human population can be projected for several decades with rather high accuracy because most of the people who will be alive in 20–30 years have already been born, and we know their cohort size. All long-term global population projections employ the cohort-component method. Initial populations for countries or regions are grouped into cohorts defined by age and sex, and the projection proceeds by updating the population of each age- and sex-specific group according to assumptions about three components of population change: fertility, mortality and migration.

Development of this approach was the major innovation in the evolution of projection methodology. It was first proposed by the English economist Edwin Cannan (1895) and was then reintroduced by Whelpton (1936), formalized in mathematical terms by Leslie (1945) and first employed in producing a global population projection by Notestein (1945). Prior to the mid-20th century, the few global population projections that had been made were based on extrapolations of population growth rate applied to estimates of the total population of the world (Frejka 1994). Since Notestein's 1945 projection, the cohort-component method has become the dominant means of projecting population and has remained essentially unchanged. The real work in producing projections lies not in refining the mechanics of the model itself, but in estimating population size and age structure in the base period and in forecasting future trends in fertility, mortality and migration.

Fertility has the greatest effect on population growth because of its multiplier effect—children born today will have children in the future, and so on. Both the projected pace of fertility decline and the assumed eventual fertility level are important in determining trends in population size and age structure. The two factors also interact—the lower the assumed eventual fertility level, the more important the pace of fertility decline becomes to projected population size (O'Neill *et al.* 1999). Mortality projections are typically based on projecting life expectancy at birth. Projections of mortality must specify how the distribution of mortality over different age and sex groups may change over time. Changes in mortality at different ages have different consequences for population growth and age structure. When child and infant mortality decline, for example, a greater proportion of babies will survive to adulthood to have their own children and contribute to future growth. Mortality declines among the older population have a more short-term effect on population growth because the survivors are already past reproductive age.

Future international migration is more difficult to project than fertility or mortality. Migration flows often reflect short-term changes in economic, social or political factors, which are impossible to predict. And, since no single, compelling theory of migration exists, projections are generally based on past trends and current policies, which may not be relevant in the future.

Projection results can be produced in one of two forms: as a set of scenarios or, more recently, as probability distributions. Population projections according to alternative scenarios, called variants in some cases, show what the future population would be if fertility, mortality and migration follow certain paths. The common practice by many statistical offices and the United Nations (UN) Population Division is to define high and low variants (in addition to the median variant), which are based on alternative fertility assumptions and are supposed to cover a 'plausible range' of future population trends. Such a definition of variants is not only imprecise but also disregards the significant uncertainties associated with future mortality and migration trends, and is inconsistent when inferences are being made from national ranges to a global

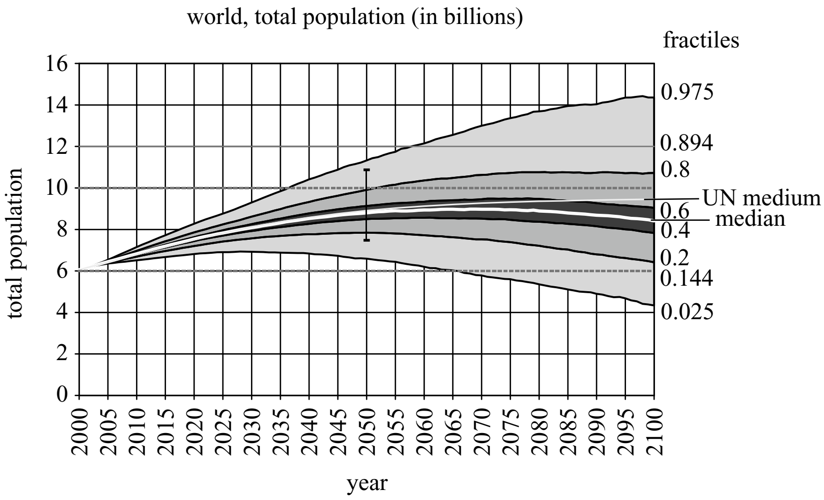

Figure 2. Forecast distributions of world population sizes. The error bar refers to the 95% interval as given by the National Research Council (2000) on the basis of an ex-post error analysis.

range (National Research Council 2000). While the ranges given by the high and low variants are therefore not very useful, the medium variants are usually taken as best-guess forecasts; they reflect the current thinking about the most likely future trends.

In 1996, the first probabilistic forecasts of the world's population using stochastic birth, death and interregional migration rates were published, based on information as of 1990–1995 (Lutz *et al.* 1996, 1997). These forecasts have recently been updated with the most recent data and analysis (National Research Council 2000) as well as an improved methodology (Lutz *et al.* 2001). Owing to the recent acceleration of fertility declines and worsening HIV/AIDS conditions, the new forecasts are lower and show a higher probability that the world's population will stop growing over the course of this century.

Figure 2 shows the distribution of simulated world population sizes over time for these newest forecasts produced by IIASA. The median value of these projections reaches a peak around 2070 at 9.0 billion people and then slowly decreases. In 2100, the median value of the projections is 8.4 billion people with the 80% prediction interval bounded by 5.6 and 12.1 billion. There is about a 60% chance that the world population will not reach 10 billion before 2100. There is around an 85% chance that the world's population will stop growing before the end of the century. In 2100, there is around a 15% chance that the world's population will be lower than it is today.

How do these results compare with other recent forecasts? Up to 2045 the IIASA median trajectory is almost identical to the forecasts of the World Bank (2000), the US Bureau of the Census (2000), and the medium variant of the UN (2001). Only the UN long-range projections provide forecasts to the end of the century. The most recent UN medium variant (United Nations 2001) is inserted in figure 2 as a thin white line. After an almost identical trend to 2050, the UN forecasts show a virtually constant world population, while the IIASA median begins to decline during the second half of the century. The difference is essentially due to the UN's assumption that after 2050 fertility in all countries will be at replacement level, even in countries where it is already significantly below that level. It also assumes that countries which are still above replacement will never go below replacement fertility. The IIASA projections do not share this assumption, as discussed below.

If we define the end of population growth slightly less literally and take it to correspond to population growth of 0.1% per annum or less, then the UN medium population projection also shows the end of population growth during the second half of the century. Their medium scenario shows world population growth first falling below 0.1% around 2075. Their timing of the end of world population growth is consistent with IIASA's.

Therefore, the general point that the world's population growth is coming to an end does not depend on whether or not the world's fertility rate falls below or remains at the replacement level. Either way, at the end of the 21st century world population growth will probably be over. But whether the population will reach a peak and decrease or just remain virtually stationary does depend on it.

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 high fertility. On this issue there is a broad consensus that fertility transitions are likely to be completed in the next few decades (National Research Council 2000). 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 National Research Council (2000) states that 'fertility in countries that have not completed transition should eventually reach levels similar to those now observed in low fertility countries' (p. 106). The IIASA assumptions of long-term sub-replacement fertility are consistent with this view.

Table 2 shows the median population sizes and associated 80% prediction intervals for the world and its 13 regions, as defined in Lutz (1996, pp. 437–439). It indicates 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.

In Western Europe (including Turkey) and North

Table 2. Forecasted median world and regional population sizes with 80% prediction intervals (in parentheses) for the world and its 13 regions. (Figures are in millions. From Lutz *et al.* 2001.)

region	year				
	2000	2025	2050	2075	2100
world	6055	7827 (7219–8459)	8797 (7347–10 443)	8951 (6636–11 652)	8414 (5577–12 123)
1 north Africa	173	257 (228–285)	311 (249–378)	336 (238–443)	333 (215–484)
2 Sub-Saharan Africa	611	976 (856–1100)	1319 (1010–1701)	1522 (1021–2194)	1500 (878–2450)
3 North America	314	379 (351–410)	422 (358–498)	441 (343–565)	454 (313–631)
4 Latin America	515	709 (643–775)	840 (679–1005)	904 (647–1202)	934 (585–1383)
5 central Asia	56	81 (73–90)	100 (80–121)	107 (76–145)	106 (66–159)
6 Middle East	172	285 (252–318)	368 (301–445)	413 (296–544)	413 (259–597)
7 South Asia	1367	1940 (1735–2154)	2249 (1795–2776)	2242 (1528–3085)	1958 (1186–3035)
8 China region	1408	1608 (1494–1714)	1580 (1305–1849)	1422 (1003–1884)	1250 (765–1870)
9 Pacific Asia	476	625 (569–682)	702 (575–842)	702 (509–937)	654 (410–949)
10 Pacific Organisation for Economic Co-operation and Development	150	155 (144–165)	148 (125–174)	135 (100–175)	123 (79–173)
11 Western Europe	456	478 (445–508)	470 (399–549)	433 (321–562)	392 (257–568)
12 Eastern Europe	121	117 (109–125)	104 (86–124)	87 (61–118)	74 (44–115)
13 European part of the Former Soviet Union	236	218 (203–234)	187 (154–225)	159 (110–216)	141 (85–218)

America, future changes will depend not only on fertility and mortality but also significantly on migration volumes. This adds to the uncertainty ranges of future population sizes, with the median starting to decline in Western Europe over the next two decades and continuing to increase in North America.

The projections show that the China region and the South Asia region, which in 2000 have approximately the same population sizes, 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 sizes 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 (O'Neill *et al.* 1999).

3. POPULATION DENSITY AND HUMAN FERTILITY

In the demographic literature there has been surprisingly little systematic analysis on the question of the relationship between population growth rate and human fertility level on the one hand, and population density on the other. As described in the previous section, the study of fertility determinants has largely been focusing on social, economic and even cultural factors influencing reproductive behaviour. Since human fertility, especially under the condition of conscious family planning during the later parts of the demographic transition, is seen primarily as socially determined, ecological factors (such as population density), which are prominent in animal ecology, have played little or no role in demographic analysis. However, population density need not operate only through direct biological mechanisms; perceived population density may also be an important psychological determinant of fertility.

Of the few studies addressing this question in very different settings, most scholars found a significant negative relationship between human population density and the birth rate. In cross-national studies, Adelman (1963), Beaver (1975), Cutright & Kelly (1978), Heer (1966) and Janowitz (1971) found such relationships after controlling the level of urbanization, economic development and other background variables. The negative relationship between density and fertility also has been observed for smaller units, i.e. Ohio counties in 1850 (Leet 1977), townships in Taiwan (Collver *et al.* 1967) and rural areas in Mexico (Hicks 1974). Hermalin & Lavely (1979) described the evolution of Taiwan's agriculture and fertility from a variety of sources using historical information and data, and concluded that the observations were reasonably consistent with theories of rural fertility that propose tenure and inheritance, land availability and capital-output ratios as crucial variables. Firebaugh (1982) studied 22 farm villages in Punjab, India, between 1961 and 1972. Correlation coefficients for pooled data show crude birth rates to be inversely correlated with density, agricultural production, female literacy, the percentage of certain castes and trend variables. Estimated density effects are statistically significant although not very large. Yasuba (1962) analysed the fertility ratios of states in the USA for the period 1800 to 1860. His principal result was that the most important factor associated with fertility dif-

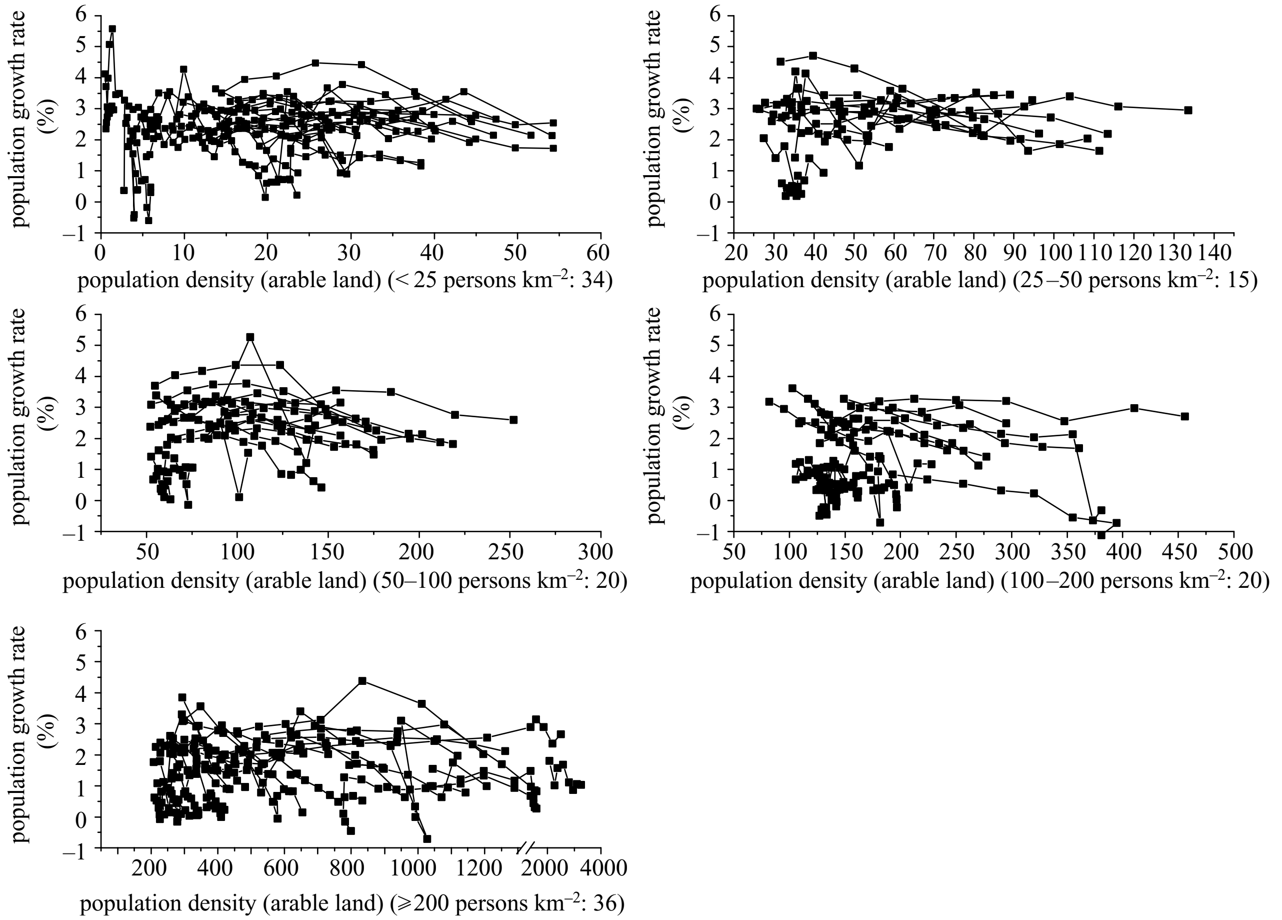

Figure 3. Bivariate relationship between population growth rate (average annual growth rate calculated from five-year intervals; United Nations 2001) and population density in five groups, according to 1960 density, 1960–2000. (Note: population growth rate lagged by five years.) Each line corresponds to the time-series of one country.

ferences and trends was population density—the higher the density, the lower the fertility ratio.

Against the background of this rather diverse set of studies, most of them several decades old, the following analysis is, to our knowledge, the first systematic study on the basis of international time-series and also using different density measures.

This analysis is also of particular relevance to the assumptions of long-term fertility levels in different parts of the world in the above-described IIASA population projections. As an alternative to the substantively unfounded assumption of universal convergence toward replacement fertility, those projections assume that long-term fertility in a region within a given range of fertility rates will depend on the population density in that region. The following analysis provides a broader empirical basis for this assumption.

When studying the possible association between population growth rates, fertility and population density, it is not immediately clear which density measure should be applied. The usual measure of dividing the total population of a country by its total area gives a measure of general space, of 'elbow room' so to speak, but it also includes areas of desert and tundra that are not appropriate for agriculture; therefore, one may be interested in considering the potentially arable land of a country rather than the total surface area. In the following analysis we study both density indicators independently, named 'population density' and 'population density (arable land)' in the tables and figures. For the latter case we excluded six Middle Eastern desert states because they greatly distort the picture with almost no arable land and rather significant populations mostly due to oil revenues. As the following results show, the two different measures of population density do not produce qualitatively much different patterns of association. The best density variable that one would like to measure in its impact on fertility is perceived density based on perceived living space as it influences behaviour, but we do not know of any data on this. The two density measures applied here cover presumably two important determinants of this perceived density and therefore in combination seem to be an acceptable proxy.

For this analysis, time-series data from 1960 to 2000 (in five-year steps) have been collected for 187 countries mostly derived from international sources (World Bank 2001; United Nations 2001; and see FAO statistical databases at http://apps.fao.org/subscriber/). These data include population size, the different population densities, annual population growth rates, total fertility rates, as well as female labour force participation rates, female literacy rates, urban proportions, GDP per capita in constant US$ and a food production index. Figure 3 depicts these data on the bivariate relationship between population density (arable land) (on the horizontal axis) and population growth rates (on the vertical axis). The lines connect the

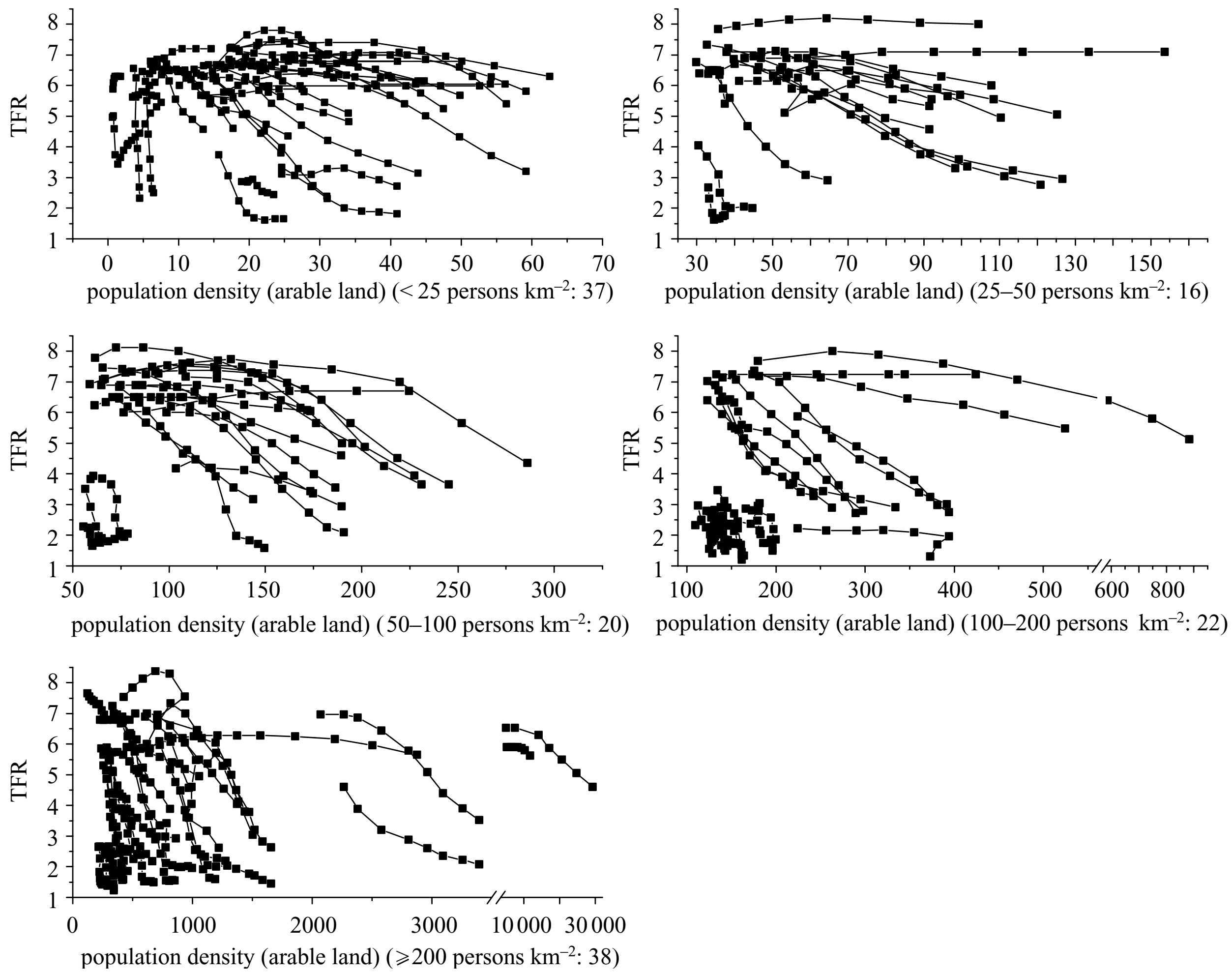

Figure 4. Bivariate relationship between total fertility rate and population density in five groups, according to 1960 density, 1960–2000. (Note: a five-year perception lag for TFR has been assumed.) Each line corresponds to the time-series of one country.

data of individual countries over time. In order to be able to discover some possible patterns among this massive amount of data, the figure sorts the countries according to their population density in 1960 into five groups ranging from the lowest with less than 25 persons per square kilometre to the highest of above 200 persons per square kilometre. Aside from some country-specific peculiarities, the graph does not show any clear bivariate association between the two variables within each of the five groups, neither cross-sectionally nor over time. By comparing across groups, however, it is evident that the average population growth rate is lower for countries with higher density.

Figure 4 plots the same country grouping of the time-series but replaces population growth rates with total fertility rates on the vertical axis. Here, a much clearer pattern of association appears. As population density increases over time the mean number of children tends to become lower. Also, when comparing across groups, it is quite apparent that countries with higher population density have on average much lower fertility rates. Why is the picture so different with respect to the fertility rates than with respect to population growth rates? To interpret this we have to be aware of the fact that even in a population closed to migration, population growth rate is determined by three factors: fertility, mortality and population age structure. Of these three, only fertility is directly a consequence of changing individual behaviour; therefore, only fertility can reflect possible psychological reactions to increasing population density. During the process of demographic transition, mortality is typically positively correlated with fertility. As mortality rates go down and life expectancy increases, fertility rates also go down. This mortality decline counteracts the negative impacts of a fertility decline on population growth rate because more people stay alive, thus contributing to a higher population size. It is also worth noting that since the advent of modern preventive medicine and hygiene, human population density does not seem to have a positive association with the level of mortality as one might infer from animal ecology and considerations of carrying capacity. If there is an association, it seems to be a negative one, with urban areas almost universally showing lower mortality rates than rural areas. This even seems to hold in some of the most polluted megacities because the generally much better access to health facilities in urban areas seems to outweigh the negative environmental impacts.

It is worthwhile to have a closer look at this apparently strong bivariate relationship between density and fertility because it might not really reflect a causal relationship, but rather could be due to some other developmental variables in the background, such as level of income or level

Table 3. Multiple linear regressions of several variables on the annual population growth rate (lagged by five years) for 187 countries, 1960–1990.

variable	1960 standardized coefficients	1965 standardized coefficients	1970 standardized coefficients	1975 standardized coefficients	1980 standardized coefficients	1985 standardized coefficients	1990 standardized coefficients
all countries ($n = 187$)							
female labour force participation rate	−0.041	0.121	0.109	−0.079	0.057	−0.029	−0.208
population density	0.266*	0.277*	0.203	0.082	0.135	0.002	−0.064
female literacy rate	0.139	0.102	0.079	−0.196	−0.105	−0.127	−0.172
population urban	−0.056	0.273	0.079	0.108	0.165	−0.044	−0.126
GDP per capita[a]	−0.076	−0.319	−0.171	−0.214	−0.289*	−0.195	−0.098
food production index[b]	−0.246	−0.122	−0.172	0.088	−0.257*	−0.246*	−0.179
R^2	0.142	0.122	0.075	0.067	0.141	0.163	0.134
LDCs[c] ($n = 143$)							
female labour force participation rate	−0.105	0.086	−0.041	−0.139	0.074	0.004	−0.217
population density	0.228	0.268*	0.185	0.070	0.124	−0.013	−0.094
female literacy rate	0.131	0.111	0.076	−0.180	−0.082	−0.099	−0.179
population urban	−0.087	0.224	0.018	0.049	0.155	−0.034	−0.088
GDP per capita[a]	−0.127	−0.252	−0.138	−0.196	−0.294*	−0.233	−0.210
food production index[b]	−0.239*	−0.102	−0.160	0.110	−0.262*	−0.296*	−0.174
R^2	0.146	0.110	0.068	0.068	0.133	0.172	0.177

[a] Constant 1995 US$ for GDP per capita.
[b] 1989–1991 = 100 as reference for food production index.
[c] Comprises all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus French Polynesia.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

of education that might simultaneously lead to lower fertility and make higher population densities possible. For this reason tables 3, 4 and 5 give sets of multiple regressions that study the relationship of population growth and fertility to population density while controlling some of the other social and economic variables measured. To get a more differentiated picture and to avoid serial autocorrelation, the regressions are given separately for the seven points in time and separately for the subset of developing countries, in order to rule out the possibility that the bipolarity between developed and developing countries dominates the appearing pattern. A perception lag of five years has been assumed between the explanatory and the dependent variables, i.e. the independent variables listed for 1960 are being related to fertility and population growth in 1965, and so on. The calculations shown here are based on giving equal weight to all countries. Additional calculations based on a weighting of the countries by their population size yielded qualitatively similar results and are given in electronic Appendix A available on The Royal Society's Publications Web site.

The results of these 28 multiple regressions cannot be discussed in detail here, but a few general conclusions can be drawn. In almost all regressions for the fertility rate, female literacy seems to be the single most important factor. This is consistent with the large body of literature on fertility determinants and with the theoretical foundations of the process of demographic transition described above. The tables show that the relationship of female literacy to the total fertility rate is more pronounced than that to the growth rates across all points in time. The urban proportion also has a consistent negative association with fertility (the higher the degree of urbanization, the lower fertility) but is not always statistically significant. GDP per capita only shows a significant negative coefficient with fertility during the 1960s on the global level, while it is insignificant with a variable sign in all the other regressions. With respect to population growth rates (table 3), the pattern and even the signs of the coefficients are much less consistent over time and are statistically insignificant in general. This has to do with the fact that changes in total population size are also influenced by mortality and migration, which tend to have less consistent associations with density. As a piece of background information, figures 5 and 6 plot the bivariate relationships of income and female literacy to the total fertility rate. The comparison of the two figures impressively confirms the view that female literacy is a much more straightforward and almost linear covariate (and determinant) of declining fertility than GDP per capita, where the picture is very mixed.

How does population density—under both definitions used here—come out as an explanatory variable in this multivariate setting? Again the relationship is much stronger and more statistically significant in the case of fertility as the dependent variable, although the signs are consistently negative for both fertility and the growth rate. When explaining the level of fertility, population density comes out second in importance after female literacy, yet still well ahead of the traditionally studied factors: female labour force participation, income, urbanization and food security. This strong negative effect of population density on the level of fertility five years later is statistically significant in almost all years, both at the global level and among the sub-group of developing countries. When comparing the results for the two definitions of density (see tables 4 and 5), the one based on arable land turns out to be slightly less significant than the one based on total area.

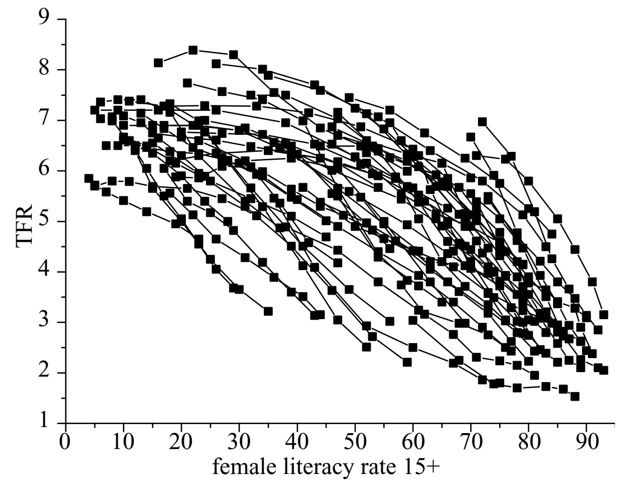

Figure 5. Bivariate relationship between literacy rates for females aged 15+ and total fertility rates for time-series of 65 developing countries, 1960–2000. Each line corresponds to the time-series of one country.

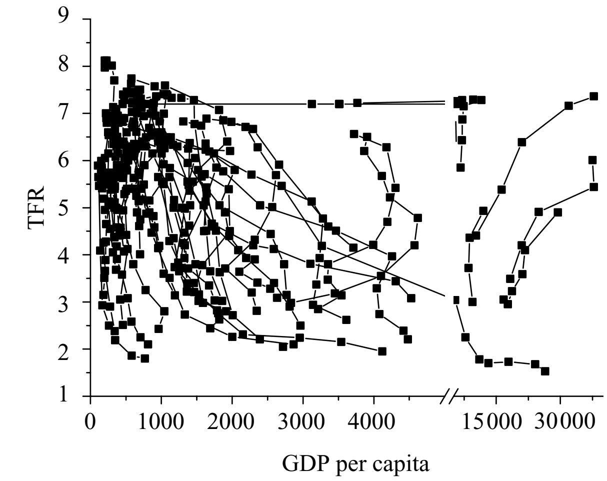

Figure 6. Bivariate relationship between GDP per capita (constant 1995 US$) and total fertility rate in 55 developing countries (same countries as in figure 5 with available income data), 1960–2000. Each line corresponds to the time-series of one country.

In order to understand better the possible effects of population density on human fertility, more research is needed in terms of studying both these associations and sub-national scales, and in terms of understanding better the possible mechanisms of causation. For the former, table 6 gives a simple correlation analysis for the 30 provinces of China, which also confirms the above-described associations at a sub-national level for the world's most populous country, which has seen dramatic fertility declines over the past three decades. While the correlations between density and fertility are consistently high over time, the relationship to the growth rate is also affected by changing patterns of inter-provincial migration.

As to the possible mechanisms of causation, direct bio-

Table 4. Multiple linear regressions of several variables on the TFR (lagged by five years) for 187 countries, 1960–1990.

variable	1960 standardized coefficients	1965 standardized coefficients	1970 standardized coefficients	1975 standardized coefficients	1980 standardized coefficients	1985 standardized coefficients	1990 standardized coefficients
all countries ($n = 187$)							
female labour force participation rate	−0.167	−0.096	−0.085	−0.144	−0.153	−0.117	−0.068
population density	−0.177*	−0.191*	−0.196**	−0.226**	−0.236***	−0.239***	−0.248***
female literacy rate	−0.387**	−0.508***	−0.601***	−0.694***	−0.701***	−0.629***	−0.618***
population urban	−0.024	−0.051	−0.106	−0.218	−0.245*	−0.275*	−0.261*
GDP per capita[a]	−0.514***	−0.389**	−0.244*	−0.051	−0.018	−0.043	−0.048
food production index[b]	−0.133	−0.088	−0.019	0.015	0.028	−0.026	0.137*
R^2	0.655	0.703	0.710	0.714	0.734	0.712	0.698
LDCs[c] ($n = 143$)							
female labour force participation rate	−0.249	−0.146	−0.104	−0.122	−0.102	−0.069	−0.025
population density	−0.193*	−0.225*	−0.229**	−0.245**	−0.264**	−0.281***	−0.296***
female literacy rate	−0.336**	−0.510***	−0.603***	−0.671***	−0.694***	−0.607***	−0.590***
population urban	−0.243	−0.274	−0.299	−0.270*	−0.266*	−0.384**	−0.340*
GDP per capita[a]	−0.399*	−0.180	−0.011	0.033	0.074	0.087	0.076
food production index[b]	−0.145	−0.062	0.011	0.060	0.074	−0.008	0.124
R^2	0.567	0.612	0.637	0.660	0.684	0.664	0.637

[a] Constant 1995 US$ for GDP per capita.
[b] 1989–1991 = 100 as reference for food production index.
[c] Comprises all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus French Polynesia.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 5. Multiple linear regressions of several variables (using density as defined by arable land) on the TFR (lagged by five years) for 181 countries, 1960–1990.

variable	1960 standardized coefficients	1965 standardized coefficients	1970 standardized coefficients	1975 standardized coefficients	1980 standardized coefficients	1985 standardized coefficients	1990 standardized coefficients
all countries ($n = 181$)							
female labour force participation rate	−0.183	−0.100	−0.056	−0.141	−0.160	−0.102	−0.057
population density (arable land)[a]	−0.184*	−0.186*	−0.162*	−0.156*	−0.153*	−0.173**	−0.203**
female literacy rate	−0.404**	−0.518***	−0.603***	−0.696***	−0.710***	−0.643***	−0.622***
population urban	0.305	0.034	0.014	−0.060	−0.123	−0.169	−0.201*
GDP per capita[b]	−0.591***	−0.492***	−0.372**	−0.257*	−0.210*	−0.196*	−0.153
food production index[c]	−0.126	−0.075	0.014	0.023	0.057	0.007	0.135*
R^2	0.671	0.725	0.727	0.727	0.738	0.722	0.704
LDCs[d] ($n = 137$)							
female labour force participation rate	−0.280	−0.166	−0.109	−0.164	−0.130	−0.068	−0.006
population density (arable land)[a]	−0.276**	−0.266**	−0.226*	−0.205*	−0.193*	−0.221**	−0.250**
female literacy rate	−0.352**	−0.534***	−0.626***	−0.715***	−0.734***	−0.654***	−0.607***
population urban	−0.204	−0.181	−0.192	−0.219	−0.216	−0.259	−0.237
GDP per capita[b]	−0.469*	−0.289	−0.123	−0.037	−0.009	−0.004	−0.033
food production index[c]	−0.154	−0.073	0.013	0.042	0.087	0.015	0.136
R^2	0.615	0.648	0.648	0.650	0.666	0.659	0.639

[a] Includes land currently used for other purposes such as grassland, forests, protected areas, buildings and infrastructure, etc.
[b] Constant 1995 US$ for GDP per capita.
[c] 1989–1991 = 100 as reference for food production index.
[d] Comprises all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus French Polynesia.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 6. Correlation coefficients between population density (under three different definitions) and the TFR as well as population growth rate (lagged by five years) in China's 30 provinces (numbers of provinces in parentheses), 1970–1990.
(Sources of data: Yin Hua & Lin Xiaohong 1996; Population Census Office under the State Council *et al.* 2001; Fischer *et al.* 1998.)

variable	1970	1975	1980	1985
population density–population growth rate	−0.764** (30)	−0.294 (30)	−0.103 (30)	−0.346* (30)
population density–TFR	−0.581** (28)	−0.587** (28)	−0.556** (30)	−0.529** (30)
population density (potential cultivated land)–population growth rate	−0.629** (29)	−0.160 (29)	−0.004 (29)	−0.339* (29)
population density (potential cultivated land)–TFR	−0.474** (28)	−0.460** (28)	−0.477** (29)	−0.479** (29)
population density (currently cultivated land)–population growth rate	−0.746** (29)	−0.254 (29)	−0.019 (29)	−0.316* (29)
population density (currently cultivated land)–TFR	−0.532** (28)	−0.536** (28)	−0.501** (29)	−0.522** (29)

* $p < 0.05$; ** $p < 0.01$.

logical factors such as decreasing fecundability due to 'density stress' are rather unlikely candidates for the human population, especially in a technologically advanced stage of development. Instead psychological factors, such as perceived living space, may play a role. An earlier study (W. Lutz, personal communication) identified a clear 'island factor' in the onset of fertility declines, i.e. the fact that in otherwise comparable socioeconomic settings, small islands—where the spatial limitations are obvious—began their fertility transitions earlier. But even with respect to contemporary European fertility levels, it is conspicuous that the very-low-density regions of northern Scandinavia have significantly higher fertility than the high-density areas of central and southern Europe. This clearly needs further investigation.

In conclusion, we have shown that the process of demographic transition has led to unprecedented growth in the human population, but will also lead to significant population ageing and the likely end of world population growth. What will determine human population growth in the very long run, once the momentum of the demographic transition-induced population growth comes to an end? This is an open question at this point. Biological and ecological factors will clearly be very important for the future human life span and health, but they may also play an increasingly important role with respect to human fertility.

The section on past population growth draws partly from O'Neill *et al.* (2001). The section on future trends draws partly from Lutz *et al.* (2001).

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GLOSSARY

GDP: gross domestic product
LDC: less developed country
MDC: more developed country
TFR: total fertility rate

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