Advances in Development Reverse Fertility Declines

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During the 20th century, the global population has witnessed unprecedented increases in economic and social development that coincided with substantial declines in human fertility levels and population growth rates (*1, 2*). More than half of the global population now lives in regions with below-replacement fertility (less than 2.1 children per woman) (*3*). In many highly developed countries, the trend towards fertility decline has been so far-reaching that it has been deemed irreversible (*4–7*). Indeed, of the 25 most advanced countries as measured by the 2005 human development index (HDI), a development indicator published by the United Nations Development Programme (UNDP) that combines health, wealth and knowledge to a single index (*8*), only one country has a total fertility rate (TFR, measuring the number of children per woman) above replacement level; four countries have TFR below 1.3, five have TFR between 1.3 and 1.5, and 15 have TFR between 1.5 and 2.1 (supplemental materials). In many highly developed countries, rapid population aging as a result of these very low fertility levels, and in some cases, the prospect of significant population declines, have become a central socioeconomic and policy challenge (*9*). Numerous studies point to the fact that the causes of low fertility are rooted in economic and social development: increased income, lower mortality and higher life expectancy, higher education, higher levels of female labor force participation, greater gender equality, and access to advanced birth control methods have all been identified as driving forces of reduced fertility (*2, 10*). 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, 2, 9, 11*).

Using new cross-sectional and longitudinal analyses of the relationship between total fertility rate and the human development index, we document that the well-established negative relationship between fertility and development is reversing as the global population enters the 21st century. While development continues to promote fertility declines at low and medium levels of HDI, at advanced HDI levels further development can *reverse* the declining trend in fertility. The previously negative development–fertility relationship has therefore become J-shaped, with 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 aging, ameliorating the social and economic problems that have been associated with the emergence and persistence of very low fertility.

Figure 1 shows the cross-country association between TFR and HDI in 1975 and 2005. In both years, the association is negative for HDI levels below the range 0.85–0.9. As countries progressed to very advanced levels of development ($\mathrm{HDI} > 0.9$), however, the HDI–fertility relationship started to fundamentally change: at HDI levels above 0.9, as is shown in Figure 1 for 2005, the HDI–fertility association reverses to a *positive* relationship where higher levels of HDI are associated with higher levels of fertility. A HDI of 0.9, which marks the approximate turning point, corresponds roughly to 75 years of life expectancy, a GDP per capita of US$25,000 in year 2000 purchasing power parity, and a 0.95 education index, which is a weighted sum of literacy rate and primary, secondary and tertiary level gross enrollment ratios. The 2005 TFR levels for countries with HDI between 0.9 and 0.92 is on average 1.24; in contrast, the average TFR is 1.89 in countries at the highest levels of development ($\mathrm{HDI} > 0.95$). These differential fertility levels at intermediate and very advanced development stages have strikingly different long-term implications: the former, if prevailing in the long term in the absence of migration, implies a *halving*

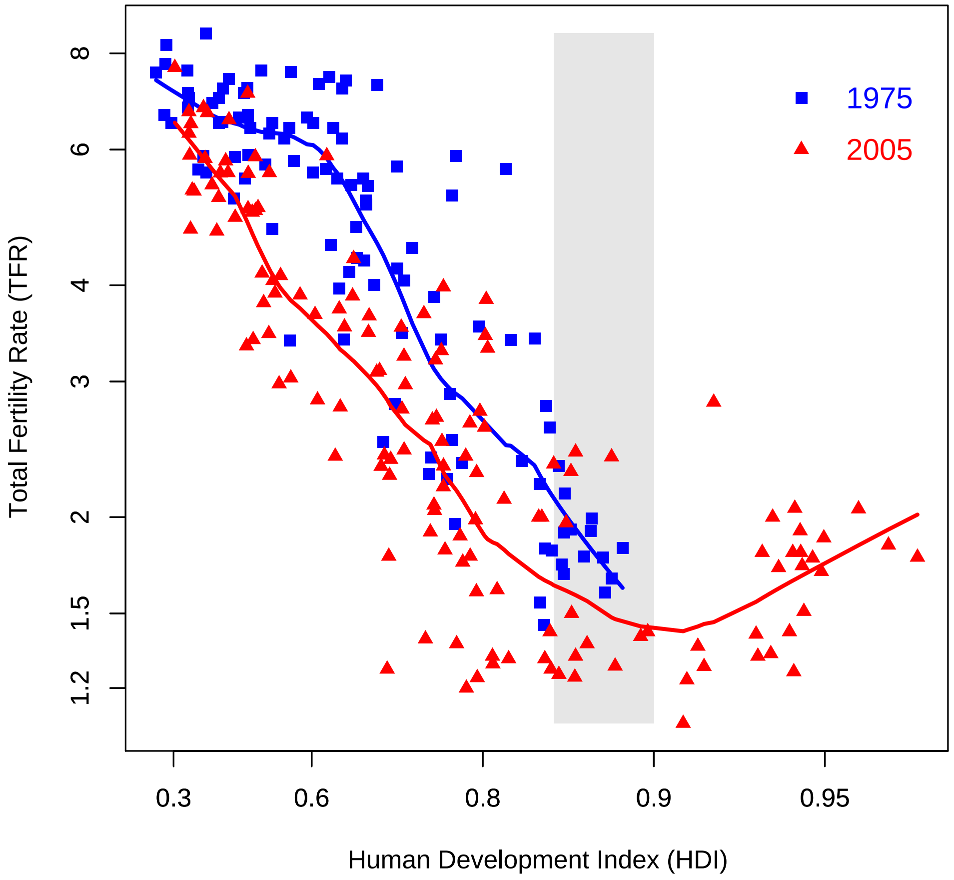

Figure 1: Cross-sectional relationship between the total fertility rate (TFR) and the human development index (HDI) in 1975 and 2005

Notes: 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. Spearman rank-correlation between HDI and TFR in 1975 is -0.85 ($p < 0.01$); Spearman 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. See supplemental materials for further details. 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), Netherlands (0.945), Finland (0.945), France (0.945), United States (0.944), Japan (0.943), Denmark (0.943), Switzerland (0.942), Belgium (0.94), New Zealand (0.938), Spain (0.938), United Kingdom (0.936), Italy (0.934), Austria (0.934), Israel (0.922), Greece (0.918), Germany (0.916), Slovenia (0.913), S. Korea (0.911). Data source: (*12*).

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 (*13*).

Figure 2 complements the cross-sectional analysis with a longitudinal perspective that focuses on the within-country trajectories of fertility and HDI. Only such longitudinal analysis can warrant a causal interpretation of the effect of HDI increases on fertility. Figure 2 includes all countries that have attained a HDI level of least 0.9 by year 2005 and for which longitudinal data from 1975 to 2005 are available (24 countries; see also supplemental materials). 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 first year in which this lowest TFR is observed is denoted *reference year*. The figure then draws a line connecting the HDI–TFR combinations for 1975, the reference year, and 2005. For four countries that we select as representative—Japan, the Netherlands, Norway and the United States—Figure 2 shows the full path of the HDI–TFR changes during 1975–2005.

Our hypothesis that the fertility–HDI relationship reverses within the HDI window of 0.85–0.9 implies that the longitudinal country-trajectories in Figure 2 should be J-shaped, beginning in the top-left quadrant, passing through the circle that marks the reference year, and ending in the in the top right quadrant where both the fertility and development index are higher than in the reference year. While there are clear exceptions, as for instance Japan, the trajectories for the large majority of countries (18 out of 24, representing 74% of the population in the 24 countries included in Figure 2) are in accordance with our hypothesis: as development has continued and countries have attained an advanced HDI level of 0.9 or higher, the trend in the total fertility rate has reversed. As a result, fertility in 2005 is higher than the minimum that was observed while a country's HDI was within the 0.85–0.9 interval. This reversal of the fertility decline can occur with different combinations of the three components that enter the HDI. For example, the U.S. fertility reversed in 1976 (=reference year) at an HDI of 0.881 (GDP/capita US$20,670, life expectancy 72.9 years, education index 0.95); the reversal in Norway occurred in 1983 at a HDI of 0.892 (GDP/capita US$21,239, life expectancy 76.1 years, education index 0.93); in Italy, the turning point occurred in 1994 at an HDI of 0.898 (GDP/capita US$22,965, life expectancy 77.7 years, education index 0.92), and in

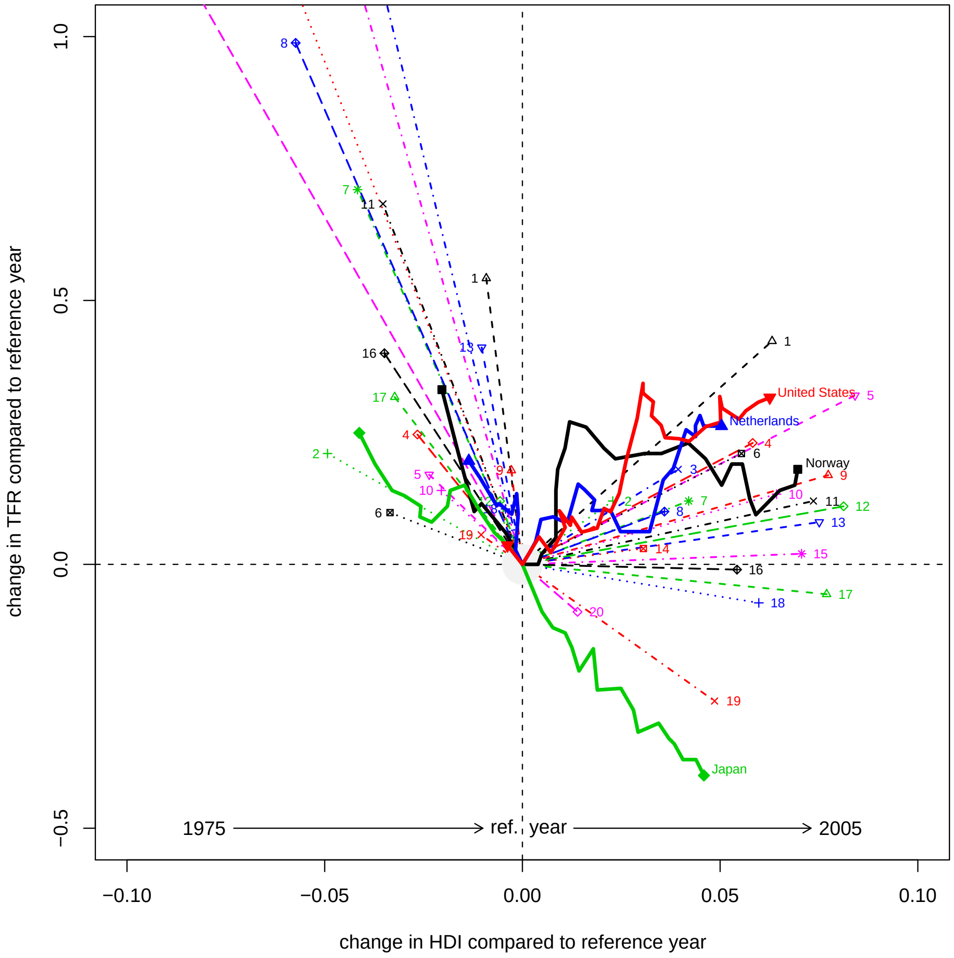

Figure 2: Within-country time-path of the HDI–TFR for all countries that attained a HDI ≥ 0.9 by 2005.
The figure depicts the difference between the TFR in 1975 and 2005 to the lowest TFR that was observed while a country's HDI was within the window 0.85–0.9. The (first) year in which this TFR is observed is denoted as the reference year. For four particularly interesting and relevant countries, the United States, Norway, The Netherlands and Japan, the graph shows the full path of the HDI–TFR development during the period 1975 to 2005. The figure includes all countries that attained a 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 2005 TFR in 2005 is higher than the TFR in the reference year.
Notes: Countries ending in top right quadrant in 2005: Norway, Netherlands, United States, (1) Denmark, (2) Germany, (3) Spain, (4) Belgium, (5) Luxembourg, (6) Finland, (7) Israel, (8) Italy, (9) Sweden, (10) France, (11) Iceland, (12) United Kingdom, (13) New Zealand, (14) Greece, (15) Ireland, Countries ending in bottom-right quadrant in 2005: Japan, (16) Austria, (17) Australia, (18) Switzerland, (19) Canada, (20) S. Korea. *Data source:* (*12*). See supplemental materials for further analyses.

Israel, the reversal in TFR decline occurred in 1992 at a HDI of 0.880 (GDP/capita US$18,812, life expectancy 76.5 years, education index 0.91).

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 supplemental material). The estimation uses panel data covering the years 1975 to 2005 for 37 countries which had reached the HDI level 0.85 by 2005 and controls for unobserved country characteristics and time trends. Specifically, our statistical model is a difference-in-differences model with time fixed-effects (*14*) and a structural change in the HDI⇒fertility relationship at a critical HDI level that is estimated from the data. This specification allows us to test whether the reversal in the HDI⇒fertility relationship documented in Figure 2 persists after controlling for potentially confounding factors such as unobserved time-invariant country-specific factors and common time trends.

The regression analyses identify that the critical level at which development⇒ fertility association reverses in the longitudinal data occurs at an HDI level 0.86 (supplemental material). Our estimates, based on 37 countries and 1,051 observations, suggest that the effect of HDI increases on fertility levels is equal to -1.59 for HDI levels below 0.86 ($p < 0.05$). 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. That is, on average across the 37 countries included in the analysis, a 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, a HDI increase of 0.05 results in an *increase* of the TFR by 0.204 ($= 0.5 \times 4.07$) once countries attain a development level characterized by HDI at least 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 Figure 2. For example, once the United States, the Netherlands and Norway had attained their lowest TFR level within the HDI range of 0.85–0.9, further increases in HDI by 0.05 were associated with, on average, TFR increases of 0.25 (USA), 0.26 (NL) and 0.13 (N). For all countries ending in the top-right quadrant of Figure 1, TFR increased on average by 0.16 per 0.05 increase in HDI after the reference year.

Our finding that the HDI⇒fertility relationship reverses near a HDI level of 0.85–0.9 in longitudinal within-country analyses is robust to alternative specifications of the statistical model, and this finding is not influenced by single data points or countries (supplemental materials). Additional analyses also document that the conclusions about a reversal of the HDI⇒fertility relationship are robust even when the total fertility rate is adjusted for "tempo effects" (*6*), that is, the distortions that occur in the TFR as a result of postponement in childbearing (supplemental material).

The finding that advances in development have the potential to reverse fertility declines has important implications in at least in two domains. First, further research is called into action to investigate the mechanisms that underlie the reversal of the fertility–development relationship, in particular in light of exceptions such as Japan and Korea, where HDI increases to very advanced levels have been associated with continued fertility decline. As recent theories of fertility highlight the relevance of cultural and institutional settings (*15, 16*), an improved understanding of the institutional pre-conditions that facilitate the reversal of fertility trends at advanced development stages is needed. For instance, analyses on Europe show that nowadays a positive relationship is observed between fertility and indicators of innovation in family behavior or female labor force participation (*17*). Also, at advanced levels of development, governments might explicitly address fertility decline by implementing policies that improve the compatibility between economic success, including labor force participation, and family life (*9*). Failure to answer to the challenges of development with institutions that facilitate work-family balance might explain the exceptional pattern for rich eastern Asian countries that are continue to be characterized by a negative HDI–fertility relationship.

Second, our findings are highly relevant in the debate on the future of world's population. While a decade ago Europe, North America and Japan were assumed to face very rapid population aging and in many cases significant population declines (*5, 6, 18*), our findings provide a different outlook for the 21^{st} Century. As long as the most developed countries focus on increasing the well-being of their citizens, and adequate institutions are in place, increases in development are likely to reverse fertility declines—even if we cannot expect fertility to raise again above the replacement threshold. As a consequence, we expect countries at the highest development levels to face a relatively stable population size, if not an increase in total population in cases where immigration is substantial. For countries in which immigration is a minor component of demographic change, our analyses suggest slower population decline than is currently foreseen in official demographic forecasts. Moreover, while significant population aging 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 further fall. More specifically, our findings reduce, if not yet completely reject, fears of population decline that have been incorporated in many national population forecasts for highly advanced countries. Nevertheless, we expect countries lagging behind in terms of development to continue their fertility decline, consistently with current scientific knowledge. Moreover, some countries at intermediate development levels are likely to face a decline in population size because these countries do not yet—and may not in the foreseeable future—benefit from the reversal of the development–fertility relationship that has occurred at advanced HDI levels.

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Supplemental Materials for Myrskylä *et al.*'s "Advances in Development Reverse Fertility Declines"

The supplemental materials to "Advances in Development Reverse Fertility Declines" document in more detail the data and statistical methods that support Myrskylä *et al.*'s finding of a reversal of the HDI–TFR relationship at intermediate development stages with HDI levels around 0.85–0.9. The supplemental materials also provide various robustness tests indicating that the key findings are not sensitive to (*i*) specific countries, data points or outliers, (*ii*) the introduction of time-lags in the HDI⇒fertility relationship, and (*iii*) the inclusion of "tempo-adjustments" that correct the total fertility rate for distortions caused by the postponement of childbearing (*19*).

Data

The human development index (HDI) and the total fertility rate (TFR) are widely used measures of, respectively, a country's development stage and fertility level. 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. In particular, the HDI combines three dimensions of socioeconomic progress into a single index (*8*), combining for each calendar year with equal weight a country's (*i*) *health conditions*, as measured by annual life expectancy at birth, (*ii*) *standard of living*, as measured by the logarithm of the annual gross domestic product (GDP) per capita at purchasing power parity (PPP) in US dollars, and (*iii*) *human capital*, as measured by average of the annual adult literacy rate (with two-thirds weight) and the combined primary, secondary, and tertiary gross enrollment ratio (with one-third weight). Since 1999, the HDI is calculated using a consistent formula that not only ranks countries in terms of their development level, but also provides an intertemporal comparison of HDI trends over time. In particular, in calculating the HDI, each dimension of the HDI is first standardized to the unit interval using

$$x_t^{standardized} = \frac{x_t - x^{min}}{x^{max} - x^{min}} \tag{S.1}$$

where x_t is the HDI measure for either health conditions, standard of living or human capital in year t, and x^{min} and x^{max} are time-invariant scaling values for each HDI dimension (for health conditions: $x^{min} = 25$ and $x^{max} = 85$; for standard of living: $x^{min} = \ln(100)$ and $x^{max} = \ln(40,000)$; and for human capital: $x^{min} = 0$ and $x^{max} = 100$). The HDI for year t is then obtained by averaging, with equal weight, across the standardized HDI measures, $x_t^{standardized}$, for health conditions, standard of living or human capital in year t. Because, contrary to UNDP's pre-1999 tradition, the scaling values x^{min} and x^{max} are now time-invariant, the human development index obtained via Eq. (S.1) is comparable over time within each country. This longitudinal consistency of the human development index therefore enables our analyses to identify if and how within-country changes in development levels during 1975–2005 causally affect trends in the total fertility rate during this period.

UNDP does not publish an annual HDI time-series that is based on the current method for calculating the index (see Eq. S.1). Published HDI values based on this method are only available for the years 1975, 1980, 1985, 1990, 1995, 2000 and 2005 (*8*). To create an annual HDI time-series for the period 1975–2005 for as many countries as possible, we have obtained the individual measures underlying the HDI—that is, life-expectancy for health conditions, GDP per capita for living standards, and literacy rates and enrollment ratios for human capital—from the World Bank World Development Indicators Online Database (*12*). The HDI used for our analyses was then calculated using Eq. (S.1) based on World Bank World Development Indicators data for life-expectancy, GDP per capita, literacy rates and school enrollment ratios. Time-series for the TFR were also retrieved from the same source (*12*).

The World Bank World Development Indicators data for 1975–2005 are almost complete for the total fertility rate (TFR), life expectancy, and gross domestic product (GDP) per capita at purchasing power parity. The data on literacy rates and school enrollment ratios are often missing for early time periods, particularly in developing countries at low HDI levels.

GDP per capita and life expectancy jointly account for two thirds of the HDI, and these two dimensions account for an even larger fraction of the year-to-year variation in the HDI because literacy rates and enrollment ratios are not subject to large short-term fluctuation. The relative completeness of the time-series data for these variables is fortunate, and it contributes to a high quality of the cross-sectional and longitudinal HDI data. In the few cases where a country's data on life expectancy includes gaps, we used linear interpolation to impute missing values. Because life-expectancy generally evolves gradually, a linear interpolation of life-expectancy data is unlikely to distort our analyses. Linear interpolation was also used to impute missing values for enrollment ratios and literacy rates. School enrollment ratios and literacy rates also evolve slowly because they are primarily cohort driven, and linear interpolation of missing data is therefore relatively innocuous in terms of data quality. Because GDP per capita and TFR are subject to large annual fluctuations, no imputations were conducted for these variables to fill in missing data. For calendar years in which a country's GPD per capital or TFR was missing, no HDI value was calculated. These missing data problems, however, occur primarily early in the 1975–2005 period that is used for our analyses, and are concentrated among developing countries with relatively low HDI levels. Our analyses focusing on the reversal of the HDI–TFR relationship at very advanced development stages are thus unlikely to be substantively affected by missing data in the HDI and TFR time-series.

The list of countries included in our analyses, and the years for which HDI data are available for each country, is reported in Table S.1. In 2005, the data is available for 140 countries, and in 1975 for 107 countries. In all of our analyses, sovereign and non-sovereign city-states such as Hong Kong, Macao, Monaco and Singapore are excluded because their predominantly urban status implies peculiar population dynamics when compared to nations that have a more balanced rural-urban composition. A complete 1975–2005 HDI and TFR time-series is available for all advanced countries with a 2005 HDI $\geq$ .90, with the exception of Slovenia for which only post-1990 data are available. Among the countries with a 2005 HDI $\geq$ .85 the data is complete for 32 out of 37 countries (Table S.1).

Comparisons between the published UNDP HDI values (only available for the years 1975, 1980, . . . , 2000, 2005) and the HDI values used for our analyses reveal a very close correspondence between these two measures, with a correlation of 0.99 or higher for all years. Our analyses are therefore unlikely to be affected by any remaining small differences between our calculations of HDI values based on World Bank database (*12*) and the published UNDP HDI values (*8*).

Table S.1: List of countries, and years for which HDI and TFR time-series are available (sorted descending by 2005 HDI)

Country	HDI 2005	TFR 2005	Time-series years	Country	HDI 2005	TFR 2005	Time-series years	Country	HDI 2005	TFR 2005	Time-series years	Country	HDI 2005	TFR 2005	Time-series years
Australia	0.966	1.77	1975–2005	Slovak Rep.	0.853	1.25	1984–2005	Tunisia	0.757	2.04	1975–2005	Congo, Rep.	0.525	5.60	1975–2005
Norway	0.961	1.84	1975–2005	Bahrain	0.849	2.34	1975–2005	Iran	0.756	2.07	1975–2005	Nepal	0.524	3.46	1975–2005
Iceland	0.956	2.05	1975–2005	Croatia	0.848	1.42	1990–2005	Ecuador	0.755	2.67	1975–2005	P. N. Guinea	0.514	3.80	1975–2005
Ireland	0.950	1.88	1975–2005	Lithuania	0.848	1.27	1990–2005	Sri Lanka	0.753	1.91	1975–2005	Sudan	0.511	4.15	1975–2005
Luxembourg	0.949	1.70	1975–2005	Latvia	0.844	1.31	1975–2005	Georgia	0.748	1.39	1975–2005	Madagascar	0.503	5.04	1975–2005
Sweden	0.947	1.77	1975–2005	Uruguay	0.843	2.00	1975–2005	Paraguay	0.746	3.67	1975–2005	Cameroon	0.498	5.00	1975–2005
Canada	0.946	1.51	1975–2005	Costa Rica	0.841	2.00	1975–2005	Belize	0.726	2.97	1975–2005	Yemen	0.497	5.87	1990–2005
Finland	0.945	1.80	1975–2005	Bulgaria	0.820	1.31	1980–2005	Algeria	0.725	2.44	1975–2005	Lesotho	0.493	3.40	1975–2005
France	0.945	1.92	1975–2005	Mexico	0.817	2.11	1975–2005	Syria	0.725	3.24	1975–2005	Kenya	0.491	4.98	1975–2005
Netherlands	0.945	1.73	1975–2005	Trinidad	0.811	1.61	1975–2005	El Salvador	0.723	2.76	1975–2005	Mauritania	0.483	5.59	1975–2005
USA	0.944	2.05	1975–2005	Romania	0.808	1.32	1980–2005	Cape Verde	0.722	3.53	1981–2005	Togo	0.482	5.03	1975–2005
Denmark	0.943	1.80	1975–2005	Russia	0.808	1.29	1989–2005	Jamaica	0.710	2.38	1975–2005	Uganda	0.482	7.10	1982–2005
Japan	0.943	1.26	1975–2005	Tonga	0.804	3.31	1981–2005	Indonesia	0.708	2.27	1975–2005	Zimbabwe	0.479	3.34	1975–2005
Switzerland	0.942	1.42	1975–2005	Saudi Arabia	0.803	3.83	1975–2005	Vietnam	0.707	1.78	1984–2005	Senegal	0.455	4.90	1975–2005
Belgium	0.940	1.72	1975–2005	Oman	0.802	3.44	1975–2005	Moldova	0.705	1.27	1980–2005	Angola	0.441	6.56	1975–2005
N. Zealand	0.938	2.00	1975–2005	Panama	0.801	2.62	1975–2005	Kyrgyz Rep.	0.702	2.41	1986–2005	Guinea	0.439	5.60	1979–2005
Spain	0.938	1.33	1975–2005	Malaysia	0.798	2.74	1975–2005	Mongolia	0.698	2.33	1996–2005	Rwanda	0.433	5.80	1975–2005
UK	0.936	1.80	1975–2005	Belarus	0.796	1.24	1990–2005	Egypt	0.696	3.10	1975–2005	Benin	0.421	5.60	1975–2005
Austria	0.934	1.41	1975–2005	Brazil	0.795	2.29	1975–2005	Nicaragua	0.693	3.08	1975–2005	Tanzania	0.417	5.20	1988–2005
Italy	0.934	1.32	1975–2005	Macedonia	0.795	1.60	1990–2005	Bolivia	0.683	3.65	1975–2005	Cote d'Ivoire	0.412	4.70	1975–2005
Israel	0.922	2.82	1975–2005	Mauritius	0.794	1.98	1980–2005	Honduras	0.682	3.47	1975–2005	Zambia	0.401	5.40	1975–2005
Greece	0.918	1.28	1975–2005	Albania	0.790	1.78	1980–2005	Guatemala	0.662	4.33	1975–2005	Congo, DR	0.389	6.70	1975–2005
Germany	0.916	1.36	1975–2005	Venezuela	0.789	2.65	1975–2005	Vanuatu	0.661	3.87	1979–2005	Malawi	0.384	5.84	1975–2005
Slovenia	0.913	1.23	1990–2005	Colombia	0.786	2.40	1975–2005	Tajikistan	0.650	3.53	1985–2005	Burundi	0.380	6.80	1975–2005
S. Korea	0.911	1.08	1975–2005	Ukraine	0.786	1.20	1987–2005	South Africa	0.644	2.78	1975–2005	Mozambique	0.356	5.30	1980–2005
Cyprus	0.897	1.42	1975–2005	Kazakhstan	0.783	1.75	1990–2005	Gabon	0.642	3.73	1975–2005	Ethiopia	0.351	5.32	1981–2005
Portugal	0.895	1.40	1975–2005	Thailand	0.781	1.89	1975–2005	Morocco	0.636	2.40	1975–2005	Sierra Leone	0.347	6.48	1975–2005
Czech Rep.	0.883	1.28	1990–2005	Armenia	0.778	1.37	1975–2005	Eq. Guinea	0.624	5.89	1985–2005	C. African Rep.	0.346	4.73	1975–2005
Kuwait	0.881	2.39	1975–2005	China	0.767	1.81	1975–2005	India	0.609	2.84	1975–2005	Burkina Faso	0.344	5.90	1975–2005
Malta	0.869	1.37	1975–2005	Azerbaijan	0.766	2.33	1990–2005	Namibia	0.605	3.66	1980–2005	Chad	0.342	6.30	1975–2005
Hungary	0.863	1.32	1975–2005	Samoa	0.765	3.98	1982–2005	Cambodia	0.581	3.89	1993–2005	Mali	0.342	6.72	1975–2005
UAE	0.863	2.43	1975–2005	Turkey	0.765	2.19	1975–2005	Botswana	0.565	3.03	1975–2005	Niger	0.304	7.67	1975–2005
Poland	0.862	1.24	1990–2005	Suriname	0.764	2.51	1975–2005	Pakistan	0.546	4.12	1975–2005				
Argentina	0.860	2.29	1975–2005	Jordan	0.763	3.29	1975–2005	Bangladesh	0.544	2.98	1975–2005				
Estonia	0.860	1.50	1980–2005	Peru	0.759	2.70	1975–2005	Swaziland	0.536	3.91	1975–2005				
Chile	0.857	1.97	1975–2005	Philippines	0.758	3.20	1975–2005	Ghana	0.532	4.06	1975–2005				

Note: Time-series years is the period for which a complete HDI and TFR time-series is available for the longitudinal analyses.

In our graphical analyses in Figure 1, HDI and TFR values are rescaled. This rescaling is implemented so that the graphical representation in Figure 1 particularly reflects HDI differences at intermediate and advanced levels of development, and the distance between different TFR levels is proportional to the different long-term population growth rates implied by the respective TFR levels. Specifically, rescaled values are obtained using $\text{HDI}^* = -\log(1 - \text{HDI})$ and $\text{TFR}^* = \log(.4886 \cdot \text{TFR})/\mu$, where $\mu = 31$ approximately equal to the mean age at childbearing in developed countries.

Table S.2 reports the list of countries that are used for the longitudinal analyses in Figure 2, along with their HDI and TFR levels in 1975, the reference year and 2005.

Longitudinal Analyses: Statistical Model and Estimation

The graphical analyses in Figures 1 and 2 suggest that the HDI–TFR relationship reverses from negative (increases in HDI are associated with *lower* TFR) to positive (increases in HDI are associated with *higher* TFR) at an intermediate HDI level in the range 0.85–0.9. We augment this graphical result with a statistical model for the effect of HDI increases on fertility change in order to (*i*) estimate the critical level HDI^{crit} at which the HDI–TFR relationship reverses in the longitudinal data, and (*ii*) ascertain the causal interpretation of our results as a reversal in the HDI⇒fertility relationship.

The starting point of our statistical model linking development to fertility is the relationship

$$\text{TFR}_{it} = (\beta_0^{pre} + \beta_1^{pre} \cdot \text{HDI}_{it}) \cdot B_{it}^{pre} + (\beta_0^{post} + \beta_1^{post} \cdot \text{HDI}_{it}) \cdot B_{it}^{post} + \varepsilon_{it}, \qquad \text{(S.2)}$$

where TFR_{it} and HDI_{it} are the TFR and HDI for country i in year t. The terms B_{it}^{pre} and B_{it}^{post} are indicator variables for whether country i's HDI level is below or above the critical HDI level, HDI^{crit}, at which the HDI⇒TFR relationship is hypothesized to reverse. B_{it}^{pre} and B_{it}^{post} change their value, respectively, from 1 to 0 and from 0 to 1 as country i's HDI level increases above the critical level HDI^{crit}. The coefficients β_1^{pre} and β_1^{post} are, respectively, the effects of development (as measured by the HDI) on the total fertility rate at HDI levels below and above the critical level HDI^{crit}. The residual ε_{it} is defined as $\varepsilon_{it} = \eta_i + \gamma_t + v_{it}$, where η_i and γ_t are respectively country-

Table S.2: Data used for longitudinal analyses in Figure 2

		1975		**Reference Year**			**2005**	
Country	Label	HDI	TFR	Year	HDI	TFR	HDI	TFR
Countries ending in the top right quadrant of Fig. 2 in 2005								
Norway		0.871	1.99	1983	0.892	1.66	0.961	1.84
Netherlands		0.881	1.66	1983	0.895	1.47	0.945	1.73
United States		0.877	1.77	1976	0.881	1.74	0.944	2.05
Denmark	(1)	0.871	1.92	1983	0.880	1.38	0.943	1.80
Germany	(2)	0.844	1.45	1994	0.893	1.24	0.916	1.36
Spain	(3)	0.845	2.79	1996	0.898	1.15	0.938	1.33
Belgium	(4)	0.855	1.74	1985	0.881	1.49	0.94	1.72
Luxembourg	(5)	0.842	1.55	1985	0.865	1.38	0.949	1.70
Finland	(6)	0.856	1.69	1987	0.889	1.59	0.945	1.80
Israel	(7)	0.838	3.41	1992	0.880	2.70	0.922	2.82
Italy	(8)	0.841	2.21	1994	0.898	1.22	0.934	1.32
Sweden	(9)	0.867	1.78	1978	0.870	1.60	0.947	1.77
France	(10)	0.860	1.93	1983	0.880	1.79	0.945	1.92
Iceland	(11)	0.848	2.61	1985	0.883	1.93	0.956	2.05
United Kingdom	(12)	0.849	1.81	1977	0.854	1.69	0.936	1.80
New Zealand	(13)	0.853	2.33	1983	0.863	1.92	0.938	2.00
Greece	(14)	0.829	2.37	2001	0.888	1.25	0.918	1.28
Ireland	(15)	0.821	3.4	1994	0.879	1.86	0.95	1.88
Countries ending in the bottom right quadrant of Fig. 2 in 2005								
Japan		0.856	1.91	1988	0.897	1.66	0.943	1.26
Austria	(16)	0.845	1.82	1987	0.880	1.42	0.934	1.41
Australia	(17)	0.856	2.15	1988	0.889	1.83	0.966	1.77
Switzerland	(18)	0.878	1.60	1978	0.883	1.49	0.942	1.42
Canada	(19)	0.887	1.82	1978	0.897	1.77	0.946	1.51
S. Korea	(20)	0.723	3.47	2002	0.897	1.17	0.911	1.08

Notes: Reference year is the year in which a country attains its lowest TFR level within the HDI range .85–.9.

and time-specific parameters (fixed effects), and v_{it} is a normally-distributed residual with zero mean and constant unknown variance. The inclusion of country and time fixed-effects controls for unobserved time-invariant country-specific factors and common time trends that may affect TFR and HDI trends across and within countries.

Preliminary analyses indicated that the residual v_{it} has a unit root: estimated autocorrelation parameter was 0.99, and also the Woolridge (*14*) and Baltagi-Wu LBI (*20*) tests suggested that the residual exhibits a unit-root. To adequately adjust for this unit-root process in the residual, therefore, our final and preferred analyses are based on the differences-in-differences model (*14*) that is obtained by differencing TFR and HDI trends in Eq. (S.2) over time:

$$\Delta \mathrm{TFR}_{it} = \beta_0 \Delta B_{it}^{post} + \beta_1^{pre} \Delta \mathrm{HDI}_{it}^{pre} + \beta_1^{post} \Delta \mathrm{HDI}_{it}^{post} + \Delta \gamma_t + \Delta v_{it}, \qquad \text{(S.3)}$$

where Δ is the difference operator with $\Delta x_t = x_t - x_{t-1}$; β_0 estimates the effect of an indicator for the year when country i crossed the critical level HDI^{crit} (ΔB_{it}^{post} is 1 for the critical year, 0 otherwise); $\Delta \mathrm{HDI}_{it}^{pre} = B_{it}^{pre} \Delta \mathrm{HDI}_{it}$; and $\Delta \mathrm{HDI}_{it}^{post} = B_{it}^{post} \Delta \mathrm{HDI}_{it}$. The coefficients β_1^{pre} and β_1^{post} continue to measure the effects of development (as measured by the HDI) on the total fertility rate at HDI levels below and at or above above the critical level HDI^{crit}. Differencing implicitly controls for the country fixed-effects γ_i and removes the unit root from the residual autocorrelation.

Our final and preferred specification in Eq. (S.3) therefore allows us to test whether whether the reversal in the HDI⇒fertility relationship documented in Figure 2 persists after controlling for potentially confounding factors such as unobserved time-invariant country-specific factors and common time trends. In particular, the hypothesis of a reversal of the HDI⇒fertility relationship at HDI^{crit} implies that $\beta_1^{pre} < 0$ and $\beta_1^{post} > 0$.

The first step in testing this hypothesis is the estimation of HDI^{crit} via an iterative search process, using all countries that attained a development level of HDI ≥ 0.85 by 2005. The exclusion of countries with a 2005 HDI of less than 0.85 is appropriate as our preliminary analyses (Figures 1–2) suggest that HDI^{crit} is within the range of 0.85–0.9. The statistically optimal value for HDI^{crit} is then estimated by including HDI^{crit} as a parameter in the maximum likelihood function of Eq. (S.3), and then using a two-stage grid-search algorithm that in first stage varies the value HDI^{crit} from .800, .835, .840, . . . , .910, and in the second stage refines the search with a step size of .0001 in the neighborhood of the best-fitting first-stage HDI^{crit} value. The estimated log likelihood for Eq. (S.3) in the range 0.80–0.910 is shown in Figure S.3. The likelihood in Figure S.3 is maximized when HDI is at 0.8598, or approximately 0.86. We therefore use 0.86 as our preferred value for HDI^{crit} in our final estimation of Eq. (S.3).

Table S.3 shows the estimated parameters $\hat{\beta}_1^{pre}$ and $\hat{\beta}_1^{post}$ for our statistical model of the HDI⇒fertility relationship (Eq. S.3). Model M.1 in Table S.3 reports our preferred estimates that are based on the differences-in-differences relationship in Eq. (S.3) for all countries with HDI $\geq$ 0.85 in 2005, controlling explicitly time

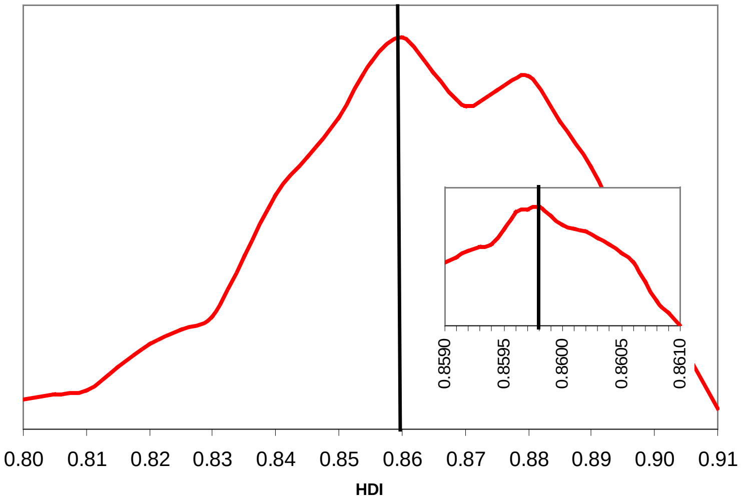

Figure S.3: Shape of the estimated log likelihood function for Model (S.3) with respect to the threshold HDI^{crit} at which the HDI⇒fertility relationship is hypothesized to reverse from negative to positive. Estimation includes all countries with a HDI ≥ 0.85 in 2005.

fixed-effects and implicitly for country fixed-effects and unit-root autocorrelation. The most important conclusion obtained from these estimation results is the reversal in the effect of HDI on fertility, with the estimated coefficients changing from a statistically-significant *negative* value for $\hat{\beta}_1^{pre} = -1.59$ to a the statistically-significant *positive* values for $\hat{\beta}_1^{post} = 4.07$.

The coefficient of development for a pre-development level of 0.86, $\hat{\beta}_1^{pre} = -1.59$ is consistent with previous knowledge on the negative effect of development on fertility (*1,2,9,11*). The coefficient $\hat{\beta}_1^{post} = 4.07$ for the effect of development on fertility for HDI levels at or above 0.86 confirms that this relationship has been reversed as countries have attained advanced stages of development. Moreover, this statistical model confirms that this reversal not only occurs in the cross-sectional data (Figure 1), but also in longitudinal analyses of HDI and TFR changes within countries that control for unobserved time-invariant country-specific factors and common time trends that may affect TFR and HDI trends. The estimated coefficient of $\hat{\beta}_1^{post} = 4.07$ implies that, above a HDI level 0.86, a five point increase in human development index is linked, on average, to a $0.05 \times 4.07 = 0.204$ unit increase in the TFR. This increase in the TFR 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

Table S.3: Estimated effects for the HDI on TFR before and after a country reached a development level HDI = 0.86. The models are fixed effects difference-in-differences model with controls for time fixed effects and implicit controlling for country fixed effects and within-country autocorrelation.

Model	**Description**		**Coef.**	***p*-value**
(M.1)	**Preferred estimates: Differences-in-differences model (Eq. S.3)**			
	Data: all countries with HDI $\geq$ .85 in 2005 ($N = 37$ countries; 1,051 observations)	$\hat{\beta}_1^{pre}$	-1.59	0.042
		$\hat{\beta}_1^{post}$	4.07	< 0.001
(M.2)	**Differences-in-differences model with lagged HDI (Eq. S.4)**			
	Data: all countries with HDI $\geq$ .85 in 2005 ($N = 37$ countries; 1014 observations)	$\hat{\beta}_1^{pre}$	-1.07	0.177
		$\hat{\beta}_1^{post}$	4.17	< 0.001
(M.3)	**Differences-in-differences model (Eq. S.3), using the tempo-adjusted total fertility rate as dependent variable**			
	Data: all countries with HDI $\geq$ .85 in 2005 for which the tempo-adjusted TFR can be calculated ($N = 37$ countries; 1,051 observations)	$\hat{\beta}_1^{pre}$	-1.55	0.106
		$\hat{\beta}_1^{post}$	2.84	< 0.001
(M.4)	**Differences-in-differences model (Eq. S.3), with adjustment for changes in mean age of mothers at first birth**			
	Data: all countries with HDI $\geq$ .85 in 2005 for which data on mean age at childbearing is available ($N = 37$ countries; 1,051 observations)	$\hat{\beta}_1^{pre}$	-1.62	0.037
		$\hat{\beta}_1^{post}$	4.02	< 0.001

Figure 2. Our preferred estimates in Model M.1 of Table S.3 therefore strongly *support* our hypothesis that the empirical HDI⇒fertility relationship has changed from negative to positive as countries attained very advanced levels of development.

Robustness Tests

To assess the robustness of our preferred results (Model M.1 in Table S.3) with respect to possibly influential single data points or single countries, we have conducted extensive influence analyses using the leverage, Cook's D, and DFBETA statistics associated with each observation. No outliers or extraordinarily influential observations or countries were detected. For example, the largest value of Cook's D was less than 0.05, well below the often used critical values 1.00.

Re-estimating our preferred model (Model M.1 in Table S.3) using different values for HDI^{crit}, does not affect our conclusions. In particular, using the alternative values 0.85, 0.87, 0.88, 0.89 and 0.90 for HDI^{crit} in estimating the differences-in-differences model (Eq. S.3), continues to result in parameter estimates with $\hat{\beta}_1^{pre} < 0$ and $\hat{\beta}_1^{post} > 0$ that confirm our hypothesis. Hence, our conclusion about a reversal of the HDI⇒fertility relationship at intermediate development levels is not sensitive to other choices of HDI^{crit} within the range 0.85–0.9.

We have also explored the extent to which our preferred estimates depend on the set of countries on which the estimates are based. We did this by studying the influence of single countries on our preferred estimates by excluding one country at a time, and re-estimating the model Eq. (S.3). The results were robust. The coefficient $\hat{\beta}_1^{pre}$ was consistently negative with the estimates ranging from -1.28 to -3.33 with maximum p-value 0.103, and the coefficient $\hat{\beta}_1^{post}$ was consistently positive, estimates ranging from 3.27 to 5.05 with maximum p-value less than 0.001.

It is conceivable that changes in HDI affect fertility levels only with some lag, especially since it takes about one year to conceive and give birth to a child. We have therefore re-estimated the HDI⇒fertility relationship including lagged values of the human development index. Specifically, we have modified our preferred differences-in-differences model to include 1-year lagged values of the human development index, HDI_{t-1}, instead of HDI_t, and estimate the relationship

$$\Delta\text{TFR}_{it} = \beta_0 \Delta B_{it}^{post} + \beta_1^{pre} \Delta\text{HDI}_{i(t-1)}^{pre} + \beta_1^{post} \Delta\text{HDI}_{i(t-1)}^{post} + \Delta\gamma_t + \Delta v_{it}, \qquad \text{(S.4)}$$

where β_1^{pre} and β_1^{post} continue to measure the effects of development (as measured by the HDI_{t-1}) on the total fertility rate. The results of this lagged HDI⇒fertility relationship are reported in Table S.3 (Model M.2). Most importantly, this lagged model continues to yield a statistically-significant estimate of $\beta_1^{post} > 0$ that supports our conclusion that a positive HDI⇒fertility relationship exists at advanced stages of development. While the point-estimate for β_1^{pre} continues to be negative in this lagged relationship, it is no longer statistically significant. This loss of statistical significance is likely the result of the shorter time period that is available for these lagged analyses. Further analyses with 5-year and 10-year lagged values of the human development index also yield a positive and statistically-significant estimate for β_1^{post}, while the estimates for β_1^{pre} are not statistically different from zero, as before, most likely as a result of the shorter time-series that are available for these analyses.

Adjustment of Total Fertility Rate for "Tempo Effects"

The recent literature on low fertility in developed countries has pointed to the important role of delayed childbearing, that is, the ongoing postponement of childbearing to increasingly later ages (*7,19*). In the context of this paper, delayed childbearing is potentially important because the postponement of childbearing can distort the total fertility rate as a measure of the *quantum* (or long-term level) of fertility (*19*). "Tempo effects", or the reductions in the total fertility rate resulting from a postponement of childbearing, have been shown to partially explain the very low fertility rates observed in some European countries (*7,19*).

We use both a graphical and statistical modeling approach to evaluate the robustness of our key finding about the reversal of the HDI⇒fertility relationship at advanced development stages with respect to tempo effects. In particular, one could speculate that tempo effects might be—at least partially—responsible for the observed change in the development–fertility association. For example, countries at development levels near the critical level $\text{HDI}^{crit} = 0.86$ might have a more rapid postponement of childbearing than more advanced countries. If this were the case, tempo effects would reduce the TFR more strongly at intermediate than at advanced HDI levels, and the positive association between HDI and TFR in Figures 1– 2 could be partially explained by differences in the pace of fertility postponement, rather than by variation in levels among advanced countries.

Figure S.4 replicates our earlier cross-sectional analyses in Figure 1, including for 2005 additionally a tempo-adjusted TFR (*19*) for advanced countries where the postponement of childbearing is most relevant. Tempo-adjusted TFRs were available in 2005 for only 41 countries, including 28 of the 37 countries which had reached a development level of 0.85 by 2005. Most importantly, however, Figure S.4 shows that the reversal of the HDI–TFR relationship at advanced development stages persists even after adjusting the total fertility rate for tempo effects.

Time series of the tempo-adjusted TFR are not readily available from official publications. Using data on distribution of births by parity (first and second or higher order births) and mean age of mothers at respective parities we were able to construct comparable time-series of tempo-adjusted total fertility rates for 24 of 35 countries that attained a HDI above 0.86 in 2005. These data were obtained from Eurostat (Eurostat New Cronos Database [Online], accessed at http://ec.europa.eu/eurostat/ on Oct 5 2008). Frequently, however, the time series are not complete for the 1975–2005 period on which preferred longitudinal analyses are based. Acknowledging these data limitations, Model M.3 in Table S.3 reports the results obtained by re-estimating our preferred model (Eq. S.3) using as dependent variable the adjusted total fertility rate (*19*), instead of the standard TFR that was used in our earlier analyses. This estimation yields a statistically-significant positive value of $\hat{\beta}_1^{post} = 2.84$ (Model M.3 in Table S.3), which, albeit being of smaller magnitude than the coefficient obtained without tempo-adjustments, supports our hypothesis of a positive HDI⇒TFR relationship between development and fertility at advanced HDI levels. The estimate for HDI for levels below 0.86 is $\hat{\beta}_1^{pre}$ is -1.55 (Model M.3), and while being only marginally significant ($p = 0.106$) as a result of the limited data availability, this is consistent with our hypothesis of a reversal in the HDI⇒fertility relationship.

To further investigate the robustness of our finding with respect to possible tempo effects, we also considered direct adjustment to the underlying process that generates tempo effects by estimating a difference-in-differences model, similar to our preferred model in Eq. (S.3), with an additional control for changes in the timing of fertility:

$$\Delta \text{TFR}_{it} = \beta_0 \Delta B_{it}^{post} + \beta_1^{pre} \Delta \text{HDI}_{it}^{pre} + \beta_1^{post} \Delta \text{HDI}_{it}^{post} + \beta_2 \cdot \Delta \bar{A}_{it} + \Delta \gamma_t + \Delta v_{it}, \quad \text{(S.5)}$$

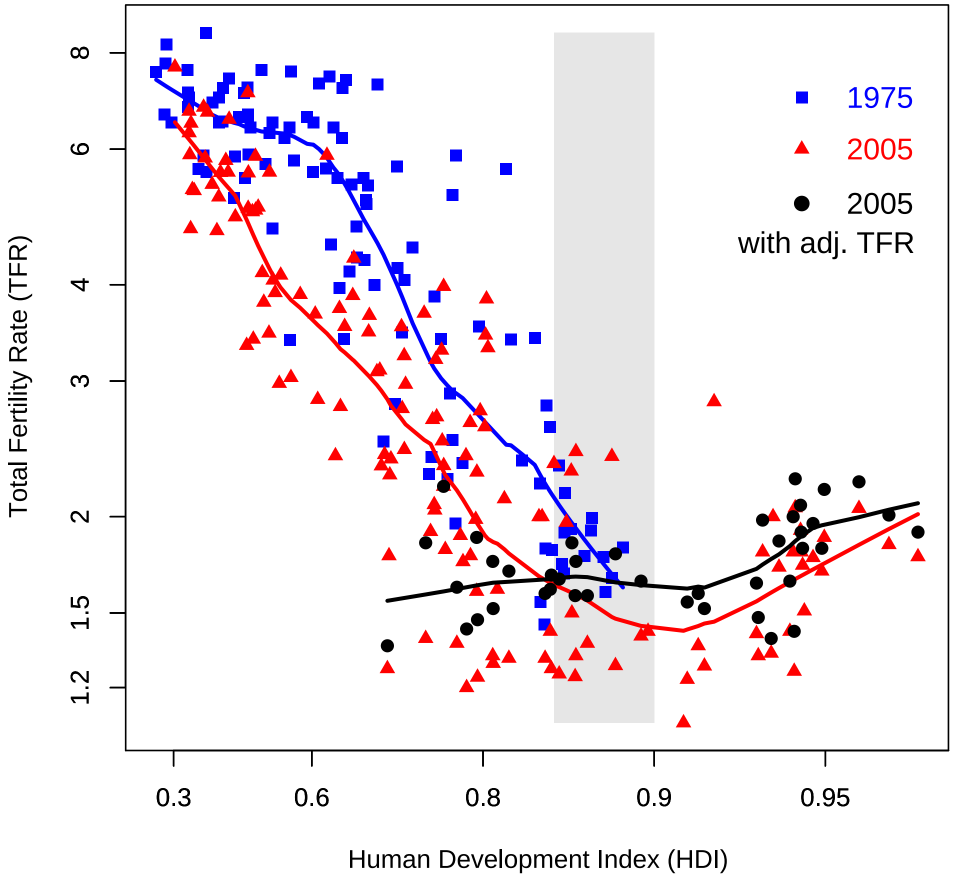

Figure S.4: Cross-sectional relationship between the total fertility rate (TFR), with and without adjustment for tempo effects, and the human development index (HDI) in 1975 and 2005

Notes: The 1975 and 2005 data for the HDI and (unadjusted) TFR are identical to Figure 1. Adjusted TFRs are available for 41 countries in 2005. The Spearman rank-correlation between HDI and the adjusted TFR in 2005 is .63 ($p < .01$) for countries with HDI $> .9$. Countries for which a 2005 adjusted TFR is available include (2005 HDI in parentheses): Australia (0.966), Norway (0.961), Iceland (0.956), Ireland (0.95), Luxembourg (0.949), Sweden (0.947), Netherlands (0.945), Finland (0.945), France (0.945), United States (0.944), Japan (0.943), Denmark (0.943), Switzerland (0.942), Belgium (0.94), Spain (0.938), United Kingdom (0.936), Italy (0.934), Austria (0.934), Greece (0.918), Germany (0.916), Slovenia (0.913). *Data source:* (*12*). Adjusted TFRs were obtained from the 'European Demographic Data Sheet 2008' (published by the Vienna Institute of Demography, Vienna, Austria) and McDonald P, Kippen R. The Intrinsic Total Fertility Rate: A New Approach to the Measurement of Fertility (Population Association of America Annual Meeting 2007, New York, 2007). Tempo-adjusted TFRs were not available for Canada, New Zealand, Israel, Korea, Cyprus, Kuwait, and Argentina, Chile or the United Arab Emirates where $\Delta\bar{A}_{it}$ is change in the mean age of mothers at first birth, measuring directly the postponement of childbearing. The estimates, shown in Model M.4 in Table S.3, are consistent with the ones obtained without adjustment for tempo-effects: The coefficient $\hat{\beta}_1^{pre}$ is negative and statistically significant, and the coefficient $\hat{\beta}_1^{post}$ is positive and statistically significant, and practically of the same magnitude as in the model that does not account for changes in the timing of childbearing (4.02 vs 4.07). Further direct adjustments in Eq. (S.5) for changes in mean age of mothers at second and higher order births did not change the results.

In summary, the additional analyses in Models M.3–M.4 confirm that, even after controlling for changes in the timing of chilbearing, the coefficient $\hat{\beta}_1^{post}$, which measures the effect of increases in HDI on the adjusted total fertility rate once a country's HDI level is above the critical level 0.86, is positive and statistically significant. Adjusting for tempo effects, either by including the adjusted TFR or by including changes in the mean age at childbearing in the regression model, therefore, does not change our main substantive conclusion that a positive HDI⇒fertility relationship emerges at advanced stages of development with HDI levels above 0.86. Therefore, while our analyses suggest that changes in the timing of childbearing contribute to the reversal of the HDI⇒fertility relationship from negative to positive at advanced development stages, the reversal of the HDI⇒fertility relationship is not driven by these changes in the timing of childbearing. In contrast, the positive HDI⇒fertility relationship at HDI ≥ 0.86 is also present in analyses that adjust for tempo effects (Models M.3–M.4 in Table S.3), suggesting that increases in HDI at advanced development stages lead to a higher quantum (or long-term level) of fertility.