LETTERS

Advances in development reverse fertility declines

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During the twentieth century, the global population has gone through unprecedented increases in economic and social development that coincided with substantial declines in human fertility and population growth rates[1,2]. The negative association of fertility with economic and social development has therefore become one of the most solidly established and generally accepted empirical regularities in the social sciences[1–3]. As a result of this close connection between development and fertility decline, more than half of the global population now lives in regions with below-replacement fertility (less than 2.1 children per woman)[4]. In many highly developed countries, the trend towards low fertility has also been deemed irreversible[5–9]. Rapid population ageing, and in some cases the prospect of significant population decline, have therefore become a central socioeconomic concern and policy challenge[10]. Here we show, using new cross-sectional and longitudinal analyses of the total fertility rate and the human development index (HDI), a fundamental change in the well-established negative relationship between fertility and development as the global population entered the twenty-first century. Although development continues to promote fertility decline at low and medium HDI levels, our analyses show that at advanced HDI levels, further development can reverse the declining trend in fertility. The previously negative development–fertility relationship has become J-shaped, with the HDI being positively associated with fertility among highly developed countries. This reversal of fertility decline as a result of continued economic and social development has the potential to slow the rates of population ageing, thereby ameliorating the social and economic problems that have been associated with the emergence and persistence of very low fertility.

The cross-country association between total fertility rate (TFR) and HDI in 1975 and 2005 is shown in Fig. 1. In both years, the association is negative for HDI levels below the range of 0.85–0.9. As countries progressed to very advanced levels of development (HDI > 0.9) in recent years, however, the HDI–fertility relationship started to change fundamentally. As the HDI approaches levels above about 0.9, the HDI–fertility association in Fig. 1 reverses to a positive relationship: higher levels of HDI are associated with higher levels of fertility. For example, the 2005 TFR levels for countries with an HDI between 0.9 and 0.92 is on average 1.24; in contrast, the average TFR is 1.89 in countries at the highest levels of development (HDI > 0.95). These differential fertility levels at intermediate and very advanced development stages have markedly different long-term implications: the former, if prevailing in the long term in the absence of migration, indicates a halving of the population and birth cohort approximately every 40–45 years; in contrast, the latter level can sustain population replacement with relatively modest levels of in-migration[12].

Figure 2 complements the cross-sectional analysis with a longitudinal perspective that focuses on the within-country trajectories of fertility and HDI. Figure 2 includes all countries that have attained an HDI level of least 0.9 by year 2005 and for which longitudinal data from 1975 to 2005 are available (24 countries; see Supplementary Information). The TFR is shown for years 1975 and 2005 relative to the lowest TFR that was observed while a country's HDI was within the window of 0.85–0.9. The reference year is the first year in which this lowest TFR is observed. A line is then used to connect the HDI–TFR

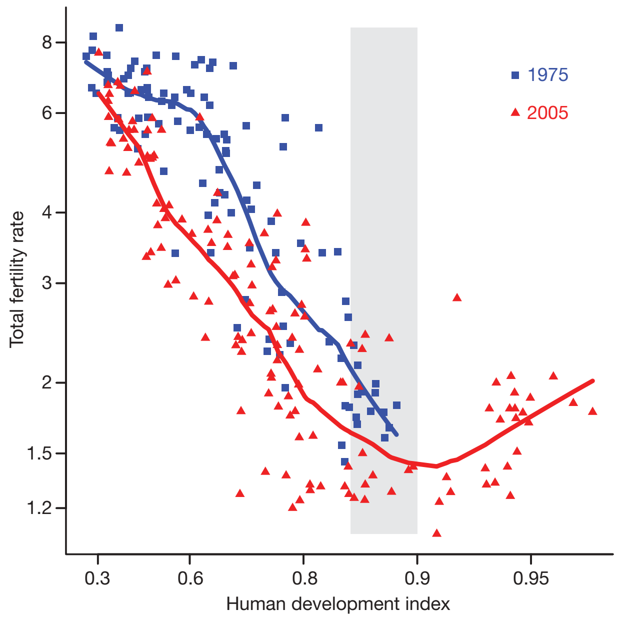

Figure 1 | Cross-sectional relationship between TFR and HDI in 1975 and 2005. The TFR reflects the number of children that would be born to a woman during her lifetime if she experienced the age-specific fertility rates observed in a calendar year. The HDI is the primary index used by the United Nations Development Programme (UNDP) to monitor and evaluate broadly defined human development, combining with equal weight indicators of a country's health conditions, living standard and human capital[11]. An HDI of 0.9 roughly corresponds to 75 years of life expectancy, a GDP per capita of 25,000 US dollars in year 2000 purchasing power parity, and a 0.95 education index (a weighted sum of standardized literacy rate and primary, secondary and tertiary level gross enrolment ratios). The 1975 data include 107 countries, with 1975 HDI levels ranging from 0.25 to 0.887, and 1975 TFR levels ranging from 1.45 to 8.5; the 2005 data include 140 countries, with 2005 HDI levels ranging from 0.3 to 0.966, and 2005 TFR levels ranging from 1.08 to 7.7. The Spearman's rank correlation between HDI and TFR in 1975 is −0.85 ($P < 0.01$); the Spearman's rank correlation between HDI and TFR in 2005 is −0.84 ($P < 0.01$) for countries with HDI < 0.85, and 0.51 ($P < 0.01$) for countries with HDI ≥ 0.9. For further details, see Supplementary Information. Countries with a 2005 HDI ≥ 0.9 include (2005 HDI in parentheses): Australia (0.966), Norway (0.961), Iceland (0.956), Ireland (0.95), Luxembourg (0.949), Sweden (0.947), Canada (0.946), Finland (0.945), France (0.945), the Netherlands (0.945), the United States (0.944), Denmark (0.943), Japan (0.943), Switzerland (0.942), Belgium (0.94), New Zealand (0.938), Spain (0.938), the United Kingdom (0.936), Austria (0.934), Italy (0.934), Israel (0.922), Greece (0.918), Germany (0.916), Slovenia (0.913) and South Korea (0.911).

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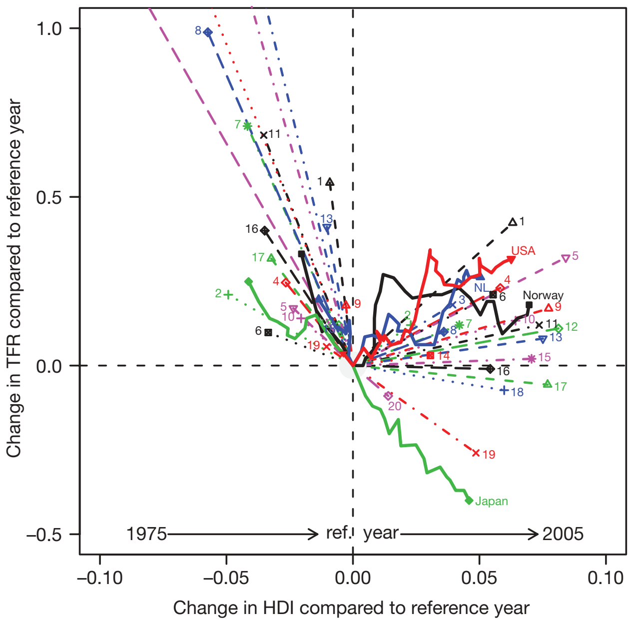

Figure 2 | Within-country time-path of the HDI–TFR relationship for all countries that attained an HDI ≥ 0.9 by 2005. The figure depicts the difference between the TFR in 1975 and 2005 compared to the lowest TFR that was observed while a country's HDI was within the 0.85–0.9 window. The (first) year in which this TFR is observed is denoted as the reference (ref.) year. For four particularly interesting and relevant countries, the United States (USA), Norway, the Netherlands (NL) and Japan, the graph shows the full path of the HDI–TFR development during the period 1975–2005. The figure includes all countries that attained an HDI ≥ 0.9 in 2005, with the exception of Slovenia for which no pre-1990 HDI time series could be constructed. For all countries, the HDI in 2005 is higher than the HDI in the reference year; for 18 of the 26 countries that attained a HDI ≥ 0.9 by 2005, the TFR in 2005 is higher than the TFR in the reference year. Countries ending in the top right quadrant in 2005 are Norway, the Netherlands, the United States, Denmark (1), Germany (2), Spain (3), Belgium (4), Luxembourg (5), Finland (6), Israel (7), Italy (8), Sweden (9), France (10), Iceland (11), the United Kingdom (12), New Zealand (13), Greece (14) and Ireland (15). Countries ending in the bottom-right quadrant in 2005 are Japan, Austria (16), Australia (17), Switzerland (18), Canada (19) and South Korea (20). See Supplementary Information for further analyses.

combinations for 1975, the reference year, and 2005. For four countries that we select as representative (Japan, the Netherlands, Norway and the United States) Fig. 2 shows the full path of the HDI–TFR changes during 1975–2005.

If the fertility–HDI relationship indeed reverses within the HDI window of 0.85–0.9, the longitudinal country-trajectories in Fig. 2 should predominantly be J-shaped. Specifically, country trajectories should begin in the top-left quadrant with relatively low HDI and high TFR levels, then pass through the circle that marks the reference year, and end in the top right quadrant where both the fertility level and the development index are higher than in the reference year. Although there are clear exceptions (as for instance Japan, Canada and South Korea), the trajectories for the large majority of countries (18 out of 24, representing 74% of the population in the 24 countries included in Fig. 2) confirm our finding of a reversal of the HDI–fertility relationship. That is, as development has progressed and these 18 countries attained an advanced HDI level of 0.9 or higher, the earlier downward trend in the total fertility rate was reversed. As a result, fertility in 2005 was higher than the minimum that was observed while a country's HDI was within the 0.85–0.9 interval. For example, US fertility reversed in 1976 (reference year) at an HDI of 0.881; the reversal in Norway occurred in 1983 at an HDI of 0.892; in Italy, the turning point occurred in 1994 at an HDI of 0.898; and in Israel, the reversal in TFR decline occurred in 1992 at an HDI of 0.880.

We confirm the graphical results of the reversal in the development–fertility relationship at advanced HDI levels by estimating a statistical model for the effect of HDI increases on fertility change (see Supplementary Information). The estimation uses panel data covering the years 1975 to 2005 for all 37 countries that had reached an HDI level of 0.85 by 2005. We use a differences-in-differences regression model with time fixed-effects[13] and a structural change in the HDI–fertility relationship at a critical HDI level that is estimated from the data. This specification controls for unobserved country characteristics and time trends, and it thus allows us to test whether the reversal in the HDI–fertility relationship documented in Fig. 2 persists after controlling for potentially confounding factors such as unobserved time-invariant country-specific factors and common time trends.

The critical HDI level at which the development–fertility association reverses from negative to positive is estimated as 0.86 (Supplementary Information). Our preferred estimates then suggest that the effect of HDI increases on fertility levels is equal to −1.59 ($P < 0.05$) for HDI levels below 0.86. The effect of HDI increases on fertility levels is estimated to be 4.07 ($P < 0.001$) for HDI levels at or above 0.86 (model 1 in Fig. 3). That is, on average an HDI increase of 0.1 results in a reduction of the TFR by 0.159 as long as countries are at development levels with HDI below 0.86; in contrast, an HDI increase of 0.05 results in an increase of the TFR by 0.204 ($= 0.05 \times 4.07$) once countries attain an advanced development stage with HDI ≥ 0.86. This fertility increase of approximately 0.2 children per woman for a 0.05 increase in HDI is sizable, and it corresponds closely to the graphical analyses presented in Fig. 2: for all countries ending in the top-right quadrant of Fig. 1, for example, TFR increased on average by 0.16 per 0.05 increase in HDI after the reference year.

The earlier finding of a positive HDI–fertility relationship at advanced HDI levels is robust even when the total fertility rate is adjusted for 'tempo effects'[7]—that is, the distortions that occur in the TFR as a result of the postponement of childbearing to later maternal ages[14]. In particular, the estimated effect of increases in HDI on the fertility level at advanced stages of development (HDI ≥ 0.86) remains positive and significant even if the tempo-adjusted TFR[15] is used as the dependent variable instead of the conventional TFR, or if the regression analyses include a further control for changes in the mean age at childbearing. Our findings are also robust with respect to alternative specifications of the statistical model that include a lagged HDI, and they are also not influenced by single data points or countries (models 2–4 in Fig. 3 and Supplementary Information).

The existence of a positive HDI–fertility relationship at advanced development stages indicates that further development has the potential to reverse earlier fertility declines once countries reach very high HDI levels. This finding has important implications in at least two domains. First, given the heterogeneity of institutional, cultural and policy contexts across developed countries, further research is required to investigate the different mechanisms that may underlie this reversal—particularly in light of exceptions such as Japan, Canada and South Korea. Specifically, an improved understanding of how improved labour-market flexibility, social security and individual welfare, gender and economic equality, human capital and social/family policies can facilitate relatively high levels of fertility in advanced societies is needed[8,16–18]. For instance, analyses on Europe show that nowadays a positive relationship is observed between fertility and indicators of innovation in family behaviour or female labour-force participation[19]. Also, at advanced levels of development, governments might explicitly address fertility decline by implementing policies that improve gender equality or the compatibility between economic success, including labour force participation, and family life[10,17,18]. Failure to answer to the challenges of development with institutions that facilitate work–family balance and gender equality might explain the exceptional pattern for rich

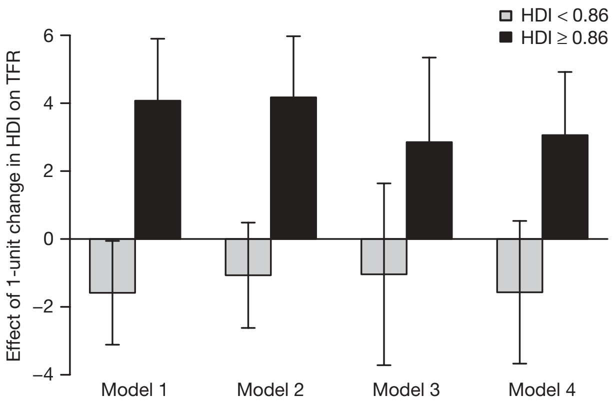

Figure 3 | Effect of 1-unit change in HDI on TFR. Estimated using differences-in-differences regression models of the HDI–TFR relationship. Analyses include time fixed-effects and allow for a structural change in the HDI–TFR relationship at a critical HDI level of 0.86 (for further details see Supplementary Table 3). Model 1 (preferred estimates): analyses include the period 1975–2005 for all countries with HDI $\geq$ 0.85 in 2005 ($n = 37$ countries; 1,051 observations). Model 2: same as model 1, except using 1-year lagged HDI as an explanatory variable ($n = 37$ countries; 1,014 observations). Model 3: same as model 1, except using tempo-adjusted TFR as a dependent variable (analyses include all countries with HDI $\geq$ 0.85 in 2005 for which a time series of the tempo-adjusted TFR is available; $n = 25$ countries; 705 observations, of which 505 include a tempo-adjusted TFR). Model 4: same as model 1, but including an additional adjustment for changes in mean age of mothers at first birth (analyses include all countries with HDI $\geq$ 0.85 in 2005 for which data on mean age at childbearing is available; $n = 26$ countries; 736 observations). The failure to identify a statistically significant negative effect of increases in HDI on the TFR at HDI levels below 0.86 in models 2–4 can be attributed to the smaller sample sizes in the alternative compared to our preferred estimates. Also, owing to the focus on the HDI–fertility relationship at advanced development levels, our regression analyses are restricted to countries that have attained a HDI of at least 0.85 by 2005, thereby excluding countries at lower levels of development for which the negative association between HDI and fertility is particularly strong (Fig. 1). Light grey bars denote moderate levels of development (HDI < 0.86); dark grey bars denote advanced levels of development (HDI $\geq$ 0.86). Error bars indicate 95% confidence intervals.

eastern Asian countries that continue to be characterized by a negative HDI–fertility relationship[20].

Second, our findings are highly relevant in the debate on the future of the world's population. Whereas a decade ago Europe, North America and Japan were assumed to face very rapid population ageing and in many cases significant population declines[6,7,21], our findings provide a different outlook for the twenty-first century. As long as the most developed countries focus on increasing the well-being of their citizens, and adequate institutions are in place, the analyses in this paper suggest that increases in development are likely to reverse fertility declines—even if we cannot expect fertility to rise again above replacement levels. As a consequence, we expect countries at the most advanced development stages to face a relatively stable population size, if not an increase in total population in cases in which immigration is substantial. For countries in which immigration is a minor component of demographic change, our analyses suggest a slower population decline than is at present foreseen in official demographic forecasts. Although significant population ageing is still certain in countries at the highest development levels, its magnitude may have been exaggerated by the widely held current perception that, as social and economic development progresses, fertility is bound to fall further. Policies targeted at further increasing HDI levels in advanced societies may therefore be suitable as a general strategy to reduce demographic imbalances caused by very low fertility levels. Consistent with current scientific knowledge, our findings also support the view that progress in development contributes to lower fertility levels in countries with low to moderately high HDI levels. Moreover, countries remaining at intermediate development levels are likely to face a decline in population size because these countries have attained low TFR levels and they do not yet—and may not in the foreseeable future—benefit from the reversal of the development–fertility relationship.

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1. Bryant, J. Theories of fertility decline and the evidence from development indicators. *Popul. Dev. Rev.* **33,** 101–127 (2007).
2. Lee, R. D. The demographic transition: three centuries of fundamental change. *J. Econ. Perspect.* **17,** 167–190 (2003).
3. Bongaarts, J. & Watkins, S. C. Social interactions and contemporary fertility transitions. *Popul. Dev. Rev.* **22,** 639–682 (1996).
4. Wilson, C. Fertility below replacement level. *Science* **304,** 207–209 (2004).
5. Lutz, W., Sanderson, W. & Scherbov, S. The coming acceleration of global population aging. *Nature* **451,** 716–719 (2008).
6. Lutz, W., O'Neill, B. C. & Scherbov, S. Europe's population at a turning point. *Science* **299,** 1991–1992 (2003).
7. Bongaarts, J. Demographic consequences of declining fertility. *Science* **282,** 419–420 (1998).
8. Kohler, H.-P., Billari, F. C. & Ortega, J. A. The emergence of lowest-low fertility in Europe during the 1990s. *Popul. Dev. Rev.* **28,** 641–681 (2002).
9. Butler, D. The fertility riddle. *Nature* **432,** 38–39 (2004).
10. Balter, M. The baby deficit. *Science* **312,** 1894–1897 (2006).
11. United Nations Development Programme. *Statistics of the Human Development Report* (UNDP Human Development Report Office) 〈http://hdr.undp.org/en/statistics/〉 (29 September 2008).
12. United Nations. *Replacement Migration: Is It a Solution to Declining and Ageing Populations?* (United Nations, 2000).
13. Wooldridge, J. M. *Econometric Analysis of Cross Section and Panel Data.* Ch. 10 (MIT Press, 2002).
14. Sobotka, T. Is lowest-low fertility in Europe explained by the postponement of childbearing? *Popul. Dev. Rev.* **30,** 195–220 (2004).
15. Bongaarts, J. & Feeney, G. On the quantum and tempo of fertility. *Popul. Dev. Rev.* **24,** 271–291 (1998).
16. Brewster, K. L. & Rindfuss, R. R. Fertility and women's employment in industrialized nations. *Annu. Rev. Sociol.* **26,** 271–296 (2000).
17. McDonald, P. Gender equity in theories of fertility transition. *Popul. Dev. Rev.* **26,** 427–440 (2000).
18. Neyer, G. & Andersson, G. Consequences of family policies on childbearing behavior: effects or artifacts? *Popul. Dev. Rev.* **34,** 699–724 (2008).
19. Billari, F. C. & Kohler, H.-P. Patterns of low and lowest-low fertility in Europe. *Popul. Stud.* **58,** 161–176 (2004).
20. Suzuki, T. Lowest-low fertility in Korea and Japan. *J. Popul. Probl.* **59,** 1–16 (2003).
21. Lutz, W., Sanderson, W. & Scherbov, S. The end of world population growth. *Nature* **412,** 543–545 (2001).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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