Broken Limits to Birth Expectancy?

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Abstract

Record life-expectancy has been rising linearly over more than 180 years. This persistent linear trend provides a clear benchmark for potential future mortality improvements. A comparable benchmark for future fertility trends had been unknown. Using data from the Human Fertility Database, here we reveal that fertility follows an equivalent regularity. At a pace of about 7 weeks per year, the age of a mother at birth of an average child – record birth-expectancy – has been rising linearly over the past 40 years. Underlying this trend, we observe a linear increase in record mean age at first birth, and linear changes for record holders in age-specific fertility contributions of age groups 25-29 and 35-39. These are fuelled by the general trend towards reducing higher birth orders and the persistently low fertility contributions of age groups below 25. We discuss a potential limit to the trend and suggest that these linear regularities could aid fertility forecasting.

Introduction

Why and when people get children hinges on a multitude of entangled factors that challenge discovery of simple models and theories of fertility[1-4]. Why and when people die is complex and hinges on a multitude of entangled factors too. Yet, researchers have found simple relationships and strong regularities that help to model and predict patterns of death[5-7]. One such striking regularity has been discovered by Oeppen and Vaupel (2002)[7]. In their highly cited contribution "Broken Limits to Life Expectancy", they reveal that over the past 180 years, people have been and still are steadily gaining additional lifetime at a constant pace of two and a half years per decade, or three month per year, which is six hours a day. This almost two-century long, linear trend sets a strong benchmark for future improvements in human lifespan.

Compared to mortality, fertility is a less deterministic process and more erratic over time, although major trends stand out, such as the first and second demographic transition.[8] Fertility rates decline as the human development index (HDI) increases, although at high levels of HDI, this trend slows and may reverse.[9] Among high income countries, related trends include the postponement of age at first birth[10], a shift of fertility contributions from younger to older ages [11], and a reduction in family size, which implies a fall in higher birth orders, particularly parity 4+.[12] Biological factors constrain fertility and set a predictable age-window between menarche and menopause.[13] Several parametric models capture the typically hump-shaped pattern of human reproduction,[14-18] but they contain comparatively little information to anticipate future changes in fertility.[19]

Main findings

Here we explore regularities in fertility applying a novel approach called *Born once, die once* (*B1D1*, see Methods section).[20] Analogous to the concept of life-expectancy, which measures the average waiting time to death, the B1D1 approach measures "birth expectancy" as the average waiting time to birth of any parity. This waiting time is purely conceptually conceived for a retrospectively defined, to-be-born offspring population. This offspring population is born to a population of mothers from a specific cohort or period. Then, birth expectancy captures the expected age of a mother at birth of a randomly selected child from this offspring population.

With this approach, we reveal a strong linear trend ($R^2 = 0.995$) in Figure 1. Since 1979, over the past 40 years, births have been and still are steadily shifted at a constant pace of 0.137, amounting to about one and a third year per decade, or about 7 weeks per year, which is more than 3 hours a day. This four decade long, linearly increasing trend in record birth expectancy may serve as a benchmark for future fertility changes.

Over the total time horizon of our data since 1945, Figure 1 shows that countries generally follow a V-shaped trajectory with an initial decline, followed by an increase. This V-shaped macro trend marks the first and second demographic transition; first the transition from high to low fertility with relatively stable age at first birth, and second a postponement of childbirths with further reduction of higher birth orders. The year 1979 marks the sharp turning point in record birth expectancy, when trends of countries at different stages of their fertility developments cross over. Turning points among individual countries differ, e.g., with Finland turning the earliest among the record holders. Turning points are unique among all but one (Japan) record holding countries. Japan experienced a rather flat transition phase. By contrast, other turning points are pronounced, again such as in Finland. Non-record holders may exhibit more wavy transitions from decreasing to increasing birth expectancy. Overall, individual countries may well show wavy patterns along the general V-shaped process.

Note that Portugal and South Korea appear in color in Figure 1, even though they never held the record. This is because both have been following steeply rising patterns and appear as good candidates that are about to take the lead, as Spain is falling behind.

Drivers of the linear, increasing trend

Explaining the linear regularity in Figure 1 is not obvious, but the underlying mechanisms are tangible. First, birth expectancy must be closely tied to the age at first birth. Figure 2 reveals that there has been a strong linear trend ($R^2 = 0.958$) over the past 40 years also in the record age at first birth. Women have been postponing their age at first birth at a pace of 0.116, amounting to more than a year per decade, which is close to three hours a day. Several countries follow parallel linear trends. Some are in a phase of catching up before apparently joining the overall pace of increase. Note that among record holders for birth expectancy (in bold colors), the trend in mean age at first birth is faster (slope = 0.143, $R^2 = 0.970$). As aspirants to become future record holders, South Korea and Portugal follow an even faster, linear pace. No country seems to follow a slower trend than the benchmark of the record in mean age at first birth. For orientation, the bottom graph of Figure 2 depicts trends in TFR, which do not behave linearly. Notably the respectively current and potential record holders Spain and South Korea had the lowest TFR values over the past decades.

Considering drivers of birth expectancy, any change must arise from changes in age-specific fertility contributions. By five-year age groups over time, Figure 3 shows the trajectories of age-specific, proportional contributions of birth counts. These results reveal – beyond the generally known trend of a shift in fertility from younger to older ages – unknown regularities for the record holding countries. Their bold, colored pieces of trajectories form linear patterns over time, especially for two age groups. A linear behavior among the record holding countries is apparent for age groups 25-29 (slope = -0.859, R^2 = 0.944) and 35-39 (slope = 0.722, R^2 = 0.970) from 1979 onwards until about 2015, when Spain experiences a halt in its trend. The three-and-a-half-decade long trend suggests that the linear shift of fertility away from the late twenties and the linear gain in birth counts in the late thirties may have fueled the linear increase in record birth expectancy. In the early thirties from 30-34, non-record holding countries increase or stagnate in their contributions to childbirth, although it might be expected that they eventually will follow the hump-shaped pattern observed for the record holders in that age group.

We interpret the dynamics in the different age groups as a wave of change marking the shift in childbirth to later ages. Record holders successively reduce their contribution to childbirth at younger ages, visible as a declining and recently leveling trend. At the same time, they successively increase their contribution at later ages, visible as the increase of contributions in the thirties. The hump-shaped pattern in age group 30-34 signals that, for the record holders, the wave of shifting fertility has already passed the early thirties. This age group now joins in with the declining trend of younger age groups. Currently the biggest gains in birth counts are seen in the late thirties, a trend which may well be expected to travers to the early forties soon. To put the current state of development into perspective, the early forties for the record holder today contribute equally many children as the early twenties.

Figure 3 indicates that persistently low levels of fertility before age 25 may have been a condition for becoming a record holder. To be a record holder further may have required high “positional energy” among countries to accelerate the change that we observe for record holders, who moved from the top to the bottom (for age group 25-29) and from the bottom to top (for age group 35-39) over the past decades crossing other countries trajectories at a fast pace. With exceptionally steep trajectories in both critical age groups, South Korea shows a large potential to become the next record holder. Note that for all countries included in our analysis, we observe small, roughly constant contributions of teenage (not shown) and late age (i.e., 45+) childbirth.

Figure 4 investigates the effect of parity as further potential driver of birth expectancy. In case of parity, similarly smooth linear trends for the record holders as those observed for age groups are not apparent. Hence, parity may not have contributed to the linearity of the trend we observe. What becomes clear, however is that especially in the last years, record holders had the lowest proportions of high parity births and one of the highest proportions of low parity births. Indeed, first and second births for the record holders today amount together to almost 90% of total births. Spain became the record holder also due to its marked decline in parity three and its lowest position in higher parity orders. At the same time, South Korea experiences a strong rise in parity one, combined with a unique fall in parity two, leading to an exceptionally steep increase in birth expectancy, whereas Spain with an increase in parity two is losing its top position. At the scale viewed in Figure 4, parity trends seem to remain relatively stable in their relative magnitude over the last 40 years across countries. Parity one contributes the largest share of birth, closely followed by parity two. Then, parities three and higher follow with a substantial gap (of roughly 20%) and successively lower contributions. Yet, within the magnitudes of each parity, changes can be considered substantial, with the record holders positioning themselves over time more towards the extremes of the distribution. Thereby, the shift from higher to lower parities contributes to the increasing trend in birth expectancy.

Together, Figures 2-4 illustrate how and what factors likely drive the linear and increasing trend in record birth expectancy. The linearity in record birth expectancy links to 1) a linear rise in age at first birth, 2) a linear fall in contribution of birth counts in the late twenties, and 3) a linear rise in contribution of birth counts in the late thirties. The increase likely results from 1) an increase in age at first birth, 2) a shift towards parity one, 3) a reduction of higher order parities and 4) a fall in total fertility. These factors also operate for the non-record holders, who follow the known global trends of postponement of age at first birth, shifting fertility weight from the late twenties to the late thirties, reduction in higher birth orders and low fertility.

Beyond the increasing trends, the linearities of the supernational, global emergent patterns in 1), 2) and 3) beg explaining. We propose that two factors dynamically balance to produce a linear increase. On the one hand, biological factors and life history tradeoffs pull towards earlier reproduction[21], and hence towards deceleration. On the other hand, social factors push for later reproduction, as women pursue an education, careers, and partner choice[22], and hence for acceleration. The two opposing pulls and pushes of biological and social factors just balance and lead to an emergent linear global pattern. This trend is expected to continue as long as trends towards delayed childbearing persist[11] and a biological limit is yet to be reached[11,23].

Is there a looming limit?

The inevitable constraint of menopause should set an end to the trend in Figure 1, eventually [24]. Thus, how close are we to the limit? Since record age at first birth has passed 30, any further rise in birth expectancy should be fueled by ages above 30, conditional upon continuously low contributions of younger ages. The latter condition is supported by Figure 3, indicating no increasing trend for births at ages below thirty. Hence, to investigate the limit, we condition birth-expectancy on "survival" until age 30, that is, we consider only those children that are born to mothers of age 30 and older.

Figure 5 reports a record conditional birth expectancy value of currently just below 35 – three years larger than the unconditional current value of 32. To put the difference of three years in perspective, at a pace of one and a third year per decade (Figure 1), three years correspond to more than two decades of persistent change. Therefore, we argue that there is no immediate biological limit that would impose a halt to the trend over at least the next twenty years.

The biological limit of menopause implies that women are no longer physiologically capable to give birth beyond an evolutionary set age[24]. This evolutionary constraint should be visible in historical patterns of childbirth at highest ages. Figure 5 highlights that historically in the late 1940th, remaining birth expectancy scored generally above age 34, whereas contemporary levels remain below 34. Going further back, in Sweden 1891, women above age 40 contributed 12% percent of all children. This was almost as many as the close to 14% children contributed by women in their early twenties (age of 20-24) at that time. By comparison, with only 4.6% contributed above age 40 in 2021 (and 7.7% between ages 20-24), contemporary women in Sweden fall short of historical levels. This lag may be explained either by the choice of contemporary women to end childbearing before the end of their fecund lifespan, once they reached their desired, typically low parity. Or it may be due to potential fecundity challenges in contemporary populations caused by environmental factors[25] that increase the number of unintended childlessness due to postponement of first birth[26,27]. The evolutionary limit of menopause, however, does not seem to be the limiting factor to the increase in birth expectancy, yet.

Finally, we note that in Figure 5, the strong linear trend of maximum values is no longer apparent. Still, record holder values roughly align since 1979 even without contributions of age groups below thirty. Over time, we observe record holders crossing over the country level spectrum from minimum to maximum values.

Discussion

If, why, and when a child is born depends on potential parents to get together, to be fecund, to want and decide for a child, or at least not to prevent it, and it depends on chance. Although a wealth of research sheds light on these determinants of fertility[2,28], the very nature of fertility implies that to model and predict this process with its entangled and unpredictable underlying drivers remains challenging[1,3,4]. Still, that a child is born is a simple fact. We are born once. We die once.

Zooming out from the micro level, here our analysis discovers two linear macro level trends, one in record birth expectancy (Figure 1) and one in record mean age at first birth (Figure 2) over four decades. We know of no other macro level regularity of human fertility, that is equally long, strong, and simple. The strength of the regularity in record birth expectancy ($R^2 = 0.995$) is on par with that observed for record birth expectancy ($R^2 = 0.992$) [7].

Finding strong linear relationships over four decades within period data of fertility is surprising because one would expect to see distortions in period data due to different sizes of birth cohorts of mothers and tempo effects of mothers postponing childbirth to later ages[29,30]. Yet, between the observed values and the estimated linear trend in Figure 1, the difference is just half a percent for record birth expectancy, and less than five percent for record mean age at first birth (Figure 2).

Although the general trends of first and second demographic transition and associated drivers have long been known, and much of those are accounted for in Baysian approaches to forecast fertility,[31,32] scholars have been calling for improved models given performance of current methods[19]. We propose that our linear macro level trends may serve as informative benchmarks to develop coherent forecasting methods for fertility analogous to those developed for mortality.[33,34] The linear age-specific trends in the late 20th and 30th may facilitate a new gap method[35,36] such that national forecasts can be tied to the dynamics and trends in those age groups.

The analysis here applies birth expectancy, a concept closely related to mean age at birth. Our results remain unchanged when using mean age at birth instead of birth expectancy, although the observed trend slightly slows and the linearity weakens (Slope=0.110, R2=0.978, see supplementary Figure S1).

Notably, birth expectancy measures the tempo or pace of fertility[29,37]. Our results do not make predictions about the level or quantum of fertility, that is, the total fertility rate TFR. Instead of focusing on a target value of fertility, our analysis provides insights into the dynamics and regularities of change in age-specific contributions to fertility. However, we highlight that the general trend of postponement implies that unintended childlessness is expected to increase[26,27].

Conclusion

Limits to life-expectancy have been repeatedly broken[7]. And although the evolutionary constraint of menopause seems rigid, the limits of birth expectancy too are higher than expected. We see that contemporary levels of birth expectancy still lag behind observed historical levels. We propose that – at the observed pace of increase – at least for the coming two decades, birth expectancy is not limited by biology. Instead, the largest constraint is of social nature. The trend will persist as long as fertility contributions below age 30 remain low, and the preference to delay childbearing continues[11]. How these individual preferences may further be supported by assisted reproductive technologies and future medical advances will eventually determine the ultimate limits to birth expectancy.

Data& Methods

Data All data used in this study derive from the Human Fertility Database (HFD; https://www.humanfertility.org/Home/Index).[38] The HFD comprises 33 nations spanning Europe, North and South America, and Asia, all available in an open-access database. The data in HFD are heavily scrutinized through quality control, thus providing comprehensive, high-quality information. We selected period years for our analyses when HFD provides data for at least 10 countries as minimum number of competitors for a record value in birth expectancy.

Method We use the concept of birth expectancy developed within the B1D1 approach by Baudisch and Alvarez (2021) [20]. This approach assumes a cohort of women that gives birth to a population of children, the *offspring population* of size *B*. Each child in the offspring population is born to a woman at a certain age *x*.

For each individual child, age x marks the end of its conceptual 'waiting time to birth', which starts at the age of female reproductive maturity, α. As women give birth over their reproductive lifetime, the (to-be-born) offspring population is decremented at every age by the number of children, $b(x)$, born to women of age x, until the maximum age of reproduction, β. In this setting, the survivorship function of birth, $S(x)$ is defined as the proportion of unborn children of women up to age x, with $S(\alpha)=1$, $S(\beta)=0$, and $S(x)=1-B(x)/B$, where $B(x)$ captures the cumulative number of children born to women up to age x, $B(x) = \int_{\alpha}^{x} b(t)dt$. Birth-expectancy $e(\alpha)$ is then given by the integral under the survivorship function, $e(\alpha) = \int_{\alpha}^{\beta} S(x)dx$.[1]

Only the mother's age at childbirth is memorized from the cohort of mothers that defines the offspring population, which is decremented by the age-specific process of birth. What mother relates to what child is ignored. Thus, there is no need to distinguish among normal, twin, multiple births, childlessness, or parities. Mother's survival is implied by the birth of her child(ren) and does not enter the framework.

Here we apply this approach to period data, creating the offspring population by taking together all children contributed by women giving birth in a particular year. We assume $\alpha=12$, and $\beta=55$. The waiting time to birth for an average child can be translated to the age of a mother at the birth of an average child, given by the sum of $\alpha + e(\alpha)$, which is what we report in Figures 1 and 5.

Applying the cohort idea of B1D1 to period data implies that each age group of children is born to different mother cohorts of different sizes and is prone to distortions by tempo effects[22, 23].

[1] Note that since birth counts and cumulative birth counts lie at the core of this method, we express our results in Figure 3 by proportion of birth counts, rather than by proportion of age specific fertility rate ASFR, which would be the more traditional way. Using ASFR leads to similar results as those shown in Figure 3, just that the linear relationship among record holders in age groups 25 and 35 is less pronounced.

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FIGURES

Figure 1. Linear Trend in Record Birth Expectancy over Time.

Figure 2. Mean Age at First Birth and Total Fertility Rate over Time.

Figure 3. Age-Specific Proportional Contributions of Number of Births among Total Births.

Figure 4. Parity-Specific Proportional Contributions of Number of Births among Total Births.

Figure 5. Trajectories of Conditional Birth Expectancy at age 30 over Time.

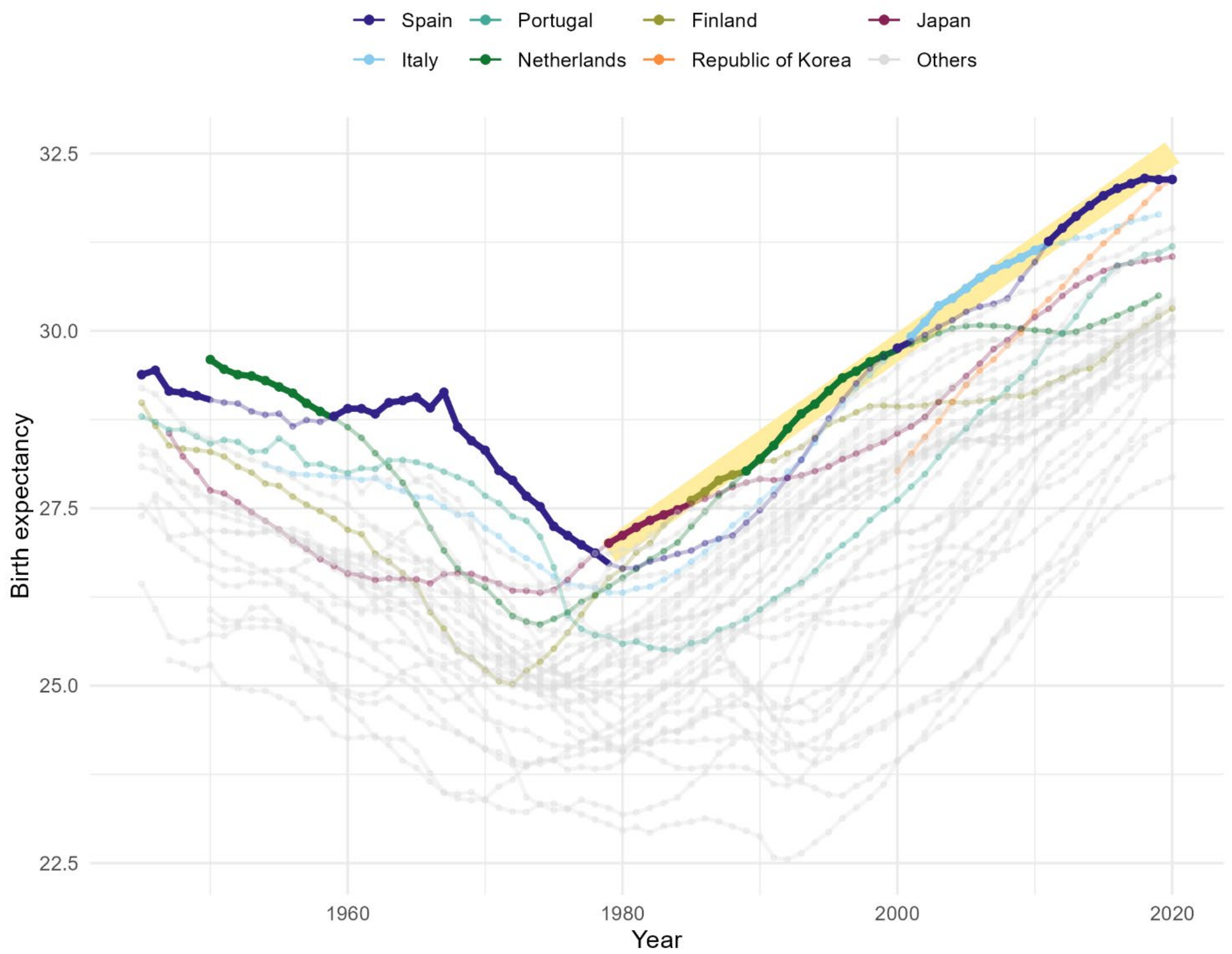


Figure 1. Linear Trend in Record Birth Expectancy over Time. A birth expectancy of 30, for example, means that the average child is born to a woman of age 30. The graph depicts all countries from the Human Fertility Database (HFD) for years when data for at least 10 countries were available. Record holders (Spain, Italy, the Netherlands, Finland, and Japan) and two future potential record holders (Portugal and South Korea) are marked and labeled by color. Bold font marks the period when a country holds the maximum value of birth expectancy in a year. Non-record holder countries are depicted in grey. The thick yellow regression line marks the linear trend of the record holding countries from 1979 to 2020 with an R-squared of 0.995, and slope of 0.137.

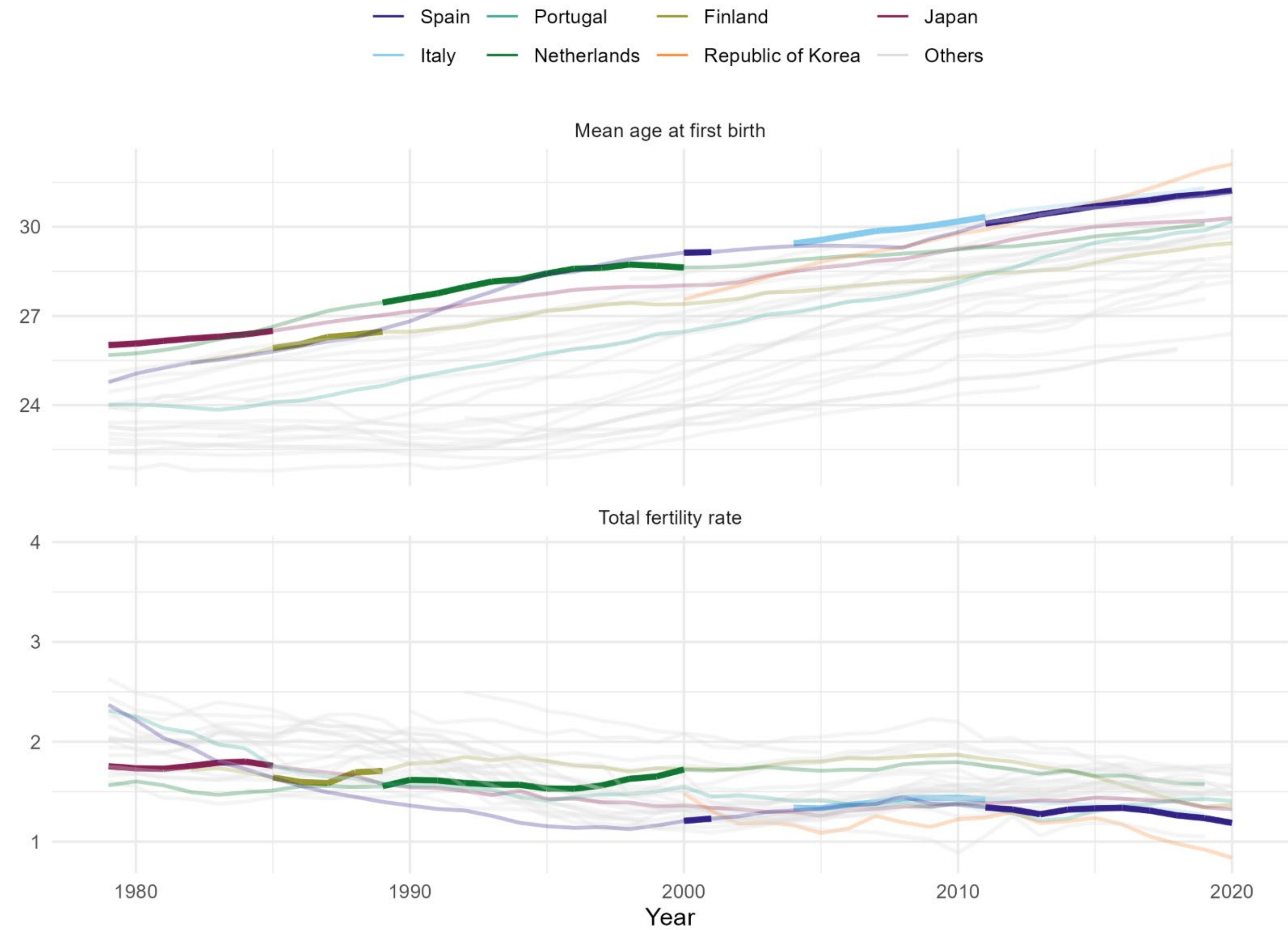


Figure 2. Mean Age at First Birth and Total Fertility Rate over Time. Data source, countries, bold marking, and color coding as in Figure 1. Regression line (not shown) through the record mean age at first birth has an R squared of 0.958 and a slope of 0.116.

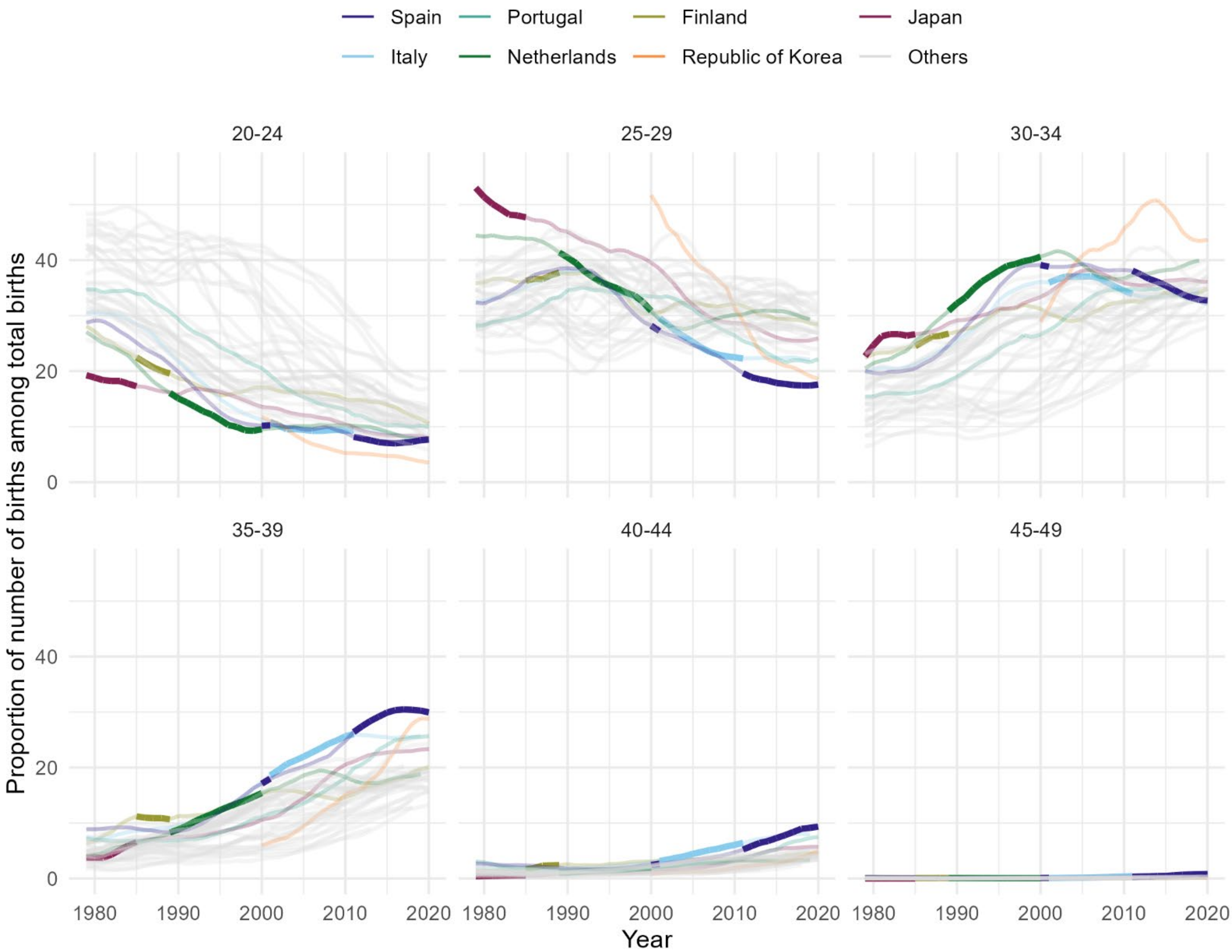


Figure 3. Age-Specific Proportional Contributions of Number of Births among Total Births. Data source, countries, bold marking, and color coding as in Figure 1. Regression lines (not shown) through the record holding countries in ages groups 25-29 and 35-39 respectively have R squared=0.944 and slope=-0.859, and an R squared=0.970 and slope=0.722.

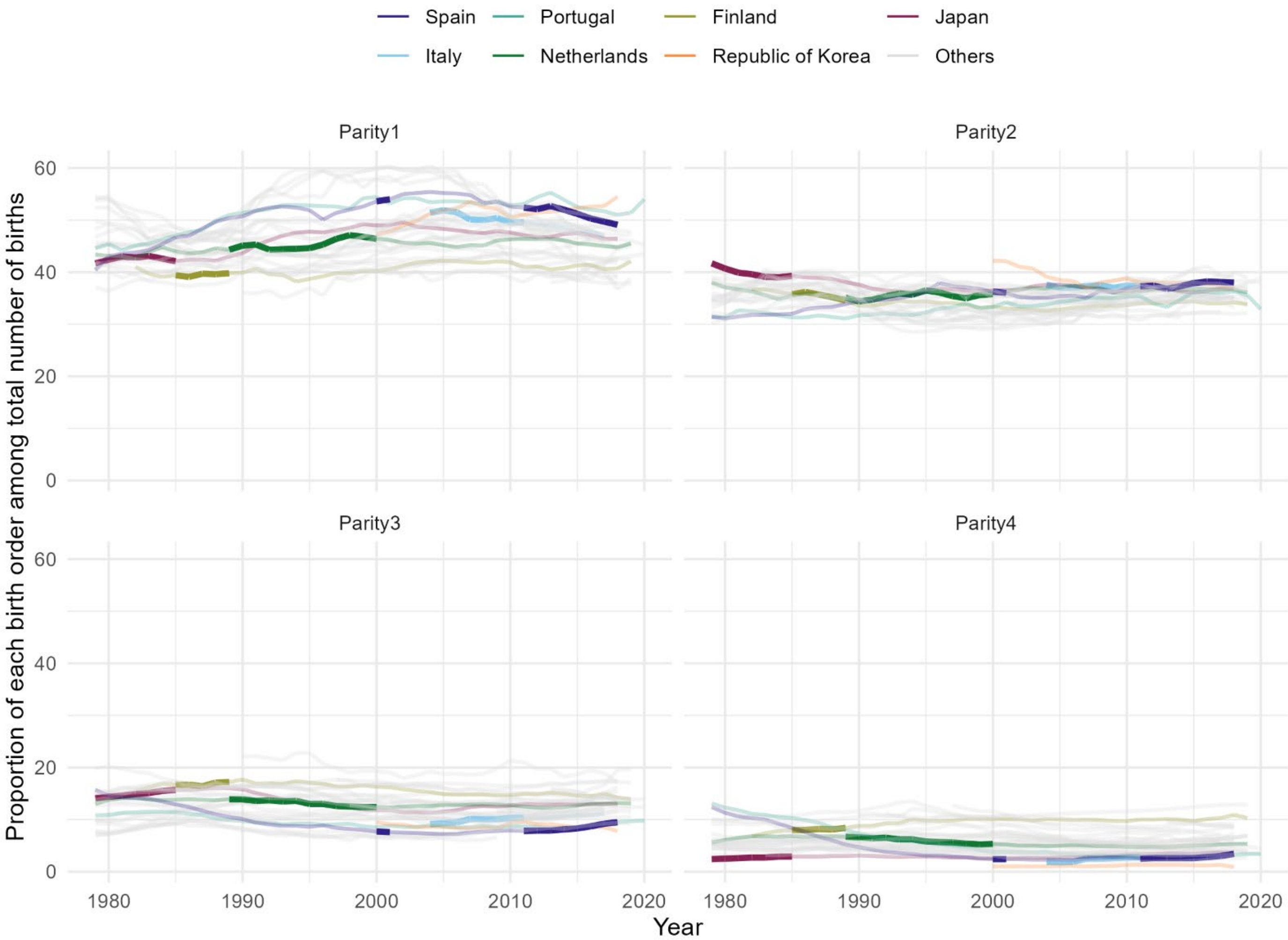


Figure 4. Parity-Specific Proportional Contributions of Number of Births among Total Births. Data source, countries, bold marking, and color coding as in Figure 1.

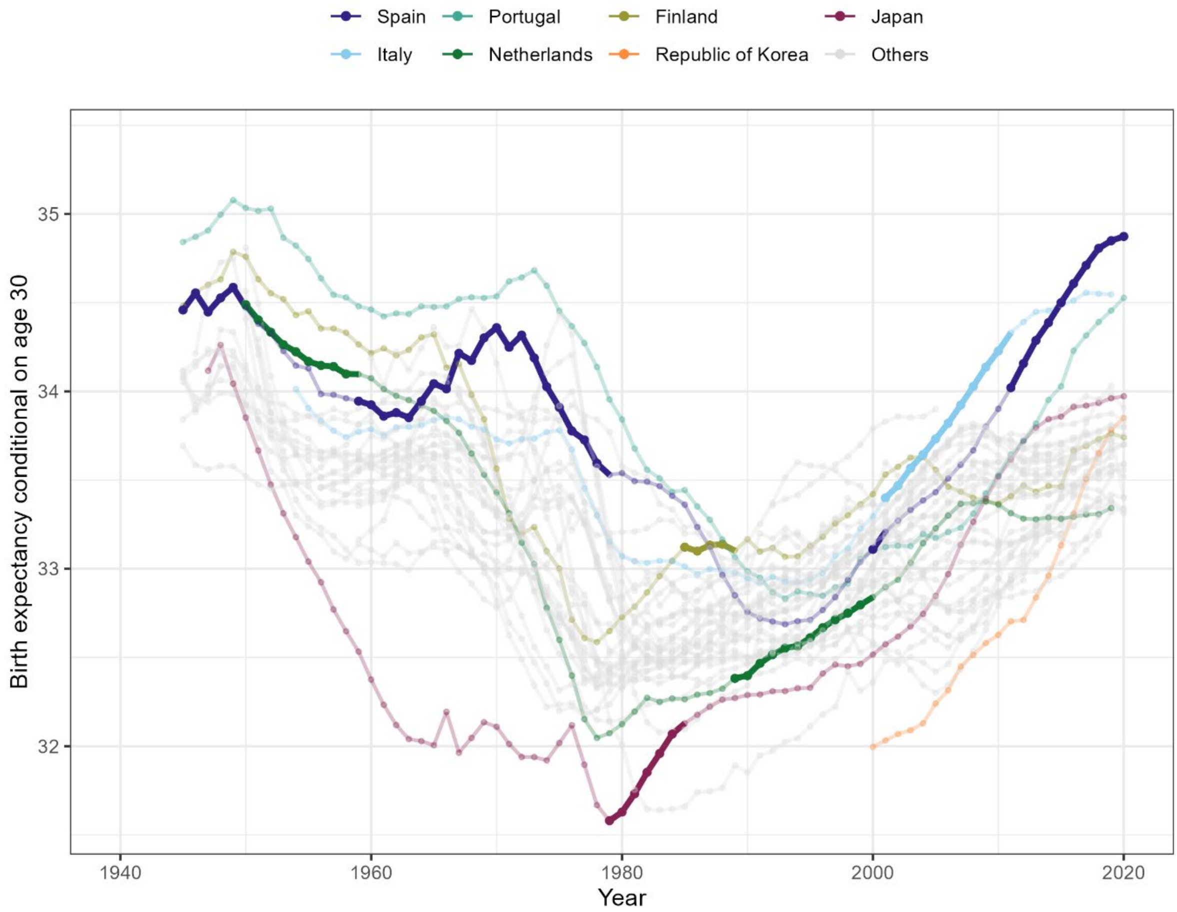
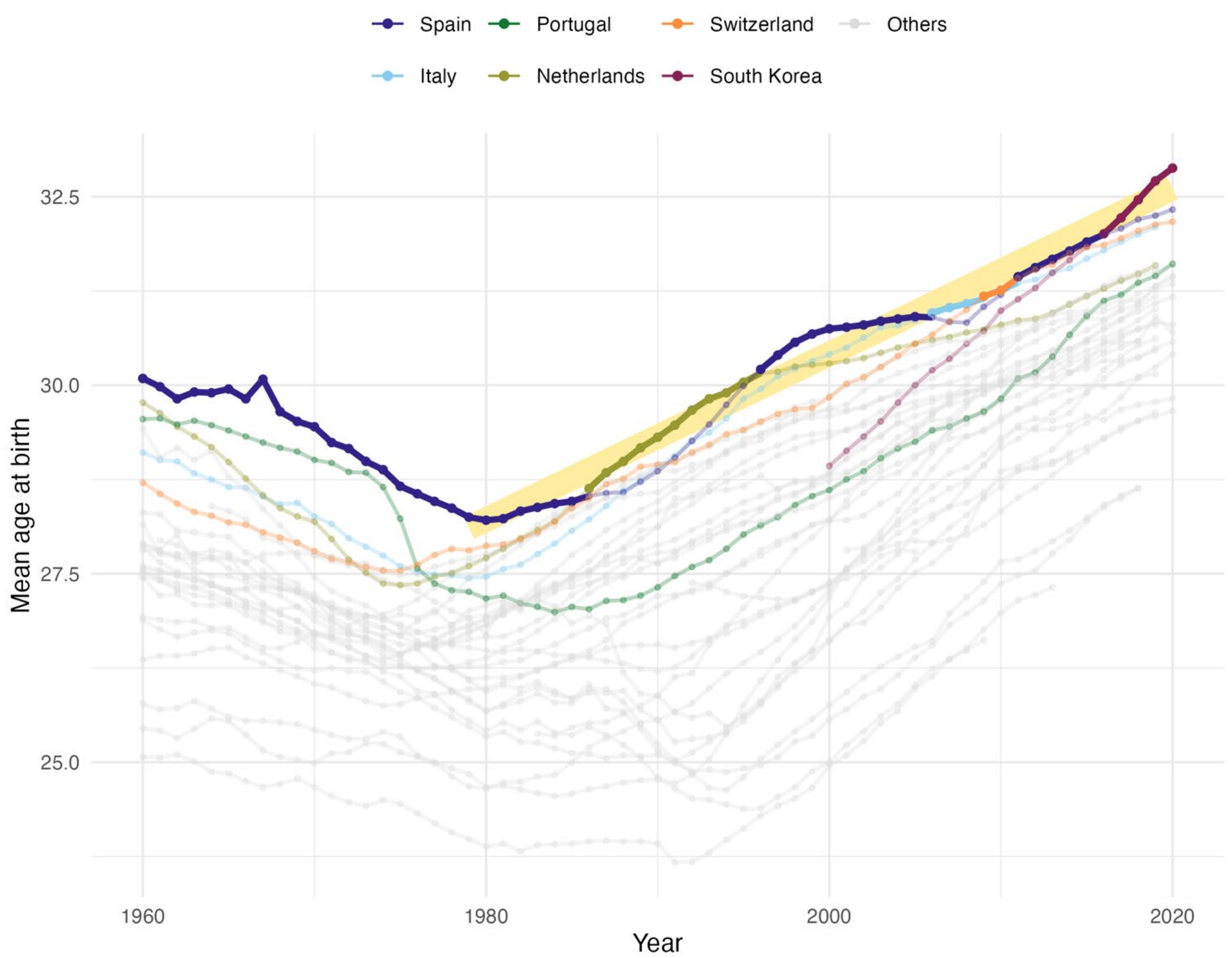


Figure 5. Trajectories of Conditional Birth Expectancy at age 30 over Time. Conditional birth expectancy at age 30 captures the age of a mother at birth of an average child that is born to women at or above age 30. Children born to women at ages below 30 do not affect this measure. Data source, countries, bold marking, and color coding as in Figure 1.



Supplementary Figure S1: Analogous to Figure 1 but based on the conventional mean age at birth instead of birth expectancy. Slope=0.110, R2=0.978.