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Federal Reserve Bank of St. Louis, Research Division, P.O. Box 442, St. Louis, MO 63166

Technology adoption and mortality*

John Hejkal[†] B. Ravikumar[‡] G. Vandenbroucke[§]

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Abstract

We develop a quantitative theory of mortality trends and population dynamics. In our theory, individuals incur time and/or goods costs over their life cycle, to adopt a better health technology that increases their age-specific survival probability. Technology adoption is a source of a dynamic externality: As more individuals adopt the better technology, the marginal benefit of future adoption increases. The allocation of time and/or goods also depends on total factor productivity (TFP): As TFP grows, more resources are allocated to technology adoption. Both channels—the dynamic externality and TFP—result in lower mortality. Our theory is consistent with three key facts: (i) The cross-country correlation between mortality and income is negative, (ii) mortality in poor countries has converged to that of rich countries although the income of poor countries has not, and (iii) mortality decline precedes economic take-off. We calibrate the model to match mortality in France from 1816 to 2010. Quantitatively, the model accounts for 54% of the closing of the mortality gap between France and low-income countries over the past 50 years.

JEL codes: I12, I15, J11, E13
Keywords: Mortality, population dynamics, technology adoption, diffusion.

*The views expressed in this article are those of the authors and do not necessarily reflect the views of the Federal Reserve Bank of St. Louis or the Federal Reserve System.

[†]Email: john.hejkal@gmail.com

[‡]Research Division, Federal Reserve Bank of St. Louis, P.O. Box 442, St. Louis, MO 63166, USA. Email: b.ravikumar@wustl.edu.

[§]Corresponding author. Research Division, Federal Reserve Bank of St. Louis, P.O. Box 442, St. Louis, MO 63166, USA. Email: guillaumevdb@gmail.com.

1 Introduction

The crude death rate—the number of deaths per 1,000 persons in a given year—declined by a factor of two between 1960 and 2000 for the world as a whole. For some regions of the world, the trend started over 200 years ago. Figure 1 illustrates the crude death rates for France and Sweden over the past 200 years. In France, for instance, the death rate declined from 27.7 around 1816 to 8.7 in 2017, a rate of decline of 0.6 percent per year.[1]

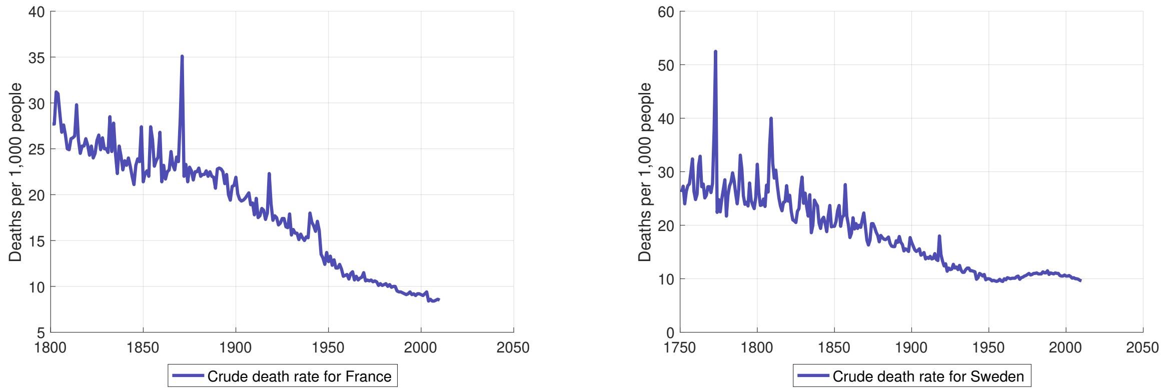
While much effort has been devoted to understanding the determinants of fertility and its role in shaping the demographic trends, the observed population growth rates cannot be explained by changes in fertility alone. Figure 2 illustrates the world population and fertility rate over the past 200 years. It took 82 years for the world population to increase from 1 billion to 1.5 billion, an average annual growth rate of less than 0.5 percent; the total fertility rate during this period was 5.7 births per woman. In contrast, it took only 8 years for the world population to increase from 3 billion to 3.5 billion; the population growth rate quadrupled to almost 2 percent per year, while the fertility rate decreased to 5 births per woman. Since the growth rate of the *world* population is the difference between the fertility and mortality rates, explaining the increasing rate of population growth would need a theory of mortality decline.[2]

Our objective is to develop a quantitative theory of mortality trends and population dynamics. An essential feature of our theory is costly technology adoption over the life cycle. There are two technologies—obsolete and modern—that are characterized by age-specific survival probabilities, with the modern technology offering a higher chance of survival at all ages. Individuals have to spend resources—time and/or goods—in order to acquire the modern technology. The probability of acquiring the modern technology is an increasing function of the resources spent by the individual. Incurring the adoption cost at any age gives the individual an opportunity to increase his survival probability at all subsequent ages permanently. Adoption also confers a dynamic externality: As more individuals adopt the modern technology, the probability of acquiring the modern technology increases. The allocation of resources depends on total factor productivity (TFP) as well.

The two-technologies feature keeps our model tractable: At any point in time, cross-sectional heterogeneity is limited to the individual's age and whether the individual has the obsolete technology or the modern technology. TFP and the dynamic externality are the two channels

[1] Figure A.1 illustrates the crude death rates for other European countries over the past 200 years.

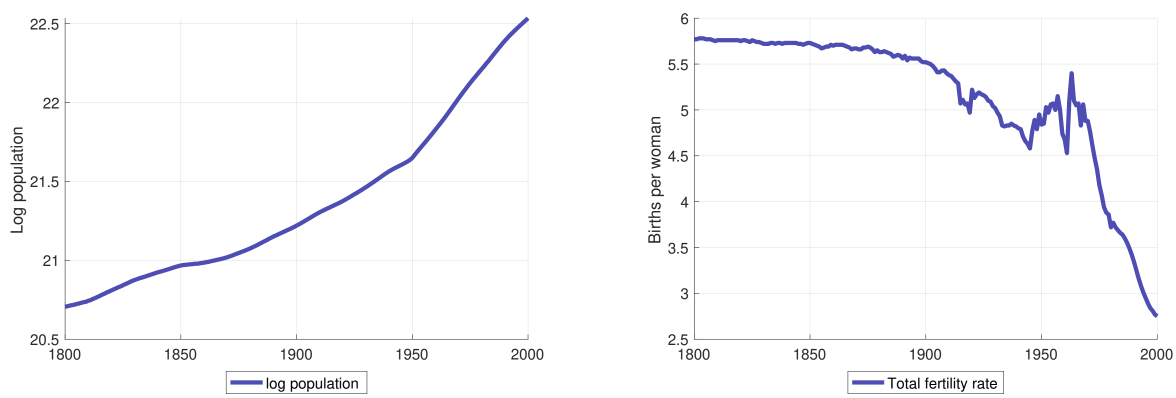
[2] For the first time in more than 200 years, the population growth rate declined in the late 1970s. (See https://www.gapminder.org/ for the data.) Horiuchi (1992) notes that as late as throughout the 1960s, the rising population growth rate resulted from declining mortality. The decline in the 1970s resulted from an accelerated fertility decline coupled with a decelerating mortality decline.



France   Sweden

Figure 1: Crude death rates in France and Sweden

Source: Mitchell (2003).



World population   World fertility

Figure 2: The world's population and fertility over time

Source: https://gapminder.org/ and https://ourworldindata.org/.

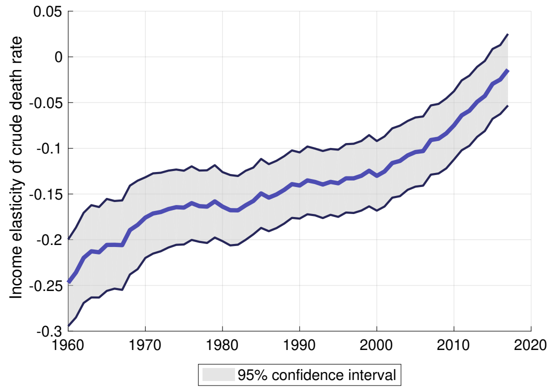


Figure 3: The correlation between mortality and real GDP per capita

Note: Consider the regression

$$\ln(\text{cdr}_{i,t}) = \delta_t \ln(y_{i,t}) + \text{constant}_t + \epsilon_{i,t},$$

where $\text{cdr}_{i,t}$ is the crude death rate in country i and year t and $y_{i,t}$ real GDP per capita. The figure shows δ_t.
Source: World Development Indicators and authors' calculations.

through which mortality declines in our model. The evolution of TFP is exogenous in the model. At low levels of TFP, the opportunity cost of time is low and the relative price of goods is high. Individuals incur the time cost to acquire the modern technology. At higher levels of TFP, goods become the cheaper alternative and individuals incur the goods cost. As TFP grows over time, more resources are spent trying to adopt the modern technology, and the mortality rate declines. The dynamic externality yields a higher marginal benefit to spending resources—incurring the time cost or the goods cost increases the odds of acquiring the modern technology, which results in more adoption and lower mortality. Starting with an exogenous proportion of individuals who have the modern technology, this proportion of individuals evolves endogenously, so the force of dynamic externality at any point in time is endogenous. The evolution of this proportion of individuals follows an S-curve, as in models of diffusion.

Our theory of mortality has to confront three key facts: (i) The cross-country correlation between mortality and income is negative, (ii) mortality in poor countries has converged to that of rich countries although the income of poor countries has not, and (iii) mortality decline precedes economic take-off.

Negative correlation between income and mortality Figure 3 shows the elasticity of the crude death rate with respect to real gross domestic product (GDP) per capita. The crude death rate is negatively correlated with income. In 1960, if a country had a real GDP per capita 1 percent higher than another country, the former's crude death rate was 0.25 percent lower than the latter's crude death rate.

The TFP channel in our model can deliver this fact: Richer countries have higher TFP relative to poorer countries and they spend more resources to acquire the modern technology, which results in a lower mortality rate. This result does not rely on the dynamic-externality channel.

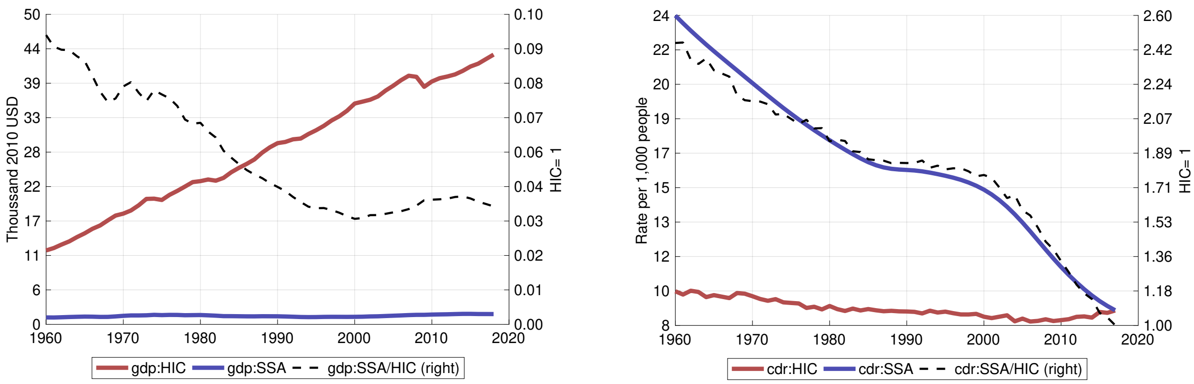
Cross-country convergence in health but not income Panel A of Figure 4 shows real GDP per capita in rich countries and in poor Sub-Saharan African countries since 1960. A well-known pattern emerges—the absence of convergence between the two groups. Poor countries are becoming poorer than rich: from 9% of GDP per capita of rich countries in 1960 to about 3% in 2018. Panel B paints a different picture, however. Despite the divergence in income, there is convergence in crude death rates: The rate was 2.6 times higher in Sub-Saharan African countries than in rich countries in 1960 but becomes essentially the same by 2018.[3] The convergence in mortality coupled with divergence in income also implies that the correlation between income and mortality approaches zero over time, as indicated in Figure 3.[4]

The TFP channel as well as the dynamic-externality channel can deliver the fact above. Consider the cross section, as in 1960 for instance: Rich countries have a lower mortality rate than poor countries. With TFP growth in both groups (the growth could be the same in both groups or it could be higher in rich countries relative to poor countries), the mortality rate would decline in both groups, as noted earlier. However, with an S-shaped diffusion curve as implied by our model, the diffusion is faster in poor countries implying a faster decline in mortality than in rich countries.

Mortality decline precedes economic take-off Despite the views of classical economists such as Adam Smith and Thomas Malthus, there seems to be little evidence of a causal effect of economic development on mortality. This disconnect has been pointed out by Fogel (2004) and Livi-Bacci (1991), for instance. As a case in point, Figure 5 shows demographic and economic data for England from the 16th to the 19th centuries. Panel A indicates that the crude death rate declined throughout the 18th century. Panel B, however, indicates that economic take-off did not occur before the early part of the 19th century. Specifically, TFP in both the agriculture and manufacturing sectors are flat throughout the 18th century, the production of

[3] Acemoglu and Johnson (2007) noted that since the 1930s life expectancy of poor countries converged to that of rich countries even though GDP per capita did not.

[4] Figures A.2-A.3 illustrate the same pattern of convergence in crude death rates without convergence in income for high-income v. low-income countries, and for the United States v. Benin.



A – Real GDP per capita B – Crude death rate

Figure 4: Demography and the economy: High-income countries (HIC) v. Sub-Saharan Africa (SSA)

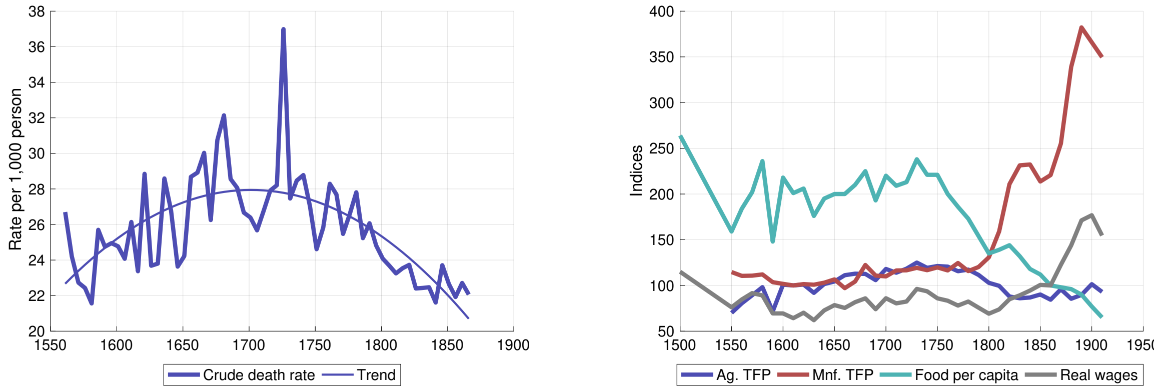
Note: Panel A shows real GDP per capita in high-income countries (HIC) and Sub-Saharan African (SSA) countries (excluding high income) with solid lines. The dashed line indicates the SSA-to-HIC ratio of real GDP per capita. Panel B shows the crude death rate (cdr) with solid lines in the two regions, and the SSA-to-HIC ratio of crude death rates (dashed line). Sub-Saharan Africa comprises Angola, Ethiopia, Niger, Benin, Gabon, Nigeria, Botswana, Gambia, Rwanda, Burkina Faso, Ghana, Sao Tome and Principe, Burundi, Guinea, Senegal, Cabo Verde, Guinea-Bissau, the Seychelles, Cameroon, Kenya, Sierra Leone, the Central African Republic, Lesotho, Somalia, Chad, Liberia, South Africa, Comoros, Madagascar, South Sudan, the Congo (Dem. Rep.), Malawi, Sudan, the Congo, Mali, Tanzania, the Ivory Coast, Mauritania, Togo, Equatorial Guinea, Mauritius, Uganda, Eritrea, Mozambique, Zambia, Eswatini, Namibia, Zimbabwe. High-income countries are those with a gross national income per capita of $12,376 or more in 2018.
Source: World Development Indicators.

food per capita is not increasing, and wages increase only at the onset of the 19th century.

The dynamic-externality channel by itself delivers this fact. Starting with a proportion of individuals who have the modern technology, others spend resources to increase their survival probability, which results in a higher proportion of individuals with the modern technology. The dynamic externality induces more resource expenditure toward the modern technology, which further increases the proportion of individuals with the modern technology. All of this results in mortality declining without an increase in income. Our results are thus consistent with the views in Fogel (2004) and Livi-Bacci (1991).

To explain all of the above facts, both channels—TFP and the dynamic externality—are important. Clearly, the cross-country negative correlation between income and mortality cannot be delivered solely by the dynamic externality, and mortality decline preceding economic take-off cannot be delivered solely by TFP growth.

The crucial parameters in our model are those of the function that maps proportion of indi-



A – Crude death rate B – Economic activity

Figure 5: Mortality and the economy in England from the 16th to the 19th centuries

Source: Wrigley et al. (1997, Tables 6.3 & A9.1), Clark (2002, Tables 1, 3 & 5) and Leukhina and Turnovsky (2016).

viduals with the modern technology and expenditures on time and goods into the probability of acquiring the modern technology. We calibrate the parameters of our model to French data. Specifically, we find parameters such that the model fits the time series of the French crude death rate given the time series of the French crude *birth* rate and a constant 2% annual growth rate of TFP. The exogenous crude birth rate makes the calibrated model consistent with the age distribution of the French population throughout the past 200 years.

We use the calibrated model to investigate mortality trends in poor countries between 1960 and 2010. We consider a stylized poor country: It starts out with a relatively young population in 1960, experiences slower TFP growth than France, and is endowed with a crude birth rate path similar to that of an average poor country. Its *initial* crude death rate is that of an average poor country in 1960. Our model implies a decline of the crude death rate of the poor country over time and closes 54% of the initial mortality gap between the poor country and France.

2 Model

2.1 Individuals

Time is discrete and indexed by t. The economy is populated by overlapping generations of individuals living up to a maximum age J. The preferences of an individual of generation t

(i.e., an individual of age 0 at date t) and age a are represented by

$$E_{t,a}\left[\sum_{j=a}^{J}\beta^{j-a}U\left(c_{t,j}\right)\right],$$

where $\beta \in (0,1)$ is the subjective discount factor, U is a utility index, $c_{t,j}$ represents consumption at age j, and $E_{t,a}$ is the expectation operator conditional on the information available to the individual at age a. Mortality is the only source of uncertainty, hence the expectation is taken against the appropriate age-specific survival probabilities. There are two health-relevant technologies available at any point in time: "obsolete" and "modern." These technologies are characterized by sequences of age-specific survival probabilities, $\left\{s_j^i\right\}_{j=0}^{J}$, where s_j^i denotes the probability of survival from age j to $j+1$, conditional on being alive at age j, for "modern individuals," i.e., individuals using the modern technology ($i = m$), and for "obsolete individuals," i.e., individuals using the obsolete technology ($i = o$). Since J is the maximum length of life, we assume $s_J^o = s_J^m = 0$.

Individuals become "economically active" at age $k > 0$. From age k to J they are endowed with one unit of time each period. The hourly wage rate is denoted by w_t in period t. Savings are not permitted. Modern individuals do not make decisions and allocate all their time to working. The value of a modern individual of generation t and age $j \geq k$ is

$$V_{t,j}^m = U(w_{t+j}) + \beta s_j^m V_{t,j+1}^m. \tag{1}$$

An obsolete individual can adopt the modern technology with some probability and become a modern individual. The probability of adoption for an age $j > k$ member of generation t is

$$Q(y_{t,j}, h_{t,j}, \pi_{t+j}), \tag{2}$$

where $y_{t,j}$ represents goods resources, $h_{t,j}$ represents time, and π_{t+j} is the proportion of modern individuals at date $t+j$. Both $y_{t,j}$ and $h_{t,j}$ are choices. The value of an obsolete individual is

$$\begin{aligned} V_{t,j}^o = \max_{y,h} U\left(w_{t+j}(1-h) - y\right) + \beta Q(y_{t,j}, h_{t,j}, \pi_{t+j}) s_j^m V_{t,j+1}^m \\ + \beta\left(1 - Q(y_{t,j}, h_{t,j}, \pi_{t+j})\right) s_j^o V_{t,j+1}^o. \end{aligned} \tag{3}$$

Since the probability of survival is 0 at age J, the terminal condition for modern and osolete individuals is

$$V_{t,J}^m = V_{t,J}^o = U(w_{t+J}).$$

At an interior, the optimal choice of an obsolete individual is characterized by the first-order conditions

$$
\begin{aligned}
y_{t,j} \quad &: \quad 0 = U_1\left(w_{t+j}\left(1-n\right)-e\right) - \beta Q_1(y_{t,j}, h_{t,j}, \pi_{t+j})\Delta_{t,j}, & (4)\\
h_{t,j} \quad &: \quad 0 = U_1\left(w_{t+j}\left(1-n\right)-e\right) w_{t+j} - \beta Q_2(y_{t,j}, h_{t,j}, \pi_{t+j})\Delta_{t,j}, & (5)
\end{aligned}
$$

where $\Delta_{t,j} \equiv s_j^m V_{t,j+1}^m - s_j^o V_{t,j+1}^o$.

2.2 Population dynamics

Let $p_{t,j}^i$ denote the population of obsolete ($i = o$) and modern ($i = m$) individuals of age j in generation t. The population of obsolete individuals at t is then $\sum_{j=0}^{J} p_{t-j,j}^o$ and, similarly, the population of modern individuals at t is $\sum_{j=0}^{J} p_{t-j,j}^m$.

Let $\mathbf{cbr}_t$ denote the crude birth rate at date t. The crude birth rate indicates the number of births per person at a point in time. We make the following assumptions: (i) We abstract from modeling age-specific fertility rates for simplicity; (ii) the crude birth rate is the same for modern and obsolete individuals; and (iii) obsolete individuals are born from obsolete individuals and modern individuals are born from modern individuals. The latter assumption represents the notion that a person cannot teach their offspring a technology they do not themselves use. Modern individuals can. The age-0 populations of modern and obsolete individuals in cohort t is

$$p_{t,0}^i = \mathbf{cbr}_{t-1} \sum_{j=0}^{J} p_{t-1-j,j}^i \qquad \text{for } i = o, m. \tag{6}$$

From age 0 to age $k-1$, the populations of modern and obsolete individuals evolve according to

$$p_{t,j+1}^i = s_j^i p_{t,j+1}^i \qquad \text{for } j = 0, \ldots, k-1 \;\text{ and } i = o, m. \tag{7}$$

Finally, the economically active ($j \geq k$) populations of modern and obsolete individuals of generation t evolve according to

$$
\begin{aligned}
p_{t,j+1}^o &= s_j^o p_{t,j}^o \left[1 - Q(y_{t,j}, h_{t,j}, \pi_{t+j})\right] & (8)\\
p_{t,j+1}^m &= s_j^m \left[p_{t,j}^m + Q(y_{t,j}, h_{t,j}, \pi_{t+j}) p_{t,j}^o\right]. & (9)
\end{aligned}
$$

The first equation indicates that a fraction $1 - Q(y_{t,j}, h_{t,j}, \pi_{t+j})$ of the age-j obsolete remain obsolete and that s_j^o of them survive to the next age. The second equation indicates that $Q(y_{t,j}, h_{t,j}, \pi_{t+j})p_{t,j}^o$ age-j obsolete become modern and that, together with the $p_{t,j}^m$ already-modern, they face survival probability s_j^m.

The proportion of economically active modern is

$$\pi_t = \frac{\tilde{p}_t^m}{\tilde{p}_t^m + \tilde{p}_t^o},$$

where $\tilde{p}_t^i = \sum_{j=k}^{J} p_{t-j,j}^i$ is the economically-active population of modern or obsolete.

The diffusion

The flow from obsolete to modern among age-j during period t is

$$Q(y_{t-j,j}, h_{t-j,j}, \pi_t)p_{t-j,j}^o.$$

If the function Q is of the form $Q(y, h, \pi) = \pi F(y, h)$—as we assume in Section 3—then the flow from obsolete to modern is

$$\begin{aligned} Q(y_{t-j,j}, h_{t-j,j}, \pi_t)p_{t-j,j}^o &= \pi_t p_{t-j,j}^o F(y_{t-j,j}, h_{t-j,j}), \\ &= \frac{\tilde{p}_t^m p_{t-j,j}^o}{\tilde{p}_t^m + \tilde{p}_t^o} F(y_{t-j,j}, h_{t-j,j}). \end{aligned}$$

We make three observations. First, this equation is similar to that found in SIR-type models in epidemiology and yields an interpretation of the function F as a "contact rate," that is, the number of meetings needed in a period for an obsolete individual to learn the modern technology. Second, adoption is costly in our model because meeting modern individuals requires resources. Upon meeting with a modern individual, the cost of acquiring the modern technology is zero. An obsolete individual can allocate resources to finding a modern individual and fail. In this case the individual does not acquire the modern technology even though he expended resources.

Finally, our model exhibits the familiar S-shaped diffusion pattern. When the proportion of modern individuals is close to 0, the flow of adopters is "small." When the proportion of modern individuals is close to 1, the population of obsolete individuals is close to 0 and, therefore, the flow of adopters is "small" as well. The S-shaped pattern of diffusion is important for understanding the convergence of mortality between poor and rich countries despite the lack of convergence in income.

3 Quantitative Analysis

3.1 Functional forms

We use the following functional forms. The probability of adoption of the modern technology is

$$Q(y,h,\pi) = \pi\Lambda\left[1 - \exp(-\lambda\chi(y,h))\right].$$

Thus Q is proportional to the proportion of modern individuals, as we discussed in Section 2. The function $\Lambda\left[1 - \exp(-\lambda\chi)\right]$ represents the contact rate of an individual. It cannot exceed Λ. Thus, the probability that an individual adopts the modern technology is increasing in χ (as long as $\lambda > 0$) and it is bounded above by $\Lambda\pi$. We use

$$\chi\left(y,h\right) = \left(\alpha_y y^\theta + \alpha_h h^\theta\right)^{1/\theta}$$

to aggregate time and goods spent in adopting the modern technology. Finally, we use a utility index from the CARA family to represent preferences:

$$U\left(c\right) = \Sigma - \exp\left(-\sigma c\right).$$

We choose a CARA form for U because, together with the formulation for Q, it yields an analytical solution for the first-order conditions of an individual's optimization problem and, therefore, greatly reduces the computational cost of fitting the model to the data. We check, in our computations, that U is always positive. This is an important restriction on preferences that is necessary in models of this nature. Rosen (1988) pointed this out: When the utility index is negative, an extra year of life reduces utility. Appendix B describes the optimal solution for y and h.

3.2 Calibration

We consider a rich country (France for our purpose) and use data on age-specific survival probabilities at two far-apart points in time. We associate these survival probabilities with our model's obsolete and modern technologies. Next, we assume that at some initial date a "small" fraction of people are endowed with the modern technology, while all the other are not. We then compute the time path of the crude death rate as the model-economy grows through time and match it to its empirical counterpart. The remainder of this section describes the details of this procedure.

A model period is 1 year. We set the discount factor β to 0.97, and we let w_t grow at 2% per year. Age-specific survival probabilities for France in 1816 represent the mortality of obsolete individuals and in 2017 represent the mortality of modern individuals.[5] The age-specific survival probabilities are available for all ages from 0 to 111. Thus, we set $J = 111$. Figure A.4 shows the survival probabilities.

We consider the economy from date $t = 1, \ldots, T$, where date 1 corresponds to 1816 and date T to 2017. The size of the date 1 population is normalized to 1, and its age distribution is given by the age distribution of the 1816 population in France. This data is from the Human Mortality Database (cf. footnote 5.) We use the crude birth rate in France from 1816 to 2017 for $\mathbf{cbr}_t$ from Mitchell (2003). Figure A.5 displays this data. We assume the wage rate grows at 2 percent per year during this period.

Let $\omega = (\lambda, \Lambda, \sigma, \Sigma, \alpha_y, \alpha_h, \theta)$ denote the list of parameters to determine. Given ω, we denote by $\mathbf{cdr}_t(\omega)$ the crude birth rate at date t implied by the model:

$$\mathbf{cdr}_t(\omega) = \frac{1}{p_t} \sum_{i \in \{m,o\}} \sum_{j=0}^{J} p^i_{t-j,j} \left(1 - s^i_j\right). \tag{10}$$

We determine ω as the solution of the following distance-minimization problem:

$$\min_{\omega} \frac{1}{\sqrt{T}} \sum_{t=1}^{T} \left[\mathbf{cdr}_t(\omega) - \mathbf{cdr}_t(\text{data})\right]^2. \tag{11}$$

Table A.1 gives the calibrated parameters. Panels A and B of Figure A.6 show the model's fit to the time series of the crude death rate (Panel A) and the annual rate of population growth (Panel B).[6] Panel C shows a comparison between age-specific survival probabilities from the model and the data in 1900—an arbitrary intermediate date between 1816 and 2017.[7] The date-t age-specific survival rate of an age-j person is

$$s^t_j = s^m_j \frac{p^m_{t-j,j}}{p^m_{t-j,j} + p^o_{t-j,j}} + s^o_j \frac{p^o_{t-j,j}}{p^m_{t-j,j} + p^o_{t-j,j}}.$$

Panel C of Figure A.6 reveals that the model is able to reproduce well the age-specific survival

[5]The data for survival probabilities are from the Human Mortality Database: University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany), available at www.mortality.org or www.humanmortality.de.

[6]We define the growth rate as the difference between the crude birth rate and the crude death rate. Thus, we abstract from migration into and out of France.

[7]We chose a date before World War I to avoid the effect of the war on the age-specific survival rates. It should be noted, however, that the effect of the Franco-Prussian War of 1870 might have affected the survival probabilites in 1900.

probabilities in 1900 up to age 60. From age 60 on, the model's implied survival probabilities exceed the actual survival probabilities. There can be two reasons for this. The first is that the model implies too fast an adoption rate of the modern technology. Panel D of Figure A.6 shows the diffusion curve of the new technology; that is, the proportion of modern individuals in the population. A second reason is that the model abstracts from various factors affecting survival probabilities in one particular year. As already noted, the war of 1870 may have an effect (most likely negative) on the survival probabilities of older people in 1900.

3.3 Experiments

We explore the implications of our calibrated model for mortality in a poor country. We will consider the poor country from 1960 onward, as the World Development Indicators data for the crude birth rates of poor countries start in 1960. The poor country is characterized as follows in our experiment:

1. At the initial date (1960) the age distribution of the population is that of the rich country (France) in 1816.
2. The crude birth rate is 47 (per 1,000 people) in 1960 and decreases at the annual rate of 0.55 percent. These numbers reproduce the behavior of the crude birth rate of the average low-income country in the World Development Indicators.
3. The growth rate of w_t is 1 percent per year. The 1960 wage level is set at 4 percent of the wage level of the rich country in 1960 in the baseline simulation. These figures corresponds to the growth rate of GDP per capita in Benin since 1960 and the ratio of GDP per capita between Benin and France in 1960.[8]
4. The initial proportion of modern individuals in 1960 is such that the crude death rate in the poor country in 1960 matches the observed crude death rate for low-income countries in the World Development Indicators: 25.13 deaths (per 1,000 people). This implies 11.55% of modern individuals in the poor country in 1960.

Figure A.7 displays the crude death rate from 1960 to 2010 for the rich and the poor countries, both from the model and from the data. The data for the rich country are French data since the model is calibrated to France. The data for the poor country is that of the average low-income

[8]The World Development Indicators does not provide GDP per capita figures for low-income countries in 1960. Thus, we use Benin. We compare Benin to France since the model is calibrated to France. The ratio of GDP per capita in Benin to high-income countries in 1960 is 4 percent as well.

country in the World Development Indicators. The 1960 crude death rate for the poor country matches the data by construction (see point 4 above).

Note the convergence between the crude death rates of the poor and the rich countries: The model implies that the crude death rate decreases faster in the poor country than in the rich country, despite the lack of convergence in income—recall that the growth rate of w_t is 1 percent in the poor country and 2 percent in the rich country. Specifically, the 1960 crude death rate in the poor country is 25.13, while in the rich country it is 11.40. Thus, the difference between the poor country's crude death rate and the rich country's in 1960 is 120.46%. In 2010 the difference is 12.68% (9.58 in the poor country and 8.50 in the rich). The model implies differences of 111.11% in 1960 (25.13 in the poor country and 11.90 in the rich) and 52.87% in 2010 (14.79 in the poor country and 9.68 in the rich). Thus, the model accounts for (52.87% − 111.11%)/(12.68% − 120.46%) = 54.03% of the reduction in the gap between 1960 and 2010.

We also describe our results in terms of the half-life of the gap between the crude death rates of the poor and the rich countries. Let the average rate of growth of the crude death rate be defined by $g = \ln(\mathbf{cdr}_{2010}/\mathbf{cdr}_{1960})/50$. The gap between the crude death rates at date $\tau \geq 1960$ is then approximately given by

$$\frac{\mathbf{cdr}_{\text{poor},\tau}}{\mathbf{cdr}_{\text{rich},\tau}} \simeq \frac{\mathbf{cdr}_{\text{poor},1960}}{\mathbf{cdr}_{\text{rich},1960}} \times \exp[n(g_{\text{poor}} - g_{\text{rich}})],$$

where $n = \tau - 1960$. The half-life of the gap is the solution n to the equation

$$\exp[n(g_{\text{poor}} - g_{\text{rich}})] = \frac{1}{2}.$$

In the data, the annual rates of growth of the crude death rates for the poor and the rich countries are −1.93% and −0.59%, respectively. This yields a half-life of 51.64 years. In the model these rates of growth are −1.06% and −0.41%, implying a half-life of 107.38 years. The model's implied half-life is longer than the half-life measured in the data because the model's implied convergence is not as fast as in the data. Note that the half-life of the gap is independent of the initial size of the gap. It is a useful property of this statistic that we exploit later.

3.4 Robustness / discussion

Goods v. time

Is the modern technology acquired through goods spending or time invested? In our calibration we assume the function χ is time invariant; i.e. the parameters α_y and α_h are constant. At an optimum, the ratio of goods-to-time spending, y/h, depends on the wage rate and the elasticity of substitution $1/(1-\theta)$. It is conceivable, however, that some technologies may require more time than goods to be adopted, while others may require more goods than time. It is also conceivable that the technologies introduced in the poor countries in the 1960s are not acquired via the same goods v. time investment necessary during the 19th century in France. To assess the quantitative importance of such considerations, we use the model to compute counterfactual transition paths in which we change the value of α_y or α_h or both. We consider 20% deviations above and below the calibrated values. For each experiment, Table A.2 reports the fraction of the close in the gap that is accounted for by the model as well as (in parentheses) the half-life. We note a couple of points before discussing Table A.2. First, in each experiment the 1960 crude death rate of the poor country remains the same as in the baseline because it depends only on the proportion of users of the new technology and not on the parameters α_y and α_h. Thus, these parameters only matter for the transition path of the poor country. Second, experiments where both parameters α_y and α_h are changing in the same proportions amount to a permanent increase (or decrease) in the probability of adopting the new technology. One should not expect these experiments to be similar to the baseline.

The message from Table A.2 is that the catching-up of the poor country's mortality rate is mostly affected by α_h. In other words, a technology that is acquired by investment in time is the most likely candidate to explain the convergence of the poor country's crude death rate. This transpires from the fact, apparent in the table, that the explanatory power of the model varies noticeably more as a function of α_h than as a function of α_y. Fixing α_y at its baseline value, we find the value of α_h such that the model closes 100% of the gap between the crude death rates of the poor and the rich countries. We find $\alpha_h = 1.23$ (v. $\alpha_h = 1.12$ in the baseline).

Growth

If the growth rate in the poor country was 0.5% instead of 1% as in the baseline, the model would account for 48.87% of the convergence of the crude death rate, instead of 54.03%. In this case the half-life of the gap would be 120.76 years instead of 107.38. With a growth rate of 1.5%, the model would account for 58.75% of the convergence (half-life of 97.19 years). Finally, if the poor country grows at the same rate as the rich country, namely 2%, the model would account for 63.05% of the convergence and the half-life would be 89.22 years.

Interventions by the WHO

Suppose we interpret part, or all, of the 11.55% of users of the modern technology in the poor country in 1960 as resulting from some WHO intervention. How effective are such interventions? To assess this we simulate the model under a variety of interventions. We represent interventions as different fractions of modern individuals in 1960, ranging from 2% to 20%. Table A.3 reports for each case the crude death rate in the poor country in 1960, the share of the gap accounted for by the model between 1960 and 2010, the half-life of the gap, and the growth rate of the crude death rate in the poor country. A few points are worth mentioning. First, larger interventions by the WHO imply a stronger convergence of the poor country's crude death rate toward the rich country's. The half-life column indicates that the half-life of the initial crude death rate gap decreases noticeably as the WHO intervention becomes larger. It is important at this stage to recall that the half-life is independent of the size of the initial gap. Thus, the better convergence obtained via WHO interventions in Table A.3 is not the result of the initial impact of the intervention on the death rate (the 1960 death rate decreases as the size of the intervention increases), but the result of the diffusion of the new technology in the population. This is exemplified in the last column of Table A.3, which shows that the rate of decline of the CDR is stronger after larger WHO interventions.

Table A.4 shows the effect of WHO interventions (measured by the fraction of modern individuals in 1960) for various values of the parameter α_h (from 80% of its calibrated value to 120%). The importance of a technology requiring time rather than goods to diffuse can again be gauged from the table. Consider for instance the case where α_h is low, that is, at 80% of its calibrated value. If, with a WHO intervention, 20% of people are endowed with the new technology in 1960, the half-life of the crude death rate gap is 111.22 years. When the parameter α_h is large, that is, 20% above its calibrated value, an intial proportion of 2% of modern individuals (small WHO intervention) yields a half-life of 42.32 years.

4 Conclusion

We are motivated by evidence that world population growth rates have been increasing over the past 200 years, while fertility rates have been declining. This evidence suggests that it would be difficult to reconcile the observed population dynamics with only fertility dynamics.

We develop a model of mortality trends and population dynamics. In our model, individuals incur time and/or goods costs over their life cycle to adopt a better health technology that increases their age-specific survival probability. Technology adoption is a source of dynamic externality: As more individuals adopt the better technology, the marginal benefit of future adoption increases. The allocation of time and/or goods also depends on total factor productivity (TFP): As TFP grows, more resources are allocated to technology adoption. Both channels—dynamic externality and TFP—result in lower mortality.

Our model is consistent with three key facts on mortality and economic development: (i) The cross-country correlation between mortality and income is negative, (ii) mortality in poor countries has converged to that of rich countries although the income of poor countries has not, and (iii) mortality decline precedes economic take-off.

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A Tables and figures

Table A.1: Model parameters

Preferences	$\sigma = 1.026$, $\Sigma = 0.227$, $\beta = 0.970$
	$k = 15$, $J = 111$
Technology	$\alpha_y = 0.049$, $\alpha_h = 1.120$, $\theta = 0.097$
	$\lambda = 0.011$, $\Lambda = 1.135$

Table A.2: Fraction of the close in the mortality gap accounted for by model (%) and half-life of initial gap (in parenthesis), various experiments

	$\alpha_h \times 0.8$	$\alpha_h \times 1.0$	$\alpha_h \times 1.2$
$\alpha_y \times 0.8$	37.46	52.11	152.29
	(163.28)	(112.07)	(22.85)
$\alpha_y \times 1.0$	37.54	54.03	153.96
	(162.89)	(107.38)	(22.25)
$\alpha_y \times 1.2$	37.64	56.23	155.40
	(162.43)	(102.43)	(21.73)

Note: The figure 37.46 is computed as follows. The 1960 crude death rate in the poor country is 25.13, while in the rich country it is 11.40. Thus, the difference between the poor country's crude birth rate and the rich country's in 1960 is 120.46%. In 2010 the difference is 12.68% (9.58 in the poor country and 8.50 in the rich). This version of the model implies differences of 111.13% in 1960 (25.13 in the poor country and 11.90 in the rich) and 70.75% in 2010 (16.52 in the poor country and 9.68 in the rich). Thus, the model accounts for $(70.75\% - 111.13\%)/(12.68\% - 120.46\%) = 37.46\%$ of the reduction in the gap between 1960 and 2010. The figure 163.28 is the half-life of the gap in the crude death rate under this parameterization.
Source: Authors' calculations.

Table A.3: The effect of WHO interventions on the 1960 CDR, the convergence of the CDR, the half-life of the CDR gap and the growth rate of the CDR in the poor country

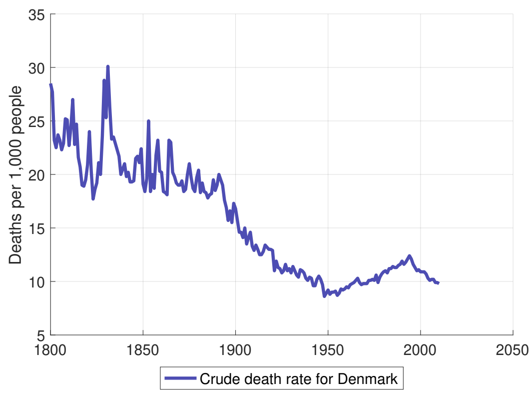
% users in 1960	CDR in 1960	% of CDR convergence accounted	half-life of CDR gap (years)	Growth rate of CDR in poor country (%)
2	27.51	17.77	400.54	−0.59
4	27.01	26.56	257.02	−0.68
6	26.51	34.94	187.12	−0.78
8	26.01	42.61	146.92	−0.89
10	25.51	49.42	121.33	−0.99
11.55	25.13	54.03	107.38	−1.06
12	25.02	55.26	104.00	−1.08
14	24.52	60.19	91.63	−1.17
16	24.02	64.28	82.40	−1.26
18	23.52	67.63	75.31	−1.33
20	23.02	70.31	69.71	−1.41

Source: Authors'calculations.

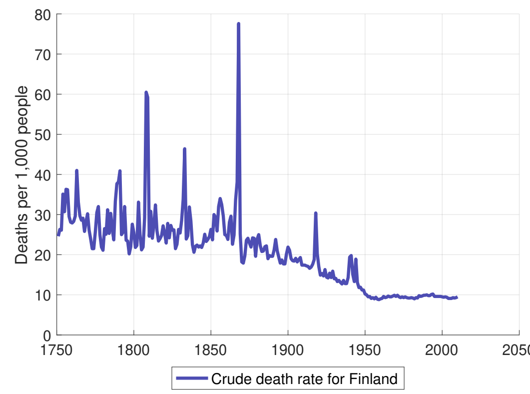
Table A.4: The effect of WHO interventions on the convergence of the CDR and the half-life of the CDR gap for various technologies

	$\alpha_h \times 0.8$		$\alpha_h \times 0.9$		$\alpha_h \times 1.0$		$\alpha_h \times 1.1$		$\alpha_h \times 1.2$	
% users in 1960	A	B	A	B	A	B	A	B	A	B
2%	15.90%	449.76	16.17%	442.05	17.77%	400.57	27.90%	248.64	119.86%	42.32
4%	21.50%	321.76	22.28%	309.83	26.56%	257.03	53.08%	119.29	150.61%	27.54
6%	26.49%	252.65	27.84%	239.50	34.94%	187.12	73.91%	78.27	156.05%	24.54
8%	30.92%	209.48	32.83%	196.20	42.61%	146.93	88.57%	60.32	156.64%	23.27
10%	34.84%	180.00	37.28%	166.99	49.42%	121.33	98.48%	50.64	155.47%	22.59
12%	38.28%	158.61	41.20%	146.04	55.26%	104.00	105.05%	44.72	153.45%	22.18
14%	41.29%	142.41	44.64%	130.31	60.19%	91.63	109.28%	40.77	150.93%	21.93
16%	43.91%	129.73	47.63%	118.09	64.28%	82.41	111.85%	37.98	148.11%	21.79
18%	46.16%	119.56	50.21%	108.36	67.63%	75.31	113.22%	35.94	145.08%	21.72
20%	48.07%	111.22	52.40%	100.44	70.31%	69.71	113.69%	34.39	141.91%	21.70

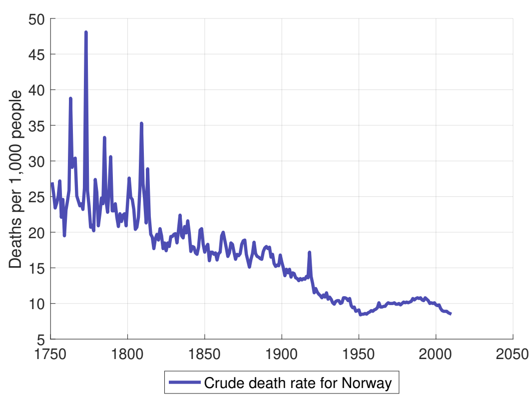
Note: A – The percentage of the reduction in the CDR gap explained by the model. B – The half-life of the CDR gap.
Source: Authors'calculations.



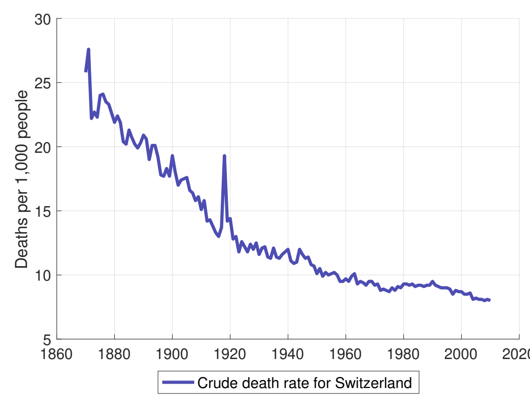
Denmark



Finland



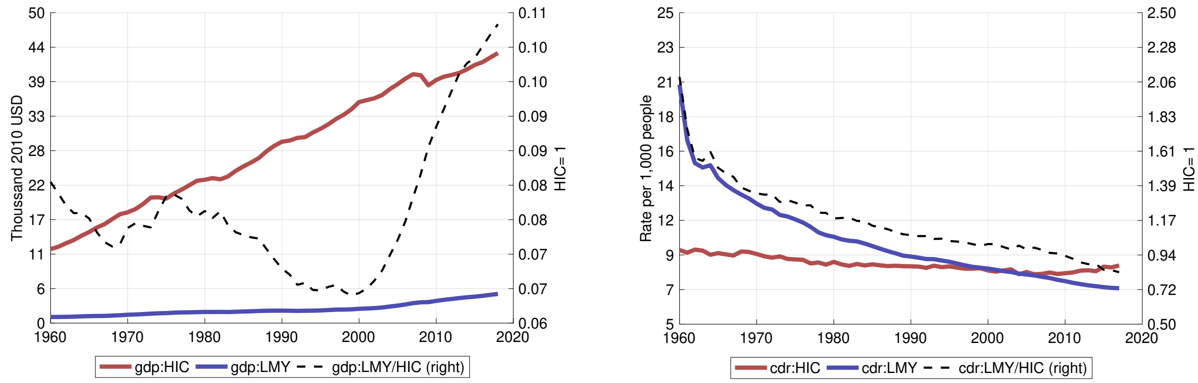
Norway



Switzerland

Figure A.1: Crude death rates

Source: Mitchell (2003).

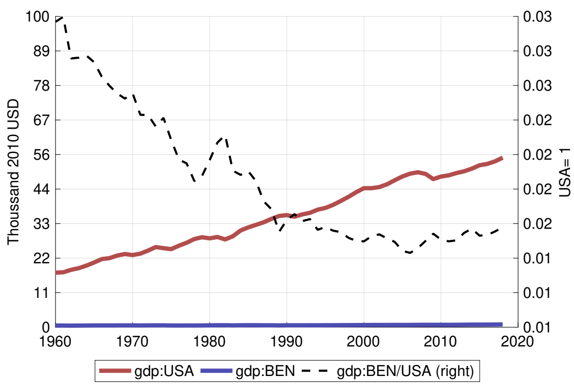


A – Real GDP per capita

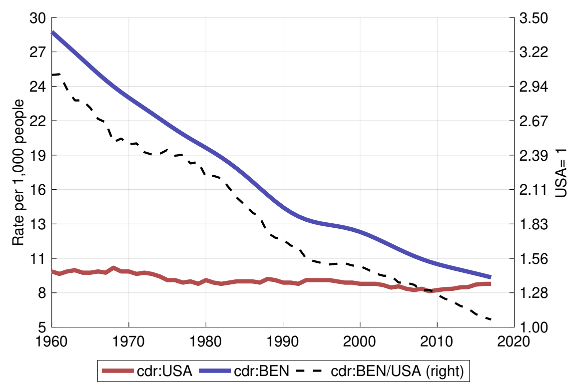
B – Crude death rate

Figure A.2: Demography and the economy: High-income countries (HIC) v. low and middle income countries (LMY)

Note: Panel A shows real GDP per capita (gdp) in high-income countries (HIC) and low and middle income countries (LMY) with solid lines. The dashed line indicates the LMY-to-HIC ratio of real GDP per capita. Panel B shows life expectancy at birth (leb) with solid lines in the two regions, and the LMY-to-HIC ratio of life expectancy at birth (dashed line). Panel C shows the crude death rate (cdr) with solid lines in the two regions, and the LMY-to-HIC ratio of crude death rates (dashed line). Low & middle income countries are those with a Gross National Income per capita of $3,995 at most in 2018. High-income countries are those with a Gross National Income per capita of $12,376 or more in 2018.
Source: World Development Indicators.



A – Real GDP per capita



B – Crude death rate

Figure A.3: Demography and the economy: The United States (USA) v. Benin (BEN)

Note: Panel A shows real GDP per capita (gdp) in the United States (USA) and Benin (BEN) with solid lines. The dashed line indicates the BEN-to-USA ratio of real GDP per capita. Panel B shows life expectancy at birth (leb) with solid lines in the two regions, and the BEN-to-USA ratio of life expectancy at birth (dashed line). Panel C shows the crude death rate (cdr) with solid lines in the two regions, and the BEN-to-USA ratio of crude death rates (dashed line).
Source: World Development Indicators.

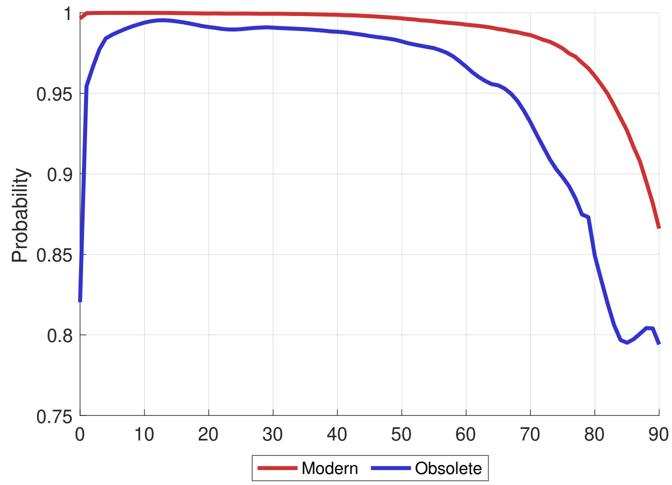


Figure A.4: Survival probabilities from age 0 to 90 for modern and obsolete individuals

Source: Life tables from the Human Mortality Database: University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany). Available at www.mortality.org or www.humanmortality.de.

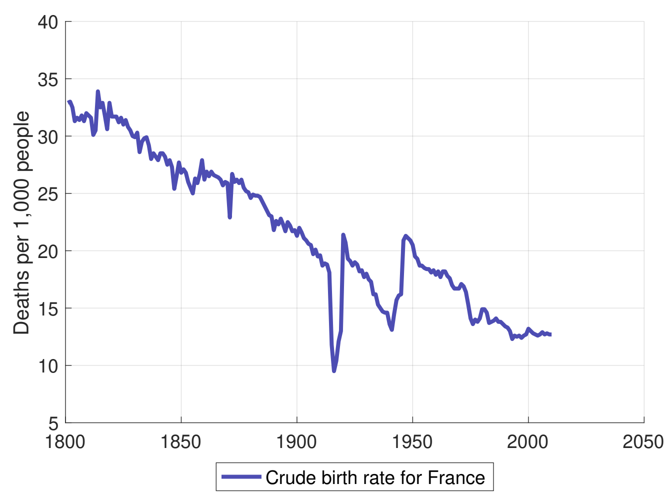
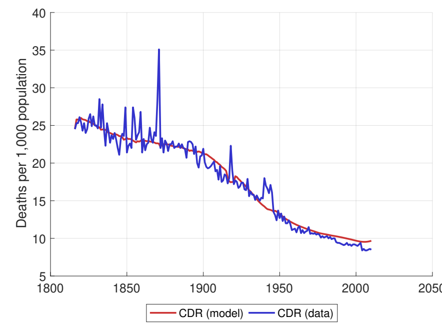
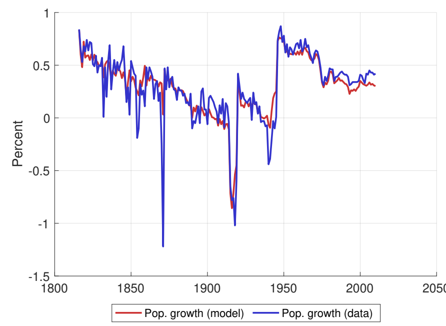


Figure A.5: Crude birth rate in France

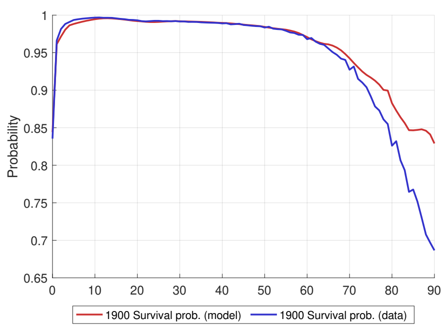
Source: Mitchell (2003).



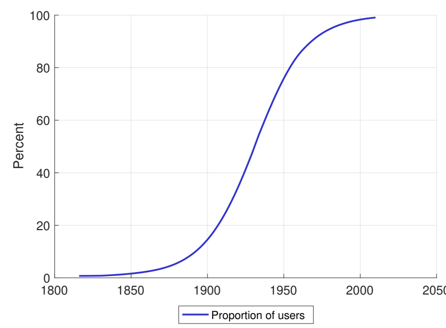
A – Crude death rate



B – Rate of population growth



C – Survival probabilities in 1900



D – Proportion of users

Figure A.6: The calibrated model

Source: Panels A and B: Mitchell (2003) and authors calculations; Panel C: Human mortality database and authors' calculations; Panel D: authors calculations.

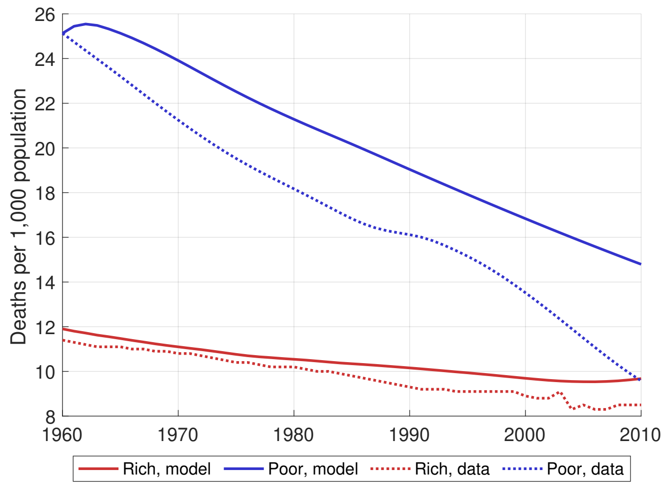


Figure A.7: Crude deaths rates, model, and data

Source: World Development Indicators and authors' calculations.

B Optimization

Consider the first-order conditions (4)-(5), abstracting from time and generation subscripts for simplicity,

$$\begin{aligned} 0 &= U_1\left(w\left(1-h\right)-y\right)-\beta Q_1\left(y,h,\pi\right)\Delta \\ 0 &= U_1\left(w\left(1-h\right)-y\right)w-\beta Q_2\left(y,h,\pi\right)\Delta. \end{aligned}$$

Given the functional form for Q (Section 3), these conditions imply

$$\begin{aligned} 0 &= U_1\left(w\left(1-h\right)-y\right)-\beta\Delta\pi\Lambda\lambda\exp\left(-\lambda\chi\left(y,h\right)\right)\chi_1\left(y,h\right)\Delta \\ 0 &= U_1\left(w\left(1-h\right)-y\right)w-\beta\Delta\pi\Lambda\lambda\exp\left(-\lambda\chi\left(y,h\right)\right)\chi_2\left(y,h\right)\Delta \end{aligned}$$

implying, $1/w=\chi_1\left(y,h\right)/\chi_2\left(y,h\right)$, where $\chi_1\left(y,h\right)=\chi\left(y,h\right)^{1-\theta}\alpha_y y^{\theta-1}$ and $\chi_2\left(y,h\right)=\chi\left(y,h\right)^{1-\theta}\alpha_h h^{\theta-1}$. Hence, $h=yX\left(w\right)$ where,

$$X\left(w\right)=\left(w\frac{\alpha_y}{\alpha_h}\right)^{1/(\theta-1)}.$$

Note that, at the optimum,

$$\chi\left(y,h\right)=y\left(\alpha_y+\alpha_h X\left(w\right)^{\theta}\right)^{1/\theta}$$

and

$$\chi_1\left(y,h\right)=\left(\alpha_y+\alpha_h X\left(w\right)^{\theta}\right)^{1/\theta-1}\alpha_y\equiv\chi_1(w),$$

where the identity, abusing notations, indicates that the first-derivative of χ with respect to y is a function of w only at the optimum. Consumption is $c=w-y\left(1+wX\left(w\right)\right)$. Given the functional form for U (Section 3), the first-order condition for y is

$$\sigma\exp\left(-\sigma w+\sigma y\left(1+wX\left(w\right)\right)\right)=\beta\Delta\pi\Lambda\lambda\exp\left(-\lambda y\left(\alpha_y+\alpha_h X\left(w\right)^{\theta}\right)^{1/\theta}\right)\chi_1\left(w\right)\Delta$$

or

$$y\left[\sigma\left(1+wX\left(w\right)\right)+\lambda\left(\alpha_y+\alpha_h X\left(w\right)^{\theta}\right)^{1/\theta}\right]=\sigma w+\ln\left(\beta\Delta\pi\Lambda\frac{\lambda}{\sigma}\chi_1\left(w\right)\Delta\right).$$