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Real interest rates and demographic developments across generations: A panel-data analysis over two centuries*

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Abstract

This paper empirically examines the effect of population growth on long-term real interest rates. Although this effect is well founded in macroeconomic theory, the corresponding empirical results have been rather tenuous and surprisingly unstable. As the demographic interest rate impact is theoretically based on intergenerational relationships, we not only contemplate gross population growth rates but also distinguish between demographic growth resulting from a birth surplus and net migration. Within a panel covering 12 countries and the years since 1820, our results suggest that there is a positive, statistically significant, and stable effect from the birth surplus on real interest rates. Conversely, the corresponding effect of net migration seems to be much more volatile. Hence, our results suggest that it is mainly population growth occurring through a birth surplus that affects the equilibrium real interest rate.

JEL classification: E43; E52; J11
Keywords: demographics; population growth; real interest rate

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1 Introduction

Over recent decades, real interest rates have declined in many countries. In the academic literature, the contemporaneous reduction in population growth has been considered a possible explanation for this decline. However, despite the popularity of this "demographic interest rate theory", the empirical link between population growth and real interest rates has been rather tenuous. For example, in Borio *et al.* (2017, 2019), basic demographic variables, and especially total population growth, had barely a significant effect on the level of long-term real interest rates within a sample covering 19 countries from 1870 to 2016. Furthermore, the corresponding empirical effect has been surprisingly unstable, in the sense that both significantly positive and negative coefficients are observed across subperiods covering different international currency systems, such as the classical gold standard (1870-1914), the interwar period (1919-1939), or the post-war era (since 1945).

To explain these results, this paper emphasises an aspect that has hitherto been neglected by the empirical literature, namely, the distinction, encapsulated in the so-called "demographic equation", between population growth caused by a birth surplus and net migration (Peston and Bouvier, 2010, pp.5-7). Within the current context, this distinction could be crucial because the birth surplus typically captures secular developments in mortality and birth rates as described by the well-known demographic transition theory (see e.g. Peston and Bouvier, 2010, pp.271-274). Conversely, net migration rates are often quite volatile and react relatively quickly to extraordinary events, such as wars and political and economic crises (Peston and Bouvier, 2010, pp.199ff.; Zaiceva and Zimmermann, 2016, pp.122-133). Therefore, the growth rate of the total population does not only capture the secular decline in mortality and birth rates observed around the world (see e.g. Zaiceva and Zimmermann, 2016, pp.127ff.). However, it is probably these long-term demographic trends, rather than the more erratic movements in migration, that can explain the abovementioned secular decline in real interest rates.

Against this background, this paper endeavours to contribute to the literature by studying the long-term relationship between the main components of population growth and real interest rates. Therefore, we collected the corresponding data for a sample covering 12 countries and annual observations beginning in 1820, which is approximately 50 years earlier than the periods considered in previous studies (see also Lunsford and West, 2019). Furthermore, the abovementioned demographic transition trends are identified by splitting total population growth rates into a component reflecting the development of birth and mortality rates and net migration. By means of panel data regressions across countries and years, we find a positive and statistically significant relationship between long-term real interest rates and population growth resulting from a birth surplus. Conversely, there seems to be no consistently significant and stable effect of net migration on real interest rates. The results are remarkably robust to a variety of regression specifications. Above all, the effect of the birth surplus also arises in subperiods covering the main international currency regimes. Then again, across these subperiods, the corresponding effects of total population growth and net migration are much more unstable. Taken together, these results seem to support the view, consistent with standard macroeconomic theory, that population growth, as measured by the birth surplus, can affect the equilibrium real interest rate. Applied to the most recent decades, our results indicate that the widespread reduction of approximately one to two percentage points in the birth surplus has caused a decline in the long-term real interest rate of approximately one percentage point.

The paper is organised as follows. To set the context, the next section provides a synoptic review of the theoretical and empirical literature on the link between population growth and interest rates. Based on this literature, Section 3 develops the empirical strategy, and Section 4 discusses the data. Section 5 presents the empirical results. Section 6 summarises and concludes.

2 Related literature

Real interest rates have long been the subject of an ancient debate in economics. In particular, the notion that positive real interest rates are a necessary side effect of productivity gains on private capital investments can be traced back to classical economists, such as Adam Smith (1776, ch.II.4). Without participation in these expected gains, investors would, indeed, have little incentive to postpone consumption and bear the financial risks of funding economic projects. An alternative to the classical theory of the real interest rate emerged with Paul Samuelson's (1958) seminal contribution to the overlapping generations (OLG) model, within which demographic variables matter (see also Lee, 2020). In particular, OLG frameworks recognise that society consists of generations of individuals, who do not produce and consume forever but are nevertheless connected across time through intergenerational relationships. Demographic developments can change the size and composition of subsequent generations and, in turn, affect their production and consumption possibilities. In a very rudimentary scenario, a growing population may expand the labour supply and, hence, increase the future potential output of the economy. Therefore, a kind of "demographic return" arises, which provides a broader basis for paying real interest rates to the current generation compared with a society witnessing demographic stagnation.[1]

The main interest rate determinants have recently resurfaced to attribute the persistently low, and in some countries even negative, nominal and real rates to a so-called "secular stagnation" in economic progress and population growth.[2] The consequences of a permanent slowdown in economic progress and lower productivity gains are discussed in, e.g., Summers (2014, 2015) and Gordon (2014). In a similar vein, the effect of a secular decline in population growth on interest rates has received renewed attention amid the current ageing of societies in many parts of the world (see e.g. Ikeda and Saito, 2014; Gagnon *et al.*, 2016; Aksoy *et al.*, 2019; Busetti and Caivano, 2019; Eggertsson *et al.*, 2019a; Eggertsson *et al.*, 2019b; Ferrero *et al.*, 2019; Papetti, 2019). Although population structures within which members of the old generation outnumber members of the young generation are historically unprecedented, they have long been anticipated by the so-called "demographic transition theory", which describes the interrelated trends in birth and mortality rates since the dawn of the modern age (see, e.g., Peston and Bouvier, 2010, pp.271-274; Bloom and Luca, 2016, pp.14ff.). In particular, preindustrial societies typically subsisted in a 'Malthusian world", where birth and mortality rates were high and, as a result, the growth rate of the population remained low. Since around the eighteenth century, improvements in nutrition, medical progress, such as the discovery of vaccines, and better hygienic standards have gradually reduced mortality rates (Peston and Bouvier, 2010, pp.125ff.; Bloom and Luca, 2016, p.16.). Because birth rates remained initially high, the early stages of industrialisation were often characterised by a marked upsurge in the birth surplus[3] and, hence, population growth (Bloom and Luca, 2016, p.16.). Depending on the development of a country, this upsurge began as early as the second part of the eighteenth century but in some cases substantially later (Bloom and Luca, 2016, p.15.). Eventually, the combination between higher income, more generous pension systems, easier access to contraception, improvements in the status of women, and changing cultural attitudes towards having a family gave rise to declining birth rates (Peston and Bouvier, 2010, pp.59ff.; Bloom and Luca, 2016, pp.14ff.). Taken together, these interrelated trends have recently reduced the birth surplus in economically advanced countries, resulted in ageing societies, and are believed to lead to an era with declining populations (Bloom and Luca, 2016, pp.5ff.).

Based on the seminal work of Samuelson (1958), Eggertsson *et al.* (2019a, pp.333ff.) and

[1] For a textbook introduction of this simple effect of population growth in an OLG environment, see Champ *et al.* (2016, pp.41ff.).

[2] The concept of a secular stagnation goes back to Hansen (1939).

[3] The "birth surplus" results from the difference between birth and mortality rates and is also called the "natural rate of population growth".

Eggertsson *et al.* (2019b, pp.8ff.) provide up-to-date versions of the OLG model to show that relatively high population growth rates are typically associated with high expected real interest rates. Intuitively, the young generation tends to have a relatively high demand for loans and capital. Hence, high population growth rates—with large young generations—increase this demand and, given a constant capital supply, the real interest rate (see e.g. Eggertsson *et al.*, 2019b, p.11). However, more elaborate theories have recognised that demographic effects on macroeconomic variables crucially depend on the degree to which the current generation cares about the well-being of future generations (Canton and Meijdam, 1996). Furthermore, real interest rates typically also depend on a range of economic variables, especially productivity growth (Ikeda and Saito, 2014; Carvalho *et al.*, 2016; Gagnon *et al.*, 2016; Papetti, 2019; Bielecki *et al.*, 2020; Aksoy *et al.*, 2020). Moreover, according to Carvalho *et al.* (2016), demographic developments do not only manifest themselves in population growth rates. Other aspects, such as life expectations or the dependency ratio, i.e., the fraction of retirees to workers, are also important because the "demand effect" for capital can be overturned by "supply effects". Among other possibilities, these effects arise when high population growth rates eventually lower the dependency ratio. Insofar as individuals tend to be net savers during their working life, a decreasing dependency ratio is associated with a higher capital supply, which puts downward pressure on real interest rates (see Carvalho *et al.*, 2016, p.209). In a similar vein, an increase in life expectations arguably puts downward pressure on real interest rates because savings have to increase to finance longer pension payments (Carvalho *et al.*, 2016, p.209). Finally, Bielecki *et al.* (2020) focused on the influence of economic openness, the demographic effect of migration, and the pension system design on the equilibrium rate of interest.

To quantify the empirical effect of ageing societies, Carvalho *et al.* (2016), Ikeda and Saito (2014), Gagnon *et al.* (2016), Papetti (2019), and Bielecki *et al.* (2020) calibrated their models and typically found that the equilibrium rate of interest has recently declined by one to two percentage points due to demographic factors alone. In a similar vein, in a sample of advanced economies, the econometric analyses of Aksoy *et al.* (2019) and Ferrero *et al.* (2019) suggest that the changing composition between workers and retirees has contributed to the recent decline in real interest rates. Favero *et al.* (2016) and Busetti and Caivano (2019) suggested that the nexus between real interest rates and the age composition of the population occurs primarily through the low frequency trends of the corresponding data. Of note, all these calibrations and estimations have analysed the effect of aging during the last couple of decades and, therefore, account for only a small part of the long-term story told by the relevant OLG models, as well as the demographic transition theory discussed above.

For the economic and demographic variables mentioned above, a study covering more than one hundred years of data was provided by Lunsford and West (2019). In particular, they found stable and positive correlations between the short-term real interest rate and the growth rate of labour force hours as well as the size of the working age population in a sample covering the United States in the years after 1890.[4] This result stands in sharp contrast to the remarkably unstable effect of total population growth rates on long-term interest rates as found in the studies of Borio *et al.* (2017, 2019), which also employed data covering the very long term. Against this background, this paper suggests that total population growth rates encapsulate vastly different demographic components, such as the birth surplus and the effects of emigration and immigration. However, before turning to this issue, the next section describes the empirical strategy.

[4]In Lunsford and West (2019), a broad range of other variables, including economic growth and total factor productivity (TFP), had no consistent effect on US real interest rates. For a US sample covering a period beginning in the nineteenth century, Hamilton *et al.* (2016) reported a similar result of a somewhat tenuous relationship between economic growth and the equilibrium level of the short-term interest rate. However, their study ignored demographic variables.

3 Empirical strategy

The literature discussed in Section 2 suggests that in a given country j in year t, the expected real interest rate r^e_{jt} is primarily a function of secular productivity increases x_{jt} and the growth rate of the population n_{jt}, that is

$$r^e_{jt} = f(n_{jt}, x_{jt}) + \alpha_j + \alpha_t + \epsilon_{jt}, \tag{1}$$

where ϵ_{jt} represents an error term with expectation zero, and α_j and α_t reflect error terms as pertaining to, respectively, country j and year t.

Similar to Hamilton *et al.* (2016, pp.664ff.) and Borio *et al.* (2019, pp.3ff.), r^e_{jt} reflects an ex-ante real interest rate, which depends on inflation expectations denoted by π^e_{jt}, and is (approximately) given by

$$r^e_{jt} \approx i_{jt} - \pi^e_{jt}. \tag{2}$$

Inserting (2) back into (1) and assuming a linear relationship of $f(n_{jt}, x_{jt}) = \beta_1 n_{jt} + \beta_2 x_{jt}$ yields a panel data equation given by

$$i_{jt} - \pi^e_{jt} = \alpha_j + \alpha_t + \beta_1 n_{jt} + \beta_2 x_{jt} + \epsilon_{jt}, \tag{3}$$

where β_1 and β_2 denote coefficients to be estimated, and ϵ_{jt} represents the usual stochastic error term.[5] In (3), α_j and α_t represent unobserved effects. These could capture, among other things, entrenched deviations in forming expectations. Such deviations can arguably arise from the long-lasting legacies of prevailing currency regimes or from global money and credit cycles (see e.g. Borio *et al.*m 2017, pp.6ff.). Although it is typically difficult to measure the corresponding trends and cycles, their impact upon real interest rates can be at least partially absorbed by the year-specific unobserved effect α_t or unobserved effects pertaining to specific countries α_j to capture, e.g., their idiosyncratic monetary traditions.

Further to the discussion of Section 2, according to which demographic effects develop over many years, a long-term interest rate is probably appropriate for i_{jt} (see also Section 4). Moreover, to quantify the real interest rate of $i_{jt} - \pi^e_{jt}$ in (3), π^e_{jt} has to be determined. Concurrent with Borio *et al.* (2017, p.8; 2019, p.6.) and Lunsford and West (2019, p.123), expected inflation is calculated via a recursive projection of an AR(1) model estimated over a rolling sample of 20 years.[6] To match the long-term interest rate, our baseline specification employs one-sided moving averages of these inflation expectations over the future five years as the relevant horizon to determine π^e_{jt}. However, other time horizons are considered for robustness checks.[7]

The way in which real interest rates are empirically constructed has implications for the specification of the coefficient standard deviations. In particular, contemplating inflation across overlapping annual sequences comprising five years is likely to introduce moving-average terms into the residuals of (3). To control for these terms, a panel data version of variance–covariance matrices that are robust to arbitrary serial correlation within country clusters is used (Wooldridge, 2002, pp.152–153; 262-263).

[5] To account for the potential dynamic interaction and the endogeneity between macroeconomic variables, such as $i_{jt} - \pi^e_{jt}$ and x_{jt}, Aksoy *et al.* (2019, pp.196ff.) specified their empirical relationship as a panel vector autoregression (VAR) with demographic characteristics, such as population growth n_{jt}, as an exogenous variable. According to Aksoy *et al.* (2019, pp.199ff.), this approach is useful for forecasting, which is not the focus of this paper. However, adopting a panel VAR would not have changed the essence of the baseline results reported below. In particular, in a panel VAR, a significantly positive coefficient arises for the effect of population growth on real interest rates.

[6] The corresponding AR(1) model is given by $\pi_{jt} = \phi\pi_{j,t-1} + \psi_j + \psi_t + \zeta_{jt}$, where ϕ is a coefficient, ψ_j and ψ_t are fixed effects, and ζ_{jt} denotes a stochastic error term.

[7] The quantification of inflation expectations is a delicate step in determining the expected real interest rate. As an alternative to the approach employed in previous papers, we have also experimented with taking averages over the *observed* values of future inflation. Our main results are robust to this modification.

4 Demographic and economic data

To uncover the empirical impact of demographic variables upon real interest rates across generations, data covering decades and preferably even centuries are required. Although population censuses go back to ancient times, economic and financial data appeared much later and are often only available for a handful of countries with sufficiently stable borders, solid monetary frameworks, and early developed capital markets. In particular, such countries include Belgium, France, Norway, Sweden, Switzerland, the United Kingdom, and the United States, for which data on interest rates, inflation, and per capita economic growth go back to the first part of the nineteenth century. For a second group of countries, including Australia, Canada, Denmark, Finland, and the Netherlands, the corresponding joint sample covers the years from 1870 onwards. Taken together, data have been collected as far back as the year 1820 and for a sample encompassing 12 countries, which either are located in Europe or emerged from European settler colonies.[8]

Table 3 of Appendix A provides the details of the sources and the definitions of the variables used in the empirical analysis below. In brief, similar to Borio *et al.* (2017, 2019), the annual growth of the residential population is used as a potential variable to explain real interest rate developments. The size of the residential population since 1820, from which the corresponding growth rate – denoted by $\tilde{n}_{jt}$ – can be calculated, is reported for a large number of countries in the Maddison project database (see Bolt *et al.*, 2018). However, according to the demographic equation, a country's population can grow thanks to a birth surplus or positive net migration rates (see Peston and Bouvier, 2010, pp.5-7). To distinguish between birth surplus and net migration effects, data on crude birth and mortality rates are collected from Mitchell (1992, 1995, 1998) for the years before 1960, and from the World Development Indicators (WDI) of the World Bank for the years thereafter. The difference between these rates determines the birth surplus, denoted here by $\ddot{n}_{jt}$. Net migration rates, denoted by $\hat{n}_{jt}$, can be indirectly derived by subtracting the birth surplus from the growth rate of the residential population, i.e., $\hat{n}_{jt} = \tilde{n}_{jt} - \ddot{n}_{jt}$. Finally, to capture alternative channels through which demographic effects could arise, as suggested by Carvalho *et al.* (2016), data on dependency ratios between retirees and workers, as well as life expectations, are collected. Unfortunately, for most countries, these variables are not available for the nineteenth century and, in some cases, not even for large parts of the twentieth century. Hence, to preserve the long-term coverage of the sample, dependency ratios and life expectations are used only for robustness checks.

Regarding the financial and economic variables, the interest rate i_{jt} is measured by the annual yields on long-term government bonds. The main source is Homer (1977) for the years before 1960 and the Organisation for Economic Co-operation and Development (OECD) for the years thereafter.[9] Inflation π_{jt} is measured by the percentage change of the Consumer Price Index (CPI) as reported by Mitchell (1992, 1995, 1998) and, for recent decades, by the OECD. Finally, across a large number of countries and for the years between 1820 and 2016, the Maddison project database reports the real GDP per capita, from which economic growth rates can be calculated. These per capita growth rates are used as a proxy for potential productivity gains on capital investments x_{jt}. Although alternative variables to

[8]Germany is a major European country that is missing in our dataset. The reason is that Germany became a unified country only during the 1870s and witnessed substantial border changes and monetary interruptions during the twentieth century (including the separation between East and West Germany between 1945 and 1990). Owing to these historical disruptions, it is difficult to construct a coherent time series for the German population, economic growth, or level of interest rates. Similar disruptions inhibit a long-term empirical analysis for countries such as Japan or Russia. Furthermore, Spain and Italy offer only patchy interest rate data during the nineteenth century.

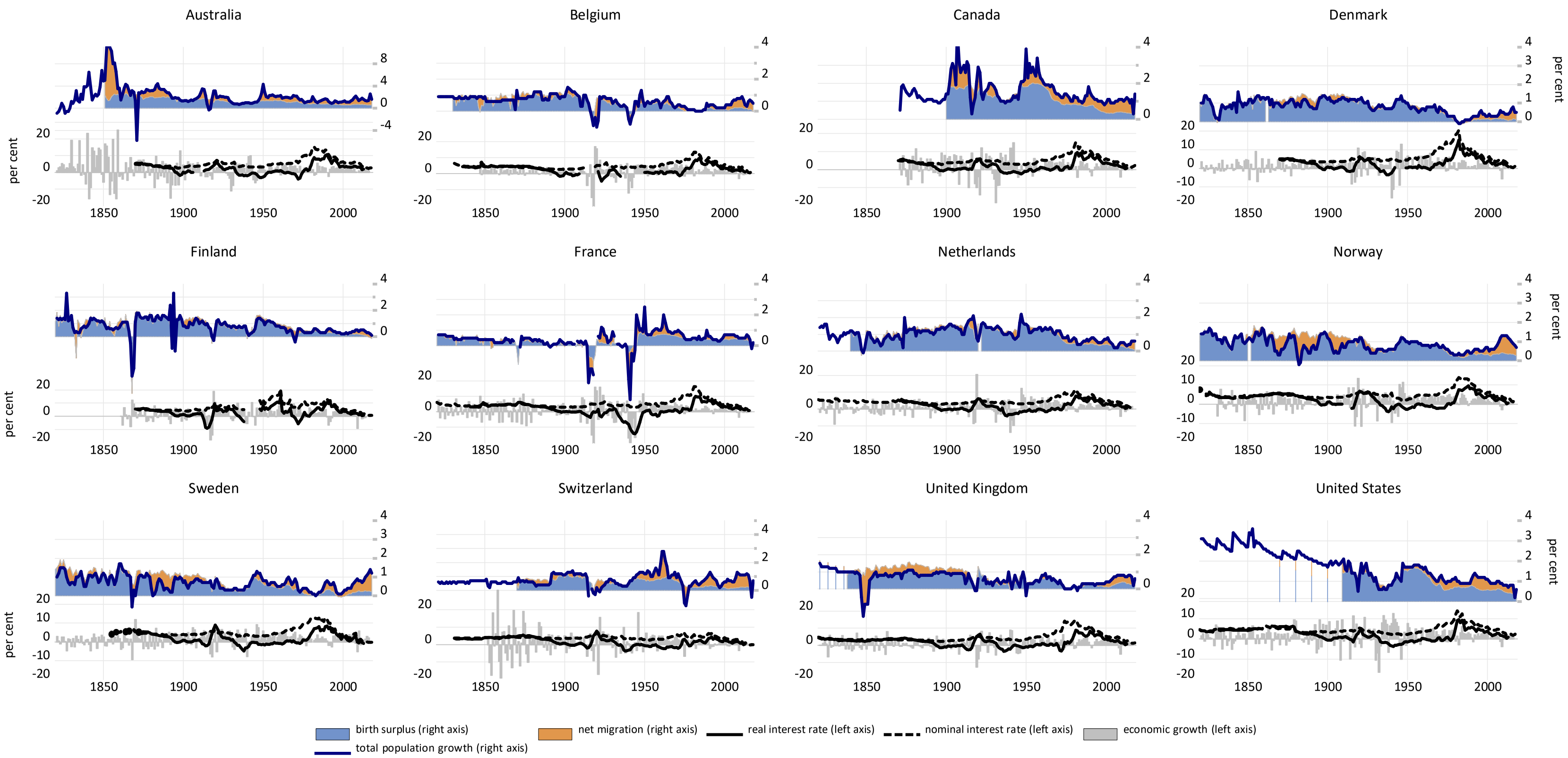
[9]Although the same sources provide data on short-term discount and money market interest rates, they are probably not ideal for capturing the intergenerational demographic effects on the secular behaviour of interest rates. Similar to Borio *et al.* (2017, p.7f.), the main results of the next section focus on long-term interest rates.

proxy for x_{jt} are available, e.g., the total factor productivity index reported in Bergeaud *et al.* (2016), these data do not go much further back than the twentieth century and, for the same reason as mentioned above, are used only for robustness checks.

Figure 1 provides an overview of the development of interest rates (see lines in the bottom part of the graphs), real economic growth per capita (grey bars in the bottom part of the graphs), and the growth rates of the population and their components (line and areas in the top part of the graphs) for the 12 countries since 1820. Of note, nominal interest rates, marked by the black dashed line, mainly follow the global inflation trends, with relatively high levels in all countries around the 1970s, i.e., when the transition towards a fiat money system gave rise to entrenched price instability. Conversely, the level of nominal interest rates was more stable during the eras of the classical gold standard, the Bretton Woods system, and recent monetary regimes based on inflation targeting. When calculating the real interest rate, unsurprisingly, a more stable development arises. Nevertheless, across countries, real interest rates, reflected by the solid black lines, have also witnessed marked upsurges and downturns, especially in times of major political and economic instability. Above all, during and after World War I (1914-1918) and World War II (1939-1945), the belligerent countries often resorted to financial repression, which manifested itself in negative real interest rates to help finance the war effort. Similar levels of instability can be observed around major economic crises, such as the Great Depression of the 1930s. Finally, although economic growth rates have been positive, on average, since the dawn of the industrial age, recurrent recessions and occasional sharp downturns lie clearly in evidence.

In a similar vein, total population growth rates, which are marked by the solid line in the top part of the graphs in Figure 1, have been largely positive over the past two centuries. However, this growth has occasionally been interrupted due to the devastating effects of major wars and epidemics. Furthermore, especially in countries such as Australia, Canada, or the United States, subsequent waves of immigration have had a profound effect on population growth. From demographics, it is indeed well-known that migration is a relatively volatile component of population growth (Zaiceva and Zimmermann, 2016, pp.127ff.). Conversely, according to demographic transition theory, the birth surplus is characterised by secular trends. In Figure 1, the postulated hump-shaped development can indeed be observed in virtually all countries. It is this development that has recently led to a decline in non-migrant population growth rates by approximately one to two percentage points, which matters for the ongoing secular stagnation debate (see Papetti, 2019; Gagnon *et al.*, 2016; Ikeda and Saito, 2014).

Figure 1: Interest rates, per-capita economic growth, and population growth (1820-2018)



5 Results

5.1 Baseline results

Table 1 presents our baseline results of estimating (3) by treating the unobserved components as fixed effects.[10] While the estimation in Column 1 follows Borio *et al.* (2017, p.14; 2019, p.8) by containing only country-specific fixed effects, Column 2 includes country- and year-specific fixed effects for, respectively, α_j and α_t. According to the R^2, the specification without year-specific fixed effects (Column 1) explains only approximately 23 per cent of the total variation in real interest rates. However, the (adjusted) R^2 increases considerably in Column 2, indicating that unobserved year-specific developments, such as global money and credit cycles, may play an important role. Furthermore, standard F-tests to determine whether or not the fixed effects are jointly insignificant and, hence, redundant (see e.g. Baltagi, 2013, ch. 3.2.1) are highly significant for both α_j and α_t. Hence, it seems appropriate to employ the specification of Column 2 as the baseline model.

Further to the discussion of Section 4, the top panel of Table 1 employs total population growth, $\tilde{n}_{jt}$, to capture the demographic effect, while the bottom panel distinguishes between the contributions of the birth surplus, $\ddot{n}_{jt}$, and net migration, $\hat{n}_{jt}$. In Column 2 of Table 1, the "birth surplus" is positive and statistically significant. Conversely, the effects of total population growth in the top panel and net migration in the bottom panel are insignificant. The empirical impact of economic growth on real interest rates is generally positive and significant.

As emphasised at the outset, Borio *et al.* (2017, 2019) noted an instable effect of demographic variables, such as population growth, on real interest rates across various subperiods since the nineteenth century. To analyse whether this instability also occurs with the birth surplus effect on real interest rates, Columns 3 and 4 of Table 1 split the sample into observations before and after the year 1918. This year not only roughly divides the first and second centuries covered by the current sample but also marks an important historical turning point. Taken together, the birth surplus has had a consistently positive and significant effect before and after the end of World War I in 1918, while a significantly positive impact of total population growth arises only within the first subperiod of Column 3.

Columns 5 to 9 of Table 1 restrict the sample further to identify the differences across the main international currency systems. The corresponding results lend further support to the view that a nexus between population growth and the real interest rate occurs mainly through the birth surplus. In particular, total population growth rates in the top panel give rise to a range of effect, from a significantly positive effect during the mixed silver and gold currencies before the year 1870; insignificant entries during the classical gold standard (1870 to 1914), the interwar years (1919-1939), and the Bretton Woods system (1945-1971); to a significantly negative effect during recent decades. In a similar vein, the effect of net migration in the bottom panel is significantly positive for the years before 1870, negative during the interwar years, which suffered from widespread political and economic instability, and insignificant during the other subperiods. Conversely, the entries of the birth surplus are significant and positive across all international currency regimes between 1870 and 1970. Before and after this period, the effect is insignificant.

To test the stability of the coefficients in a formal manner, a pooled equation with time varying population growth coefficients across years is estimated and compared with the

[10]The potential correlation between the unobserved effects and the observed regressors introduces a major econometric issue when estimating panel data regressions, such as (3), with random effects. In particular, the monetary traditions reflected by α_j or the global monetary trends and cycles potentially absorbed by α_t could be correlated with the growth rate of the population n_{jt} or productivity x_{jt} (see, e.g., Wooldridge, 2002, pp.265ff.). Standard Hausman tests (see Baltagi, 2013, ch. 4.3) applied to equation (3) indeed provide evidence against using random effects. For the sake of brevity, the corresponding results are not reported here but are available on request.

Table 1: Baseline results: Demographic effects on real interest rates

Sample:	All	All	Pre 1918	Post 1918	Mixed standards 1820-1869	Gold standard 1870-1914	Interwar 1918-1939	Bretton Woods 1945-1970	Floating 1971-2018
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Total population growth									
Population growth	0.10	0.03	0.18**	0.13	0.31***	0.08	-0.35	0.24	-0.49**
(total $\tilde{n}_{jt}$)	(0.12)	(0.09)	(0.08)	(0.24)	(0.10)	(0.05)	(0.26)	(0.33)	(0.25)
Economic growth	-0.001	0.03**	0.02*	0.02	-0.002	0.003	-0.03	0.02	-0.18
(x_{it})	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)	(0.03)	(0.05)
Country FE	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	no	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	1,862	1,862	763	1,099	203	517	251	296	516
R^2	0.23	0.78	0.90	0.76	0.80	0.95	0.84	0.69	0.85
Adj. R^2	0.22	0.75	0.88	0.74	0.72	0.94	0.81	0.64	0.83
α_j-insign. (F-stat)	5.2***	16.0***	7.7***	18.0**	23.3***	19.7***	14.4***	41.1***	19.1***
α_t-insign. (F-stat)		21.5***	43.7***	21.2**	4.9***	127.4***	37.2***	2.1***	44.5***
Population growth from the birth surplus and net migration									
Population growth	0.15	0.40**	0.97***	1.71***	-0.08	0.59***	2.31***	1.06*	-1.05
(from birth surplus $\ddot{n}_{jt}$)	(0.21)	(0.17)	(0.26)	(0.39)	(0.23)	(0.18)	(1.00)	(0.64)	(0.65)
Population growth	-0.27***	-0.19	0.09	-0.54**	0.37***	0.04	-0.94**	-0.02	-0.35
(from net migration $\hat{n}_{jt}$)	(0.14)	(0.11)	(0.06)	(0.26)	(0.13)	(0.04)	(0.27)	(0.32)	(0.31)
Economic growth	0.002	0.04**	0.02*	0.03	0.004	0.004	-0.03	0.02	-0.19***
(x_{it})	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)	(0.03)	(0.05)
Country FE	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	no	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	1,742	1,724	626	1,098	130	453	250	296	516
R^2	0.23	0.78	0.90	0.77	0.88	0.95	0.85	0.69	0.85
Adj. R^2	0.22	0.74	0.88	0.75	0.80	0.94	0.83	0.64	0.83
α_j-insign. (F-stat)	5.6***	12.6***	8.7***	17.7***	33.2***	20.1***	12.0***	37.8***	18.9***
α_t-insign. (F-stat)		20.1***	37.9***	22.6***	64.0***	110.7***	27.3***	2.2***	42.9***

Notes: This table reports estimates of Equation (3) with real interest rates, $i_{jt} - \pi^e_{jt}$, as the dependent variable. All regressions include dummy variables indicating fixed exchange rate regimes, the occurrence of a world war, a systemic financial crisis, and the installation of the gold standard, the Bretton Woods system, or inflation targeting in country j during year t. To measure interest rates i_{jt}, long-term bond yields are used. Recursive projections of an autoregressive model of inflation estimated over a rolling twenty-year window and averaged over the future 5 years are used to calculate π^e_{jt}. Coefficient estimation is by panel data estimators with fixed effects. Robust standard errors to heteroscedasticity and serial correlation are reported in parentheses (based on country clusters). Significant coefficients are indicated by * at the 10% level; ** at the 5% level, and *** at the 1% level. The diagnostic statistics appear in the lower part of each panel. Obs. denotes the number of observations. $\alpha_{(.)}$-insignificant refers to the F-test (based on HAC standard errors) on redundant fixed effects. Owing to the two-way nature of the panel data, this can pertain to the country-specific and the year-specific fixed effects. Diagnostic statistics that reject the null-hypothesis at the 10% level are marked by *, at the 5% level by **, and at the 1% level by ***.

results of Column 2 of Table 1.[11] This comparison lends itself to a standard test between unrestricted and restricted statistical models. For the effect of total population growth of the top panel, the corresponding F-statistic equals 1.5 and therefore rejects the restrictions of a stable demographic effect across years, even at the 10 per cent level.[12] With an F-statistic of 1.7, the same conclusion arises for the effect of net migration in the bottom panel. Conversely, an F-statistic of 1.0 does not reject a stable effect for the birth surplus in the bottom panel. Taken together, these results are perhaps not surprising, insofar as the birth surplus typically encapsulates the secular trends of demographic transition theory and is probably a better variable to reflect the intergenerational relationships that are arguably encapsulated in the long-term real interest rate, than the rather volatile development of international migration or total population growth.

5.2 Robustness checks

Our baseline results turn out to be robust to the following changes. First, as mentioned in Section 3, the measurement of inflation expectations poses a key challenge to determining the long-term real interest rate. Therefore, Columns 1 and 2 of Table 2 replace the main specification of Column 2 of Table 1 by employing, respectively, a one-sided moving average over the next *ten* years and a *centered* moving average over the past and future five years of expected inflation to calculate π^e_{jt} in (3). However, changing the measurement of inflation expectations does not alter the main result that the significantly positive effect of population growth arises mainly through the demographic trends associated with the birth surplus.

Second, similar to Hamilton *et al.* (2015) and Lunsford and West (2019), Column 3 of Table 2 employs the short-term interest rate for i_{jt} to estimate (3). This approach greatly simplifies the calculation of expected inflation π^e_{jt}, which can now be derived from the projection of the above-mentioned AR(1) for the current year to match the maturity of less than one year. However, contemplating short-term interest rates does not change the essence of the baseline results.

Third, seemingly unrelated regressions (SUR) are estimated across countries j and time t, see Columns 4 and 5 of Table 2. Fourth, to better absorb short-term shocks, our baseline model has been re-estimated with averages per decade (see Columns 6 and 7).[13] Finally, additional explanatory variables, such as life expectations, dependency ratio, total factor productivity, and inequality are considered in Column 8.[14] The inclusion of these additional variables is associated with a substantial reduction in the number of joint observations. However, except for the SUR standard deviations over time in Column 5, the main result that the birth surplus has a significantly positive effect on the real interest rate development remains through all these robustness checks.

5.3 Economic significance

Across the various specifications of Tables 1 and 2, the coefficient estimates pertaining to the birth surplus are almost always in the range between 0.4 and 1. These estimates imply that the reduction in the birth surplus of approximately one to two percentage points observed during the last decades (see Fig. 1) has caused a decline in the long-term real interest rate of approximately one percentage point. This estimated decline due to the demographic

[11] For the sake of brevity, the results of this pooled regression equation are not reported here, but are available on request.

[12] The degrees of freedom of the critical F-values of comparing a restricted model with an unrestricted model are given by the number of restrictions (here, that the population growth coefficients are equal across the 198 years of the sample) and the number of observations minus the number of coefficients (with the current sample size of more than 1,000).

[13] In this specification, the country-fixed effect becomes insignificant in the bottom panel of Table 2 and can thus be excluded.

[14] See Borio *et al.* (2017, pp.8ff.) for an economic motivation of these explanatory variables.

Table 2: Robustness checks: Demographic effects on real interest rates

Robustness check:	$\pi^e_{j,t+10}$	$\pi^e_{i,t\pm5}$	Short-term i_{jt}	Country SUR std.	Year SUR std.	10-year av.	10-year av.	Large model
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Total population growth								
Population growth	0.10	0.29**	0.14	0.03	0.03	0.05	0.26**	-0.33
(total $\tilde{n}_{jt}$)	(0.09)	(0.12)	(0.09)	(0.08)	(0.18)	(0.20)	(0.13)	(0.29)
Life expectancy								0.17***
								(0.06)
Dependency ratio								6.46***
								(1.42)
Economic growth	0.02*	0.02	0.02	0.03***	0.03*	0.26	0.32	0.04
(x_{it})	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)	(0.21)	(0.20)	(0.03)
TFP								0.26***
								(0.07)
Inequality								0.001
								(0.04)
Obs.	1,772	1,843	1,811	1,862	1,862	202	202	765
R^2	0.81	0.78	0.73	0.78	0.78	0.82	0.80	0.81
Adj. R^2	0.78	0.75	0.70	0.75	0.75	0.79	0.78	0.77
α_j-insign. (F-stat)	15.4***	13.5***	16.3***	16.0***	16.0***	2.0**		16.5***
α_t-insign. (F-stat)	23.3***	21.3***	14.4***	21.5***	21.5***	39.5***	37.0***	12.7***
Population growth from birth surplus and net migration								
Population growth	0.28*	0.40***	0.55**	0.40**	0.40	0.09	0.63**	1.01**
(birth surplus $\ddot{n}_{jt}$)	(0.16)	(0.17)	(0.27)	(0.19)	(0.51)	(0.36)	(0.28)	(0.51)
Population growth	-0.04	0.16	-0.07	-0.19*	-0.19	-0.39	-0.40	-0.71***
(net migration $\hat{n}_{jt}$)	(0.11)	(0.15)	(0.11)	(0.10)	(0.19)	(0.36)	(0.34)	(0.33)
Life expectancy								0.11
								(0.07)
Dependency ratio								3.47**
								(1.66)
Economic growth	0.03**	0.02	0.02	0.04***	0.04**	0.28	0.33	0.05
(x_{it})	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.21)	(0.20)	(0.03)
TFP								0.24***
								(0.07)
Inequality								0.002
								(0.04)
Obs.	1,639	1,705	1,733	1,724	1,724	192	192	764
R^2	0.80	0.77	0.73	0.78	0.78	0.82	0.80	0.82
Adj. R^2	0.77	0.74	0.70	0.74	0.74	0.78	0.77	0.78
α_j-insign. (F-stat)	12.6***	11.2***	8.0***	12.6***	12.6***	1.6		14.3***
α_t-insign. (F-stat)	21.8***	19.8***	12.6***	20.1***	20.1***	34.9***	33.8***	12.8***

Notes: This table reports estimates of (3) with real interest rates, $i_{jt} - \pi^e_{jt}$, as the dependent variable. Except for columns 6 and 7, all regressions include dummy variables indicating the occurrence of a world war, a systemic financial crisis, a fixed exchange rate, or the installation of the gold standard, the Bretton Woods system, or inflation targeting in country j during year t. For a detailed description of the estimation and definition of the diagnostic statistics, see the notes of Table 1. Columns 4 and 5 employ a seemingly unrelated regression (SUR) structure across countries and years, respectively, to calculate the coefficient standard deviations. Columns 6 and 7 average the observations across ten years. In the bottom panel of column 7, the country fixed effect is also dropped because it is insignificant. The detailed definition and sources of the additional variables employed in column 3 and 8 can be found in Table 4 of the Appendix.

transition generally coincides with the corresponding simulated values reported by Gagnon *et al.* (2016) for the United States and Papetti (2019) for the euro area.

6 Summary and conclusion

Although the effects of population growth on real interest rate levels are well founded in macroeconomic theories, such as the overlapping generations model, the corresponding empirical results have been rather elusive. Within a sample comprising the historical development of interest rates, inflation, population growth, and per capita economic growth for 12 countries since the year 1820, panel data regressions uncover a positive relationship between population growth and long-term real interest rates. In particular, considering the birth surplus as a component of population growth, the corresponding relationship is positive, statistically significant, and quite stable over time when splitting the sample across various subperiods. Hence, consistent with standard macroeconomic theory, our results suggest that population growth through the birth surplus indeed affects the equilibrium real interest rate.

Our results help reconcile standard macroeconomic models with the empirical literature. However, although our empirical findings could also help explain the currently low interest rate levels by the secular decline of the birth rate, which has in some countries fallen even below the mortality rate, the long-term nature of these relationships should be kept in mind. Non-demographic factors, such as credit cycles, monetary policy, increased wealth, or productivity growth, could still profoundly affect both nominal and real interest rate developments over the coming years and possibly even decades.

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A Description and sources of the data

Table 3: Description of the data set

The data have an annual frequency and cover 12 countries and the 1820-to-2018 period.

Variable	Unit	Description
Nominal interest rate i_{jt}	per cent	Nominal interest rate typically measured in terms of the yield on long-term government bonds. The main source is Homer (1977) before 1960, and thereafter the OECD statistics (long-term interest rates). Country details are: Australia: 1870-1929, long-term interest rate, Jorda-Schularick-Taylor macrohistory database (http://www.macrohistory.net/data/). 1930-1970, long-term government bond yields, Homer (1977, Tab. 77). Since 1970, OECD. Belgium: 1831-1918, yield on 2.5% rentes, Homer (1977, Tab. 30, 64). 1919-1944, yield on 3% rentes , Homer (1977, Tab. 64). 1945-1959, yield on 4% rentes, Homer (1977, Tab. 64). Since 1960, OECD. Canada: 1870-1899, long-term interest rate, Jorda-Schularick-Taylor macrohistory database. 1900-1919, Province of Ontario bond yields, Homer (1977, Tab. 70). 1920-1959, long-term government bond yields, Homer (1977, Tab. 70). Since 1960, OECD. Denmark: 1870-1929 and 1976-2000, long-term interest rate, Jorda-Schularick-Taylor macrohistory database. 1930-1975, long-term government bond yield, Homer (1977, Tab. 76). Since 2001, OECD. Finland: 1870-1987, long-term interest rate, Jorda-Schularick-Taylor macrohistory database. Since 1988, OECD. France: 1825-1899. Average yield on 3% rentes, Homer (1977, Tab. 25). 1900-1959, yield on perpetual 3% yields, Homer (1977, Tab. 60). Since 1960, OECD. Netherlands: 1820-1959, 2.5% perpetual bond yield, Homer (1977, Tab. 28, 62). Since 1960, OECD. Norway: 1820-1984, long-term government bonds yields quoted in various financial markets, Norges Bank, Historical Monetary Statistics for Norway – Part II. Since 1985, OECD. Sweden: 1856-1993, yields on long-term government securities, Sveriges Riksbank, Historical Statistics of Sweden, Tab. II.A6.3. Since 1994, OECD. Switzerland: 1831-1898, interest rate on saving account of various banks, Swiss National Bank historical time series, Tab. 4.3a. 1899-1954, yield on five-year federal government bond, SNB historical time series, Tab. 3.1. Since 1955, OECD. United Kingdom: 1820-1960, average yield on consols, Homer (1977, Tab. 19, 57). Since 1960, OECD. USA: 1820-1829, annual average yield U.S. 3s of 1790 (Homer, 1977, Tab.40). 1830-1859, current yield on Boston City 5s, Homer (1977, Tab. 41). 1860-1879, current yield on U.S. 6s of 1861-1881, Homer (1977, Tab. 42). 1880-1899, current yield on US Refunding 4s of 1907, Homer (1977, Tab. 43). 1900-1920, High Grade Municipal Bonds, Homer (1977, Tab. 45). 1921-1960, long-term government bond yield, Homer (1977, Tab. 48,50). Since 1960, OECD.
Inflation π_{jt}	per cent	Inflation in terms of the annual change of the consumer-price index (CPI). The main source is Mitchell (1992, 1995, 1998) before 1960, and thereafter the OECD statistics (inflation (CPI)). Country details are: Australia: 1862-1959, Mitchell (1995, Tab. H2). Since 1960, OECD. Belgium: 1836-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. Canada: 1871-1910, CPI change, Jorda-Schularick-Taylor macrohistory database (http://www.macrohistory.net/data/). 1911-1959, Mitchell (1998, Tab. H2). Since 1960, OECD. Denmark: 1821-1966, Mitchell (1992, Tab. H2). Since 1967, OECD. Finland: 1871-1914, Jorda-Schularick-Taylor macrohistory database. 1915-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. France: 1841-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. Netherlands: 1870-1880, Jorda-Schularick-Taylor macrohistory database. 1881-1960, Mitchell (1992, Tab. H2). Since 1961, OECD. Norway: 1820-1902, Norges Bank Historical Statistics. 1902-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. Sweden: 1831-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. Switzerland: 1820-1890, CPI change, Swiss economic and social history database (Tab. H39). 1891-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. United Kingdom: 1820-1959, Mitchell (1992, Tab. H2). Since 1960, OECD. USA: 1820-1959, Mitchell (1998, Tab. H2). Since 1960, OECD.
Population growth $\tilde{n}_{jt}$	per cent	Growth of the residential population calculated from the population size of the Maddison project database (vers. 2018). For France, the years 1870, 1871, and 1919 are dropped due to the loss and the recovery of parts of Alsace-Lorraine. For the United Kingdom, the year 1921 is dropped due to the independence of the Republic of Ireland.
Birth surplus $\ddot{n}_{jt}$	per cent	Birth surplus (positive/negative) in terms of the difference between the crude birth rate and the crude mortality rate. This is also called the "rate of natural population growth".
Net migration $\hat{n}_{jt}$	per cent	Net migration is given by the difference between total population growth ($\tilde{n}_{jt}$) and the birth surplus ($\hat{n}_{jt} = \tilde{n}_{jt} - \ddot{n}_{jt}$).
Economic growth x_{jt}	per cent	Real economic growth in terms of annual change of real GDP per capita. The data are taken from the Maddison project database (vers. 2018) with a US$ 2011 benchmark.
World War	nom.	Variable indicating that country j is involved in World War I or World War II during year t.
Crisis	nom.	Systemic financial crisis in country j during year t. Sources: Kindleberger and Aliber (2011, pp.302ff.) before 1870, and thereafter Jorda-Schularick-Taylor macrohistory database (http://www.macrohistory.net/data/).
Monetary regime	nom.	Variable indicating that country j adhered to the gold standard, the Bretton Woods System, or inflation targeting during year t. Sources: Bordo *et al.* (2017, p.27), Benati (2008, pp.1051ff).
Peg	nom.	Fixed exchange rate in country j during year t. Sources: Bordo *et al.* (2017, p.27) before 1870, and thereafter Jorda-Schularick-Taylor macrohistory database (http://www.macrohistory.net/data/).

Table 4: Description of the data set

Data used for the robustness checks

Variable	Unit	Description
Nominal interest rate i_{jt} (short-term)	per cent	Nominal interest rate typically measured in terms of the discount or money market interest rate. The main source is Homer (1977) before 1960, and thereafter the OECD statistics (short-term interest rates). Country details are: Australia: 1870 -1936, short-term interest rate, Jorda-Schularick-Taylor macrohistory database (http://www.macrohistory.net/data/). 1937-1960, short-term government bond yields, Homer (1977, Tab. 77). Since 1968, OECD. Belgium: 1848-1959, discount rate, Homer (1977, Tab. 31, 65). Since 1960, OECD. Canada: 1935-1959, discount rate, Homer (1977, Tab. 70). Since 1960, OECD. Denmark: 1875-1929 and 1976-1986, short-term interest rate, Jorda-Schularick-Taylor macrohistory database. 1930-1975, official discount rate, Homer (1977, Tab. 76). Since 1997, OECD. Finland: 1870 -1987, short-term interest rate, Jorda-Schularick-Taylor macrohistory database. Since 1987, OECD. France: 1863-1969, discount rate, Homer (1977, Tab. 27, 61). Since 1970, OECD. Netherlands: 1820-1975, discount rate, Homer (1977, Tab. 29, 63). 1976-1981, money market rate (Q1), IFS of IMF. Since 1982, OECD. Norway: 1820-1978, marginal liquidity rate, Norges Bank, Historical Monetary Statistics for Norway – Part II. Since 1979, OECD. Sweden: 1854-1975, discount rate, Homer (1977, Tab. 35, 69). 1976-1981, yields on short-term government securities, Historical Statistics of Sweden, Table II.A6.3. Since 1982, OECD. Switzerland: 1837-1973, discount rate, Homer (1977, Tab. 34, 68). Since 1974, OECD. United Kingdom: 1820-1975, discount rate, Homer (1977, Tab. 23, 59). 1976-1985, short-term interest rate Measuring Worth (www.measuringworth.com). Since 1986, OECD. USA: 1857-1964, call money rate, Homer (1977, Tab. 44, 51). Since 1965, OECD.
Life expectancy	years	Life expectancy at birth. Source: www.mortality.org. The data refer to the total (male and female) population.
Dependency ratio	ratio	Population with age below 20 and above 65 as a fraction of the population between 20 and 65. Compiled from population tables of www.mortality.org.
Total factor productivity	index	Total factor productivity (TFP). Source: Long-term productivity database (www.longtermproductivity.com). See also Bergeuad *et al.* (2016).
Inequality	ratio	Share of top 1 per cent in gross income (tax units, excluding capital gains). Source: Chartbook of Economic Inequality (www.chartbookofeconomicinequality.com).

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