Demographic Transitions Across Time and Space

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Abstract

The demographic transition, i.e., the move from a regime of high fertility/high mortality into a regime of low fertility/low mortality, is a process that almost every country on Earth has undergone or is undergoing. Are all demographic transitions equal? Have they changed in speed and shape over time? And, how do they relate to economic development? To answer these questions, we put together a data set of birth and death rates for 188 countries that spans more than 250 years. Then, we use a novel econometric method to identify start and end dates for transitions in birth and death rates. We find, first, that the average speed of transitions has increased steadily over time. Second, we document that income per capita at the start of these transitions is more or less constant over time. Third, we uncover evidence of *demographic contagion*: the entry of a country into the demographic transition is strongly associated with its neighbors, countries that are geographically and culturally close, having already entered into the transition even after controlling for other observables. Next, we build a model of demographic transitions that can account for these facts. The model economy is populated by different locations. In each location, parents decide how many children to have and how much to invest in their human capital. There is skill-biased technological change that diffuses slowly from the frontier country, Britain, to the rest of the world.

Keywords: Demographic Transition, Skill-Biased Technological Change, Diffusion.

JEL codes: J13, N3, O11, O33, O40

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1 Introduction

Demographic transition theory constitutes one of the most powerful ideas in economics and demography. The text book description of demographic transition is as follows:

> “The recent period of very rapid demographic change in most countries around the world is characteristic of the Central phases of a secular process called the demographic transition. Over the course of this transition, declines in birth rates followed by declines in death rates bring about an era of rapid population growth. This transition usually accompanies the development process that transforms an agricultural society into an industrial one. Before the transition’s onset, population growth (which equals the difference between the birth and death rate in the absence of migration) is near zero as high death rates more or less off set the high birth rates typical of agrarian societies before the industrial revolution. Population growth is again near zero after the completion of the transition as birth and death rates both reach low levels in the most developed societies.” (Boongaarts 2009, page 2985).

In this paper we do two things: First, we put together and analyze data set on crude death rates (CDR) and crude birth rates (CBR) for 188 countries that spans more than 250 years. Following the text book description of the demographic transition, we then estimate for each country in our sample: i) initial (pre-transition) levels of the CDR and CBR, ii) the start dates of the mortality and fertility transitions, iii) the end dates of the mortality and fertility transitions, iv) final (post-transition) levels of the CDR and CBR. This procedure also allows us to estimate the length and the speed of each transition.

Looking at demographic transitions across time and space, we show that: 1) transitions are becoming faster, 2) the average level of GDP per capita at the start of a transition is more or less constant, 3) an important predictor of a country’s transition is the prior transition of other countries which are ”close” to it in a geographical and a linguistic sense, and which have similar legal systems.

We then build a model economy that can account for these facts. We consider an economy with multiple locations. Each location is populated by a representative household that decides how many children to have and how much to invest in their education. Having and educating children is costly. A production technology combines unskilled and skilled labor. Economy is initially in a Malthusian steady state with high but constant levels of mortality and fertility. At a certain point in time, technological progress becomes skill biased. This occurs first in the frontier country, Britain in our analysis, and then diffuses slowly to other locations. Skill-biased technological progress makes investment in children more valuable and parents react by reducing the number of children but educating them better. We first calibrate the model economy to replicate the demographic transition in Britain. We then show that a simple mechanism of diffusion where skill-biased technological change travels from Britain to the rest of the world in a manner that only depends on geographic distance is able to generate sequences of demographic transitions, each happening faster than the previous one, exactly as we observe in the data.

Understanding the relationship between income and population is one of the oldest challenges in economics, going back to Malthus (1803) who developed a powerful model that links better technology with constant living standards. In a Malthusian world, technological change allows a higher income per capita which leads to higher population through higher fertility and lower mortality. In the presence of a fixed input such as land, this higher population translates into lower marginal productivities that decrease per capita income back to the stationary level previous to the technological advance. Malthus' model is quite successful at accounting for the main facts that prevailed until the nineteenth century, but it fails to explain the coexistence of growth in per capita income and low fertility. Becker (1960) and Becker and Lewis (1973) develop the idea of a trade-off between quantity and quality of children to show that higher per capita incomes and low fertility can go together. The interest in this mechanism was revived with the presentation of an operational dynastic model of fertility in Barro and Becker (1989) and Becker and Barro (1988).

Building on this initial work, Becker, Murphy, and Tamura (1990), Lucas (1988, 2002), Jones (2001), and, in particular, Galor and Weil (1996, 1999, 2000) present models that try to capture the historical evolution of population and output. Several recent papers, e.g., Fernandez-Villaverde (2001), Kalemli-Ozcan (2003), Doepke (2017), and Bar and Leukhina (2010), present quantitative versions of these models that can account for historical evidence on demographic transitions for specific countries. Jones, Schoonbroodt, and Tertilt (2011) and Greenwood and Vandenbroucke (2017) provide recent reviews of this literature.

Few recent papers study the historical evolution of fertility. Spolaore and Wacziarg (2014) document that genetic and linguistic distance from France was associated with the onset of the fertility transition in Europe. De la Croix and Perrin (2017) focus on the fertility and education transition in France during the 19th century, and show that a simple quality-quantity model can do a decent job in explaining variations of fertility across time and counties in France. De Silva and Tenreyro (2017) focus on post-1960 transitions and emphasize the role of social norms and family planning programs in recent declines in fertility rates in developing countries. Our paper is also related to recent studies that provide an empirical analysis of demographic transitions across countries. Reher (2004) looks at a broad panel of countries and compares earlier with later demographic transitions, with a particular focus on the role of mortality in driving fertility changes. Murtin (2013) also constructs a panel and .finds evidence for a robust effect of early childhood education on fertility decline. Building on these earlier contributions, our paper is the first to detect empirically a "demographic contagion" effect at a global scale, and to investigate it within a quantitative framework.

Finally, by proposing technology diffusion as a mechanism linking the process of the demographic transition in different countries, our analysis also borrows from recent literature on technology diffusion, such as Lucas (2009) and Comin and Hobijn (2010).

2 Demographic transitions: a methodology

In this section, we propose a methodology for documenting the shape and speed of demographic transitions across time and space. For that purpose, we will compile and analyze country-level vital statistics and apply it to the historical data on the crude birth rate (CBR) and the crude death rate (CDR).[1] We focus on the CBR and the CDR instead of the other statistics such fertility rate or life expectancy because the CBR and CDR are easily measured from the data: a researcher only needs to count births, deaths, and total population. Thus, the CBR and CDR are available for long periods of time and across many different countries. In comparison, a fertility rate or a life expectancy require more involved computations, such as finding exact current age-specific fertility rates, which are often not available for historical data or subject to large measurement error.

In the textbook case, a demographic transition has four stages (Chesnais, 1992):

- In Stage 1, both the CBR and the CDR are high and stationary.
- In Stage 2, the CDR starts to decline while the CBR stays high.
- In Stage 3, the CBR also starts to decline.
- In Stage 4, both the CDR and the CBR stop falling and become stationary at a lower level.

We take this 4-stage demographic transition as a benchmark model of the evolution of the CBR and CDR and try to fit it to available data for each country. More concretely, for the CBR and the CDR, we estimate, for each rate, the variables to describe the data as best as possible: i) an initial (pre-transition) average level of the CBR and CDR; ii) the start dates of the declines of the CBR and CDR (which, in general will be different); iii) the end dates of the declines of the CBR and CDR (also, in general different); and iv) a final (post-transition) average level of the CBR and CDR. We do not impose that, either before or after the demographic transition, the average level of the CBR and CDR are equal to each other. The population of a country can be growing (the average CBR is higher than the average CDR) or declining (the average CBR is lower than the average CDR).

2.1 Econometric model

Consider a dependent variable y_t observed for periods $t \in \{1, ..., T\}$. We will assume that y_t can be represented as a linear function of a vector x_t of k regressors and a residual. Furthermore,

[1] Recall that the CBR is the number of live births per year per 1,000 in a population. The CDR is the number of deaths per year per 1,000 in a population.

suppose that instead of being constant over time, the relationship between y_t and x_t evolves over time and can be broken into S distinct stages $s \in \{1, 2, ..., S\}$ connecting $S+1$ distinct endpoints represented by $\{\tau_1, \tau_2, ..., \tau_{S+1}\}$, such that $\tau_1 = 1$, $\tau_{S+1} = T$, $\tau_s \in \{2, ..., T-1\}$ for $s \in \{2, ..., S\}$ and $\tau_s < \tau_{s+1}$ for all $s \in \{1, ..., S\}$.

At each endpoint τ_s, $s \in \{1, ..., S+1\}$, the dependent variable is defined by:

$$y_{\tau_s} = x'_{\tau_s}\alpha_s + \sigma_s \nu_{s,\tau_s}, \tag{1}$$

where $\nu_{s,t} \sim \mathcal{N}(0, 1)$ for all s, α_s is a $k \times 1$ vector of regression coefficients, and σ_s is a scalar that determines the volatility of the residual at point τ_s.

Now suppose that in each stage s, i.e., when $\tau_s < t < \tau_{s+1}$, the dependent variable is defined by:

$$y_t = x'_t f_s(\alpha_s, \alpha_{s+1}, t) + \varepsilon'_{s,t} g_s(\sigma_s, \sigma_{s+1}, t) \text{ for } \tau_s < t < \tau_{s+1},$$

where $\varepsilon_{s,t} \sim \mathcal{N}(0, 1)$ for all s, and f_s and g_s are continuous functions $f_s : \mathbb{R}^k \times \mathbb{R}^k \times \mathbb{R} \to \mathbb{R}^k$, $g_s : \mathbb{R}^+ \times \mathbb{R}^+ \times \mathbb{R} \to \mathbb{R}^+$ such that

$$\begin{aligned} f_s(\alpha_s, \alpha_{s+1}, \tau_s) &= \alpha_s, \\ f_s(\alpha_s, \alpha_{s+1}, \tau_{s+1}) &= \alpha_{s+1}, \\ g_s(\sigma_s, \sigma_{s+1}, \tau_s) &= \sigma_s, \end{aligned}$$

and

$$g_s(\sigma_s, \sigma_{s+1}, \tau_{s+1}) = \sigma_{s+1}.$$

While it is possible to analyze the more general class of transition functions we just defined, we will restrict our attention to the simplest case where f_s and g_s are linear transitions with respect to time between the parameters at τ_s and τ_{s+1} for all $s \in \{1, ..., S\}$, i.e.,

$$f_s(\alpha_s, \alpha_{s+1}, t) = \frac{1}{\tau_{s+1} - \tau_s} \left[(\tau_{s+1} - t)\alpha_s + (t - \tau_s)\alpha_{s+1} \right], \tag{2}$$

and

$$g_s(\sigma_s, \sigma_{s+1}, t) = \frac{1}{\tau_{s+1} - \tau_s} \left[(\tau_{s+1} - t)\sigma_s + (t - \tau_s)\sigma_{s+1} \right]. \tag{3}$$

To apply this theoretical framework to the specific context under study, suppose that the dependent variable y_t is either the CBR or the CDR for a particular country and that $S = 3$ (i.e., there is a stage where y_t is stationary, another stage it is declining, and a final stage it is stationary again). Furthermore, we are interested in transitions between two stable regimes (high vs. low CBR and CDR), so let us assume that $\alpha_s = \alpha_{s+1}$, $\sigma_s = \sigma_{s+1}$, and $\nu_{st} = \nu_{s+1,t} = \varepsilon_{st}$ for $s \in \{1, 3\}$.

Substituting in for f_1 and g_1 as given by equations (2) and (3), we can write y_t as

$$\begin{aligned} y_t &= d_{1t}[x_t'\alpha_1 + \varepsilon_{1t}\sigma_1] \\ &+d_{2t}[x_t' \frac{1}{\tau_3 - \tau_2} [(\tau_3 - t)\alpha_1 + (t - \tau_2)\alpha_3] \\ &+d_{2t}[\frac{1}{\tau_3 - \tau_2} [(\tau_3 - t)\sigma_1 + (t - \tau_2)\sigma_3] \, \varepsilon_{2t} \\ &+d_{3t}[x_t'\alpha_3 + \varepsilon_{3t}\sigma_3], \end{aligned} \tag{4}$$

where $\{d_{st}\}_{s=1}^{3}$ are indicator functions given by

$$d_{1t} = 1\{t \leq \tau_2\}, \quad d_{2t} = 1\{\tau_2 < t < \tau_3\}, \text{ and } d_{3t} = 1\{t \geq \tau_3\}.$$

Equation (4) can then be rearranged as

$$\begin{aligned} y_t &= \left[d_{1t} + d_{2t}\left(\frac{\tau_3 - t}{\tau_3 - \tau_2}\right)\right] x_t'\alpha_1 + \left[d_{3t} + d_{3t}\left(\frac{t - \tau_3}{\tau_3 - \tau_2}\right)\right] x_t'\alpha_3 \\ &+ \left[d_{1t}\varepsilon_{1t} + d_{2t}\left(\frac{\tau_3 - t}{\tau_3 - \tau_2}\right)\varepsilon_{2t}\right]\sigma_1 + \left[d_{3t}\varepsilon_{3t} + d_{2t}\left(\frac{\tau_3 - t}{\tau_3 - \tau_2}\right)\varepsilon_{3t}\right]\sigma_3, \end{aligned} \tag{5}$$

where $\tau_2 \in \{1, ..., T-1\}$ and $\tau_3 \in \{\tau_2 + 1, ..., T\}$, with $\tau_2 \leq \tau_3$.

2.2 Estimation

The model, as we specified above, has $2k+2$ free parameters: the k parameters in α_1, the k parameters in α_3, plus τ_2 and τ_3. We choose these parameters according to the criterion of minimizing the unweighted sum of squared errors. This means that for a given (τ_2, τ_3) pair, estimation of (α_1, α_3) reduces to ordinary least squares (OLS). The optimal (τ_2, τ_3) can then be located by a search algorithm across the possible values.

To this end, we define the scalars

$$z_{1t} \equiv d_{1t} + d_{2t}\left(\frac{\tau_3 - t}{\tau_3 - \tau_2}\right)$$

and

$$z_{3t} \equiv d_{3t} + d_{2t}\left(\frac{t - \tau_2}{\tau_3 - \tau_2}\right).$$

Then given

$$\underset{1 \times T}{y'} \equiv [y_1 \ldots y_T],$$

and

$$\underset{2k\times T}{Z'} \equiv \left[\left[\begin{array}{c} z_{11}x_1 \\ z_{31}x_1 \end{array} \right] \cdots \left[\begin{array}{c} z_{1T}x_T \\ z_{3T}x_T \end{array} \right] \right],$$

the OLS estimators of (α_1, α_3) given (τ_2, τ_3) have the following closed-form expression:

$$\left[\begin{array}{c} \widehat{\alpha}_1 \\ \widehat{\alpha}_2 \end{array} \right] = [Z'Z]^{-1}Z'y.$$

Estimating σ_1 and σ_3 in this configuration is straightforward, except for the fact that the contribution of each variance to the total variance differs across periods and so the errors must be weighted accordingly.

Define

$$e_t \equiv y_t - [z_{11}x_1 \;\; z_{31}x_1] \left[\begin{array}{c} \hat{\alpha}_1 \\ \hat{\alpha}_3 \end{array} \right],$$

$$\underset{1\times T}{e_z^{1\prime}} \equiv [z_{11}e_1 \ldots z_{1T}e_T],$$

and

$$\underset{1\times T}{e_z^{3\prime}} \equiv [z_{31}e_1 \ldots z_{3T}e_T].$$

We calculate the following estimators for σ_1 and σ_3 given (τ_2, τ_3), which are asymptotically equivalent to the OLS estimators:

$$\widehat{\sigma}_1^2 = \left(\sum_{t=1}^{T} z_{1t} \right)^{-1} e_z^{1\prime} e_z^1$$

and

$$\widehat{\sigma}_2^2 = \left(\sum_{t=1}^{T} z_{3t} \right)^{-1} e_z^{3\prime} e_z^3.$$

When $\sum_{t=1}^{T} d_{st} = 1$ and $\sum_{t=1}^{T} d_{2t} = 0$ for $s \in \{1,3\}$, σ_s is not identified, but this is of little consequence as none of the estimators for the other parameters depend on the variance estimates.

While in general it may be interesting to include a larger number of regressors in x_t, the only specification of this model that we will use in the analysis that follows is the one where x_t contains only a constant term, $x_t' = 1$ for $\forall t$ and $k = 1$. Hence, before a transition start, i.e., while $t < \tau_2$, $y_t = \alpha_1$ (stage 1), between τ_2 and τ_3, y_t declines linearly (stage 2), and at τ_3, $y_t = \alpha_3$, (stage 3).

2.3 Restricted cases

A challenge in estimating the econometric model described above is data limitations. Even if the three-phase model is a useful characterization of the empirical evidence, one or more of the phases might not be observed, either because of the sample is too short or because the demographic transition is still on-going. In particular, we can have six different cases, as illustrated in Figure 1 (we plot the six cases of CBR transitions, but a comparable figure exists for the CDR transitions).

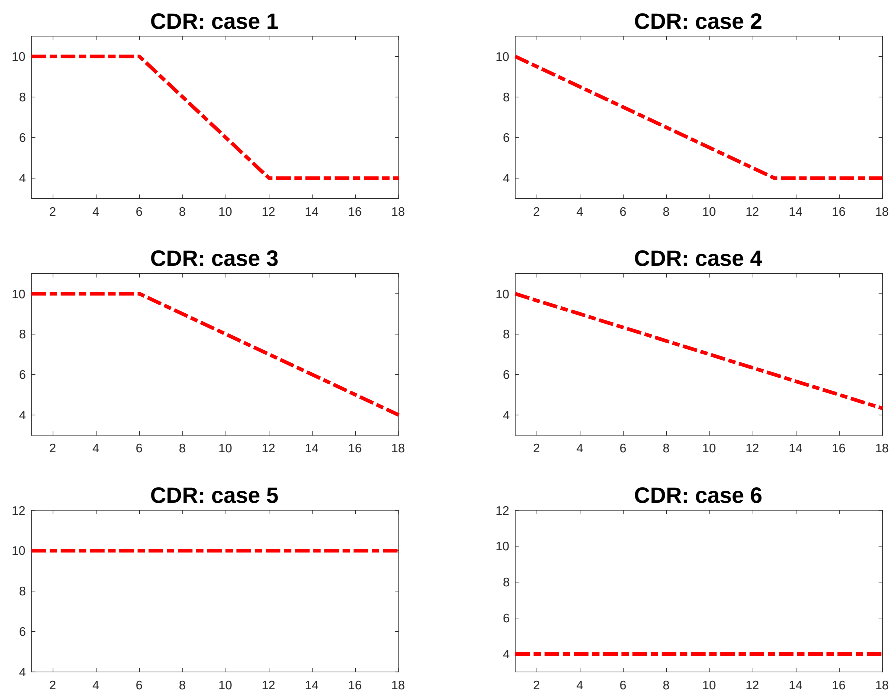


Figure 1: 6 cases of the CBR transition

In the top left panel of Figure 1, we have Case 1: all three phases are observed. In the top right panel, we have Case 2: only phases 2 and 3 are observed. In the Middle row, we see Cases 3, only phases 1 and 2 are observed, and 4, just phase 2 is observed. In the bottom left panel, we see the rare Case 5, where only phase 1 is observed, and in the bottom right panel, Case 6, where only phase 3 is observed. To distinguish Case 5 from Case 6, as they are equivalent econometrically, we use external information about the levels of the CBR and CDR to classify the country either as Case 5 or as Case 6. As we will see later, in our sample, we only estimate 4 countries in Cases 5 for the CBR and none for the CDR. We have a few more observations of Case 6, 15 for the CDR and 3 for the CBR. Cases 2 and 6 will usually be associated with vital statistics not going back in time for a sufficiently long period, while Cases 3 to 5 will be more often linked with ongoing transitions.

To discriminate among all these different possibilities, we estimate, for each country in the data, all six cases. Table 1 summarizes the nesting structure among cases.

Table 1: Different cases of the general model

	Parameter restriction	Explanation	Num. of parameters
Case 1	–	All 3 stages are observed	$2k+2$
Case 2	$\tau_2 = 1$	Only stages 2 and 3 are observed	$2k+1$
Case 3	$\tau_3 = T$	Only stages 1 and 2 are observed	$2k+1$
Case 4	$\tau_2 = 1, \tau_3 = T$	Only stage 2 is observed	$2k$
Case 5	$\tau_2 = 1, \tau_3 = T, \alpha_1 = \alpha_3$	Only stage 1 is observed	k
Case 6	$\tau_2 = 1, \tau_3 = T, \alpha_1 = \alpha_3$	Only stage 3 is observed	k

We select, among the five cases, the version of the model that has the best trade-off between fitting the data and fewer restrictions. That is, we select a less restricted case only if it does a significantly better job of fitting the data. In the first pass of such selection, we use an F-test at the 95% confidence level:

$$\frac{\frac{SSE^b - SSE^a}{m^a - m^b}}{\frac{SSE^a}{T - m^a}} \tag{6}$$

where a nests b, and, as mentioned in the previous section, $m^I = 2k+2$. We find that this statistical test performs best for countries with a long series of observations extending both before and after the transition in birth rates and/or death rates. To prevent this statistical method from over-fitting short-run anomalies in countries for which the time series is not as extensive, we also apply a set of simple auxiliary rules. For example, if he statistical method detects the end of a fertility transition at a final level of higher than 20 per thousand, with an end date less than 20 years before the end of the data series, we throw out this transition end date, moving the country from Case I to Case III, or from Case II to Case IV. A complete description of the auxiliary rules can be found in Appendix C.

3 Data

3.1 Vital statistics and GDP per capita

We merge data from different sources to obtain time series for CBRs and CDRs that go back as long as possible for the greatest possible number of countries. From 1960 onwards, we rely on the World Bank Development Indicators. For many countries, we fill in 1950-1960 with data from the UNData service of the United Nations Statistics Division. To gather vital statistics before 1950, we start with data from Chesnais's (1992) classic book on the demographic transition and augment them with observations from Mitchell's (2013) International Historical Statistics. We also use additional sources for few countries: State Statistical Institute of Turkey (1995) and Shorter and Macura (1982) for Turkey, Swiss Federal Statistics Office (1998) for Switzerland, Maines and Steckel (2000) for the U.S., and Davis (1946) for India. The resulting data set on CDRs and CBRs covers 186 countries from 1735 to 2014. We take data on purchasing power parity GDP per capita (GDPpc), given in constant 2011 US Dollars purchasing power parity (PPP), from the 2018 version of Maddison's database.[2] Table 2 shows the means and the standard deviations of the CBR, the CDR, and the log GDP per capita in our sample.

Table 2: Summary statistics of demographics and GDPpc

Variable	sample mean	st. Dev.	N. Obs.
crude death rate *(CDR),* per 1000	14.1	8.0	16206
crude birth rate *(CBR),* per 1000	30.5	11.8	16198
ln GDP per capita *(lnGDPPC)*	8.3	1.1	16729

Table 3 shows the correlations across the three variables. We see i) a strong negative correlation between the CBR and the log GDP per capita; ii) a slightly less strong negative correlation between the CDR and the log GDP per capita; and iii) the positive comovement of the CBR and the CDR.

Table 3: Correlations among key variables

	CDR	CBR	lnGDPPC
crude death rate *(CDR),* per 1000	1	0.48	-0.56
crude birth rate *(CBR),* per 1000		1	-0.71
ln GDP per capita *(lnGDPPC)*			1

3.2 Projecting CDR backward

Vital statistics for only a few countries are available back into the 19th century and for a great many not until after 1950. As a result, there are numerous countries for which the start of either the CBR or the CDR transition is not observed. Since the CDR transition starts, on average, earlier than the CBR transition, we have many more "missing starts" for CDR transitions than for CBR transitions. In all, there are 89 countries for which the start of the CBR transition is estimated to be observed, but the beginning of the CDR transition is not.

[2] Bolt, Robert, Herman, and van Zanden (2018). The database can be accessed here: https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018

One way to address this gap is to apply the 3-phase framework and project the CDR backward to an initial level, α_i^d, which is predicted according to the country's initial CBR level, α_i^b, and perhaps other observables. To this end, we estimate:

$$\alpha_i^d = \beta_0 + \beta_1 \alpha_i^b + \beta_2 \left(\alpha_i^b\right)^2 + \beta_3 s_i^b + \beta_4 s_i^d + \varepsilon_i, \tag{7}$$

where $s^b \equiv \frac{\alpha_{3,i}^b - \alpha_{1,i}^b}{\tau_{3,i} - \tau_{2,i}}$ and $s_i^d \equiv \frac{\alpha_{3,i}^d - \alpha_{1,i}^d}{\tau_{3,i} - \tau_{2,i}}$ are the calculated slopes for CBR and CDR, respectively, during the transition, and ε_i is a mean-zero *iid* error term.

We estimate the parameters of equation (7) using the 24 countries for which i) we observe both the CBR and CDR transitions and ii) the CBR transition started before 1950. We select these earlier transitions because the estimated gap of the CBR over the CDR is systematically higher for the later cohort of countries, suggesting that these estimated initial levels may not reflect the true, long-run pre-transition levels of birth and death rates. Otherwise, these alternative CBRs would imply a counterfactually high rate of population growth before the onset of the demographic transition. Table 4 shows the results of the estimation of equation (7), with t-statistics in parentheses. The R^2 of 0.730 indicates a good fit for such a simple regression.

Table 4: CDR projections

β_0	β_1	β_2	β_3	β_4
-20.5605	1.9103	-0.0151	0.4924	2.3426
(21.7166)	(1.2044)	(0.0164)	(6.0341)	(1.8494)
N = 23	R^2=0.690			

The estimated parameters are then used to predict initial CDR levels for 89 countries for which the start of the CBR transition is observed, but the start of the CDR transition is not. After removing outliers and unreasonable results, predictions for 77 countries remain.[3] Our procedure more than doubles the number of countries for which some estimate of the CDR transition start date is available, from 53 to 130.

3.3 Extension of GDP per capita data

Recall that the main source for GDP per capita data that we use is the 2018 version of Maddison's database. While this database provides us with estimates for some countries going

[3]We exclude a projection if: (a) the predicted initial level of CDR is higher than the estimated initial level of CBR, as this would imply an initial zero population; (b) if the gap between the initial level of the CBR and the CDR is larger than the largest gap observed in the 24-country sample used to estimate the parameters, as this would imply an inordinately high initial population growth rate; or (c) if the total length of the implied CDR transition is longer than the longest transition observed in the 24-country sample used to estimate the parameters, as this would imply too long of a transition.

as far back as the year 1 CE, the time series for other countries does not start until the late 19th or early 20th centuries, long after many countries entered the CBR and CDR transitions.

To analyze the relationship between GDP per capita and demographic trends, we impute a value for GDP per capita in the year 1500 for most of the countries in our sample. We do this by recursively dividing countries into two sets.

The first set contains two kinds of countries: i) those countries that are already assigned a value for the year 1500 GDP per capita in Maddison's database; and ii) those countries that have a value for a year that is either prior to or after 1500, but before any evidence of the onset of modern economic growth in such country. For the latter countries, the value for the closest year is assigned to the year 1500 directly (in a few cases where we have data from before and after 1500, but not 1500 itself, we interpolate linearly). This approach (and the other imputations below) implicitly assume that economies before the arrival of modern economic growth lived in a quasi-Malthusian world, with little or no long-run economic growth and small differences in GDP per capita. To reduce the likelihood that we are projecting backward levels of GDP per capita that are the result of early modern growth, we remove from this set any country for which the closest GDP per capita value that can be assigned is i) for a year after 1650 and ii) exceeds $1176, the mean GDP per capita for England during its first 50 years in the database (1262-1302). The removed countries are added to the second set. After the removals, the first set consists of 43 countries.

The second set consists of all countries that were not assigned a year-1500 value in the first step. Each of these countries is assigned an index country from the first group based on geographical proximity. A year-1500 GDP per capita value is computed either by assuming that the ratio of GDP per capita in these two countries has remained constant from the year 1500 until the first year for which the Maddison database assigns them both a value or by merely assuming that the GDP per capita was the same in both countries. There are two oil-producing countries, the United Arab Emirates and Gabon, for which it is not possible to assign a valid index country because they began large-scale oil production before the first observation assigned to them in the Maddison database. No year 1500 estimate is imputed for them. Excluding the UAE and Gabon, the second set consists of 113 countries. There are 31 countries, most of them tiny island territories, for which we have data on CDRs and CBRs, but which are not included in Maddison's database. Maddison's database has data for Slovakia, but we exclude it to avoid double-counting, as for the majority of the covered period Slovakia was part of Czechoslovakia. Table B1 in the appendix provides details of the year 1500 GDP per capita imputations.

4 Results

Figure 2 displays time series of the CBRs and CDRs, along with the fitted 3-phase transitions for each of these rates, for six countries. Each country is a representative example of a form of demographic transition. The top left panel is the demographic transition of Great Britain/UK, a typical instance of an early demographic transition. The CDR started falling in 1794 and stabilized by 1958 while the CBR began dropping in 1885 and stabilized around 1937. The top right panel is the demographic transition of Denmark, later than the Great Britain/UK's, but representative of many Western European countries that followed the Great Britain/UK's lead with only a few decades delay.

The right Middle panel is the demographic transition of Spain, a late but completed transition, with the CBR stabilizing as recently as 1999. The left Middle panel is the demographic transition for Chile, a typical case of late and on-going transitions, where the CBR still has not stabilized. Finally, in the bottom row, we have Malaysia, a late demographic transition for which we calculate a projected start date for the fall of the CDR, and Chad, the one remaining country in our sample where it is not clear whether the fall of CBR has even started. Table A in the Appendix documents the start and end dates of the demographic transition if they can be estimated, for each country in our sample.

Table 5: Summary statistics

	CDR	CBR
mean initial level	25.76	42.88
mean lnGDPpc at transition start	7.55	7.96
N	118	129
mean final level	8.20	12.80
mean lnGDPpc at transition end	8.50	9.46
N	146	69

Table 5 presents some summary statistics of the CDR and CBR at the start and end of the transitions as well as log GDPpc the for those countries that we observe starts (or ends) of such transitions. We can see, in particular, the large drop of around 66% in both mean CDR and CBR, with a difference between both of them much small at the end of the transition than at the start.

Figure 3 displays scatter plots of CDR and CBR, for every country in every year that they are observed, against log GDP per capita. Superimposed onto the plots is the best fit for a 3-phase transition as specified previously, but with log GDP per capita taking the place of time. While admittedly a crude first exercise, this structure provides a reasonably good fit for the panel data with R^2 coefficients of 0.339 and 0.531, respectively. According to this estimation, the "average" pre-transition CDR for the entire panel is 19.5 per year per 1000 people, and the

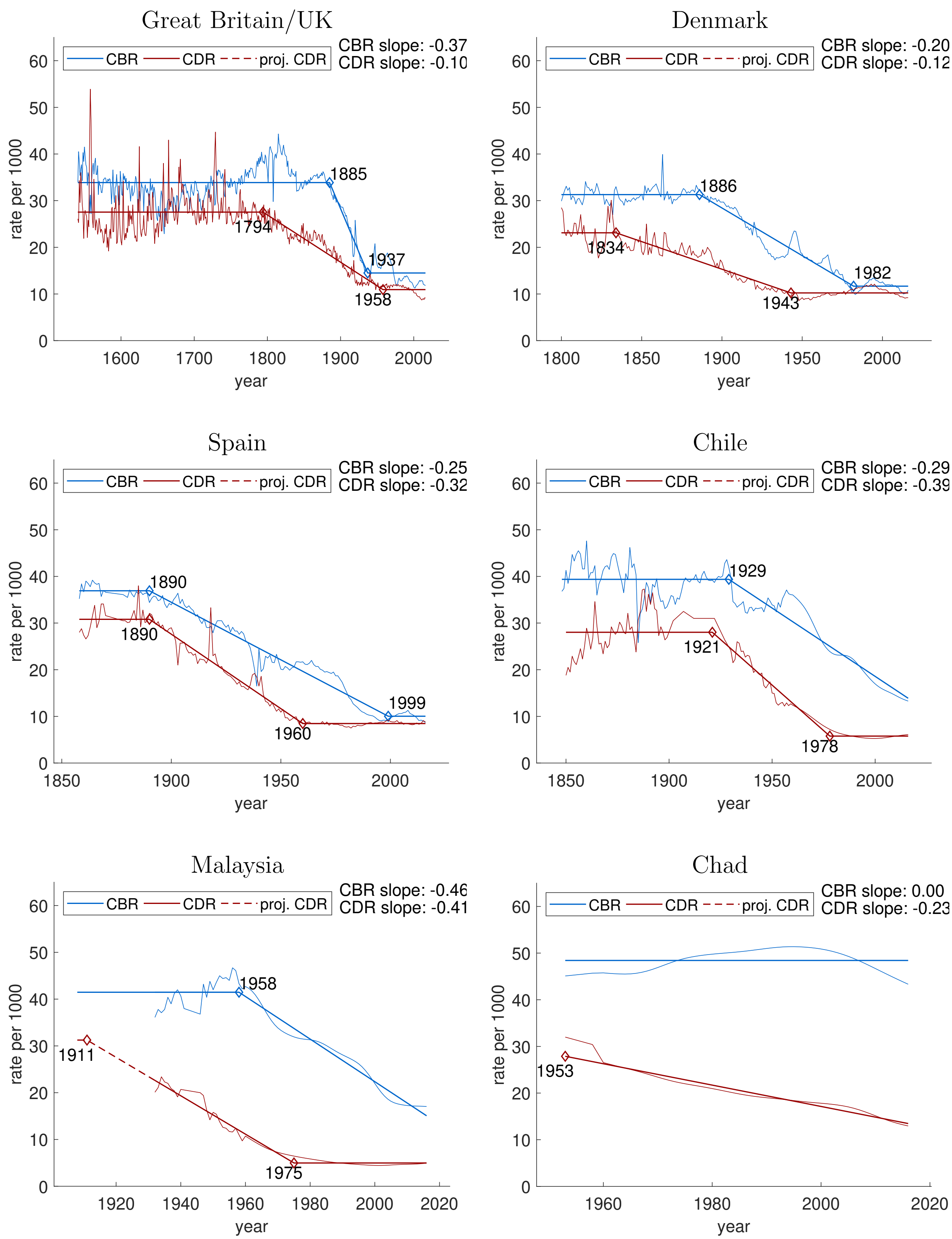


Figure 2: Six examples of demographic transitions.

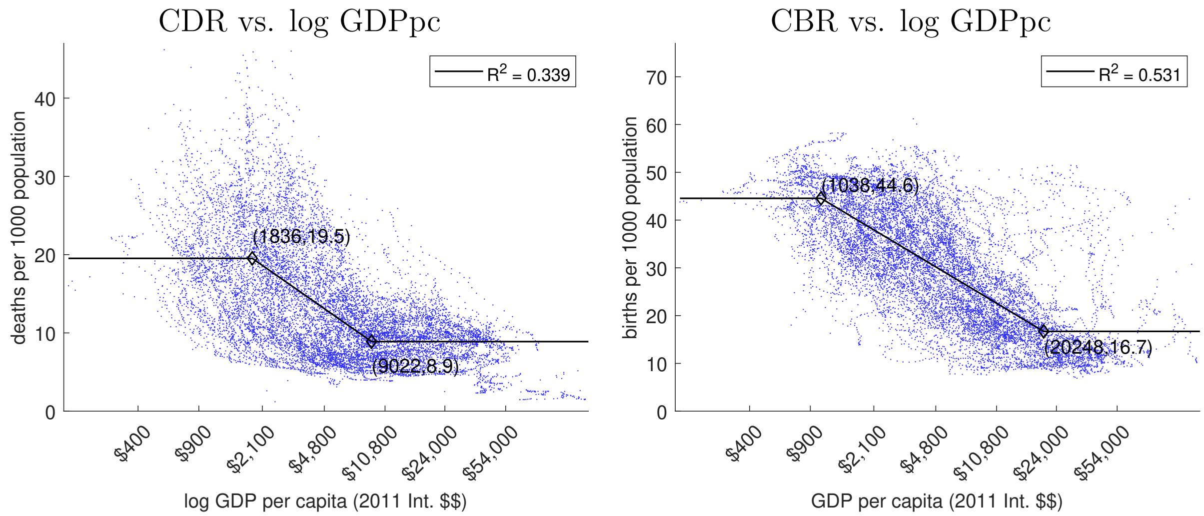


Figure 3: CDR and CBR vs. log GDPpc.

pre-transition CBR for the entire sample is 44.6. The estimated post-transition CBR and CDR for the entire sample are 8.9 and 16.7, respectively. The CDR transition is estimated to start, on " average," when a country achieves a real GDP per capita of $1,836 constant 2011 constant US dollars PPP. The "average" start of the CBR transition is estimated to be at the lower level of $1,038. The end of the CDR and CBR transitions are placed at $9,022 and $20,248, respectively.

Table 6 documents the distribution of all countries in our sample according to different cases outlined in Table 1. Out of 186 countries, we have 175 countries that have completed the death transition (Cases 1 and 2) and 80 that have completed the birth transition. This shows how the global drop of death rates is more considerably more advanced than the decline of birth rates: most of the planet has finished the drop in CDRs, but there is still much space to cover in the fall of CBRs. Notice how for the CDR, we have large count (131) of countries where stages 2 and 3 of the transition are observed, but not stage 1, most likely because data does not go back enough in time. We do not find any country where the start of the drop in the CDR has not started. We find one country, Chad, where we do not detect the beginning of a CBR transition. Finally, we have 7 countries in Case 6 of the CDR. These are typically Eastern European countries that started their demographic transitions earlier than the availability of data.

Figure 4 plots the empirical frequency of log GDP per capita at the start of each type of transition. These distributions are roughly uni-modal, which may be adequately approximated by a normal distribution.

Table 6: Case counts

CDR \CBR	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Total
Case 1	27	0	17	0	0	0	44
Case 2	26	20	79	6	0	0	131
Case 3	0	0	1	0	1	0	2
Case 4	0	0	2	0	0	0	2
Case 5	0	0	0	0	0	0	0
Case 6	0	7	0	0	0	0	7
Total	53	27	99	6	1	0	186

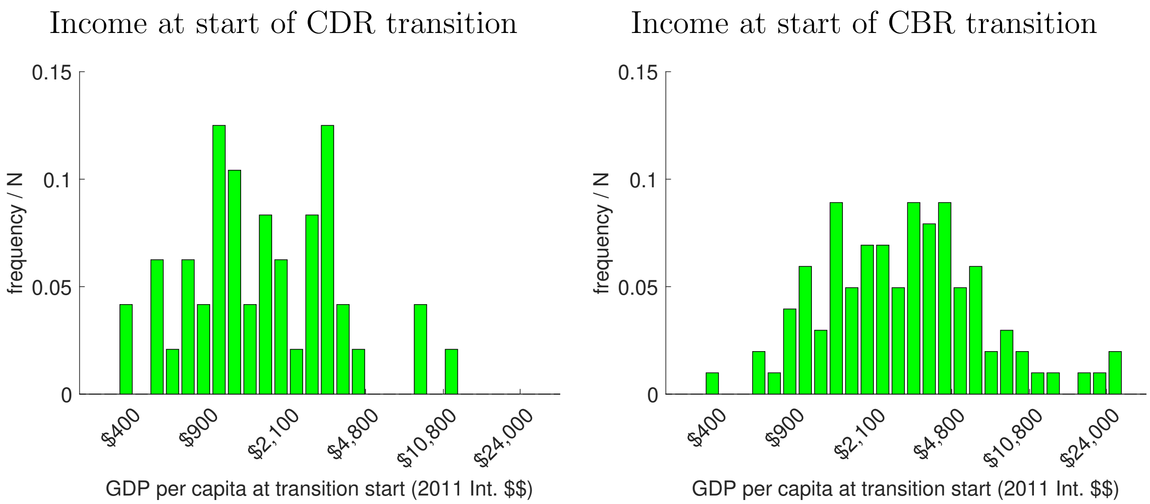


Figure 4: log GDP per capita at the start of each transition.

4.1 Are demographic transitions getting faster?

Table 7 reports summary statistics for some features of countries as they enter the CDR and CBR transitions, broken into groups according to the period in which their transition started. Table 7 reveal three patterns of interest. The first pattern is that start dates of the CDR transitions are more dispersed over time than the start dates of the CBR transitions. The former also peak sooner, with many starts clustered between 1900 and 1960. In comparisons, most CBR transitions start between 1960 and 1990, with 9 transitions starting since 1990.

The second pattern in Table 7 is that later transitions are faster. The slope of the reduction in CDR and CBR during the transition (i.e., the decline in the rates per year) is much larger for later transitions. Figure 5 shows this pattern graphically for all the countries in our sample with complete transitions.

An alternative way to make the same point is to plot, in Figure 6, the measured transition length from plateau to plateau.

To measure the strength of this downward trend more precisely, we use a linear regression, which allows us to control for additional factors that may affect transition speed and length

Table 7: Countries entering transitions

	before 1870	1870-1900	1900-1930	1930-1960	1960-1990	after 1990	All
mean initial lnGDPpc	7.84	7.73	7.45	7.42	7.58	–	7.55
mean initial CDR	25.07	25.40	24.40	27.43	29.94	–	25.76
mean slope CDR	-0.18	-0.26	-0.37	-0.68	-1.13	–	-0.44
N	15	23	42	33	5	0	118

	before 1870	1870-1900	1900-1930	1930-1960	1960-1990	after 1990	All
mean initial lnGDPpc	7.52	8.39	7.92	8.00	8.02	7.33	7.96
mean initial CBR	42.53	35.90	39.70	40.29	44.36	46.40	42.88
mean slope, CBR	-0.19	-0.32	-0.34	-0.51	-0.56	-0.50	-0.50
N	6	11	6	20	75	11	129

CDR transition slope

CBR transition slope

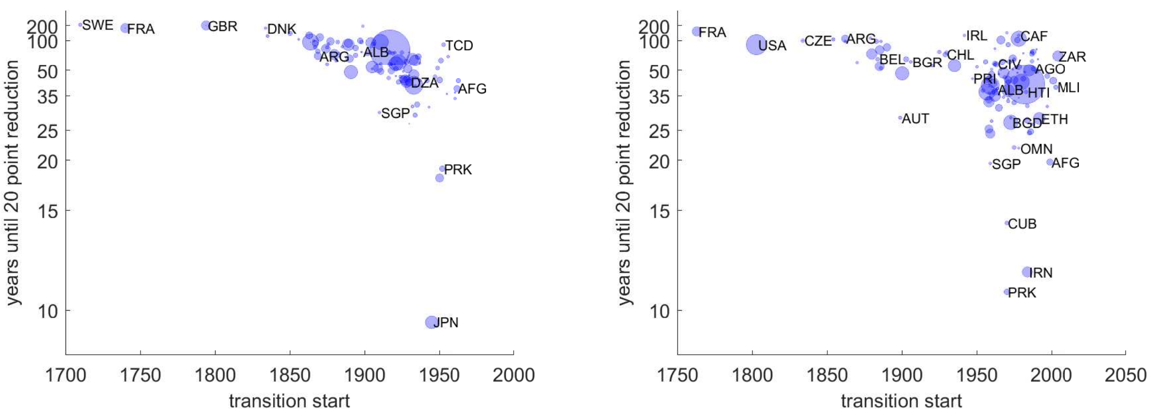


Figure 5: Transition slopes.

CDR transition length

CBR transition length

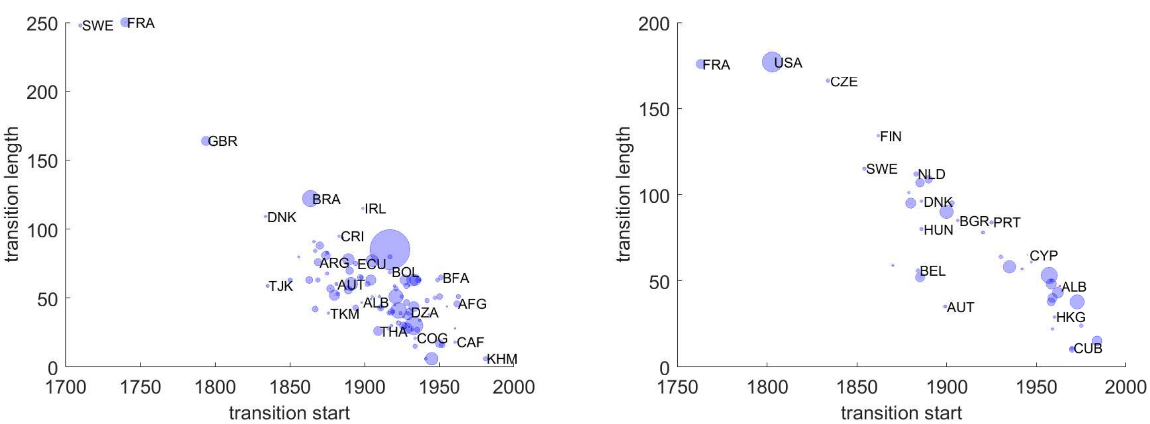


Figure 6: Transition lengths.

beside timing. We hypothesize that, in addition to the timing of the transition start, the speed of the transition may also be affected by the level of GDP per capita at the transition start and by how high crude birth rates were initially.[4] Table 8 displays the results of the linear regressions for the slope and length of the transition speeds. In each case, the transition start date is significantly related to transition speed.

Table 8: Transition Speed

Dependent variable	CDR slope	CBR slope	CDR length	CBR length
Cons	-0.06	0.23	275.16	254.28
	(-0.08)	(0.65)	(8.36)	(5.17)
ln GDPPC at start	-0.03	-0.05	-7.75	-10.65
	(-0.33)	(-1.34)	(-2.44)	(-2.09)
starting CBR /10	0.23	0.03	-2.24	3.81
	(2.68)	(0.77)	(-0.62)	(0.84)
start date /10	-0.06	-0.03	-7.64	-7.29
	(-4.79)	(-4.29)	(-14.70)	(-13.27)
N. Obs.	106	116	102	41
R^2	0.195	0.145	0.695	0.827

The third pattern in Table 7 is that, while the GDP per capita at the start of the CDR transition is lower for later transitions, there is no clear trend in the GDP per capita at the beginning of the CBR transitions. The GDP per capita is remarkably similar, for example, for the CBR transitions that started during the 1870-1900 period and the 1960-90 period. Figure 7 shows scatter plots of log GDP per capita in each country at the start of its CDR and CBR transition, respectively.

[4] The initial level of the CBR is highly correlated with the initial level of CDR. Thus, including the latter in the regression does not significantly affect the results.

Log GDPpc at the start of the CDR transition Log GDPpc at the start of the CBR transition

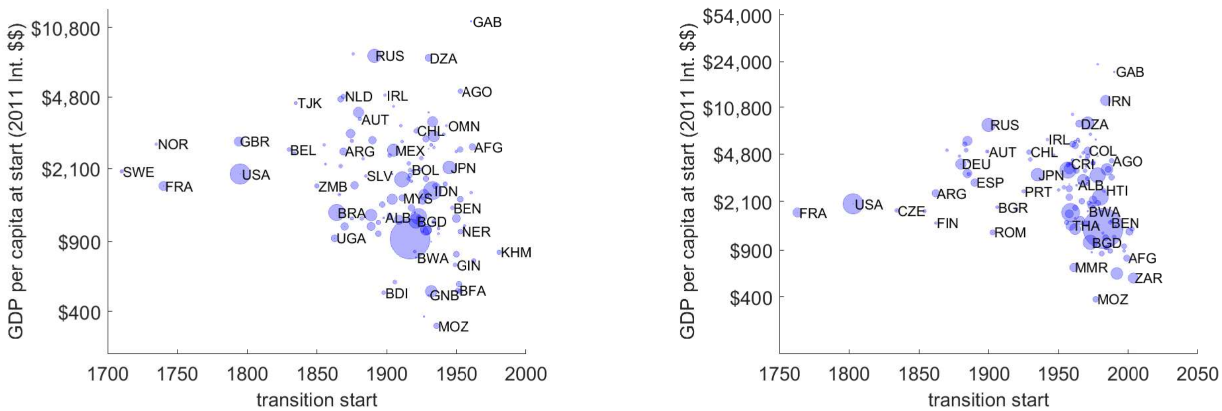


Figure 7: Log GDPpc at the start of transitions.

5 An empirical analysis of demographic transitions

In the previous section, we saw that the distributions of log GDP per capita levels at the start of transitions in crude birth rates or death rates are fairly stable over time and possess uni-modal distributions. This suggests that a modeling strategy that links the level of log GDP per capita to transition takeoffs may have some explanatory power. One possible approach is to model the start of each transition as a random event whose probability of occurring depends on log GDP per capita and possibly other variables. Let T represent the time at which a one-off event, such as the start of a CDR or CBR transition, occurs. Suppose that the probability of the event occurring at time t in country i, conditional on not having occurred previously, can be expressed as:

$$\Pr(T^i = t | T^i \geq t) = G\left(\sum_{l=0}^{k-1} x_{l,it}\beta_l\right), \tag{8}$$

where $G(.)$ is a function bounded between 0 and 1. In the exercise that follows, we will assume that $G(.)$ is the logistic cumulative distribution function and that $(x_{0,it}, x_{1,it}, ..., x_{k-1,it})$ are a set of k explanatory variables.

Consider a world populated with N different countries indexed by $i \in \{1, 2, ..., N\}$ for which a set of variables $x_{it} \in X$ is observed time $t = 1$ until T. Let T^i represent the time at which a given one-off event occurs in country i, and let $\mathcal{I}_{it}$ be an indicator function taking the value 1 if the event occurs in country i at time t and 0 otherwise. Let $\Pr(T^i = t | T^i \geq t) = G\left(\sum_{l=0}^{k-1} x_{l,it}\beta_l\right)$ (according to 8). The parameters of this model can then be estimated by maximizing the log-likelihood:

$$\log L_N = \sum_{i=1}^{N} \sum_{t=1}^{T_i} \log \left[\mathcal{I}_{it} G \left(\sum_{l=0}^{k-1} x_{l,it} \beta_l \right) + (1 - \mathcal{I}_{it}) \left(1 - G \left(\sum_{l=0}^{k-1} x_{l,it} \beta_l \right) \right) \right]. \tag{9}$$

Table 9: GDPpc and CBR transition, Logit results

Variable	Estimates
Cons	-23.55
	(7.53)
lnGDPPC	2.74
	(1.89)
lnGDPPC ^{2}	-0.05
	(0.12)
LLn	-713.4
Pseudo-R^2	0.128
N	52183

Table 9 reports the Logit estimation for the CBR (the results for the CDR are reported in the Appendix) when the only explanatory variable is log GDP per capita. As shown in Figure 8, this specification replicates well the distribution of log GDP per capita at the start of the transition. This specification does not perform well, however, in replicating the distribution of transition starts over time or in predicting transition start dates for individual countries, as seen in Figures 9 and 10.

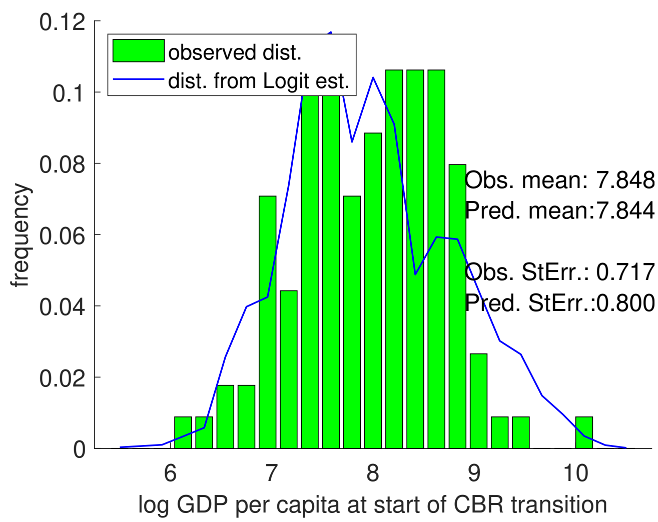


Figure 8: Distribution of log GDPpc at the start of the CBR transitions

Next, we extend the Logit analysis by including network effect. In particular, we estimate

$$\Pr(T^i = t | T^i \geq t) = G\left(\sum_{l=0}^{k-1} x_{l,it}\beta_l + \beta_k \mathcal{A}_{it}\right),$$

where $\mathcal{A}_{it}$ is a measure of location i's access to transitions in other locations at time t, and is defined as:

$$\mathcal{A}_{it} \equiv \left[\sum_{j=1}^{N} g_{ij}\mathcal{I}_{j,t-1}\right]^{\psi}.$$

where $\mathcal{I}_{j,t} = 1$ if the transition has already started in country j, and g_{ij} measures the inverse of *the distance* between country i and country j. Hence, if a country j is very far from country i, then g_{ij} is close to zero, and as a result, whether or not country j has already started its transition has nearly no effect on the probability that country i starts its transition. On the other hand, if country j is close to country i, then whether country $j's$ transition has a material effect on the probability that country i also starts its transition.

Figure 9: Within Sample Predictions

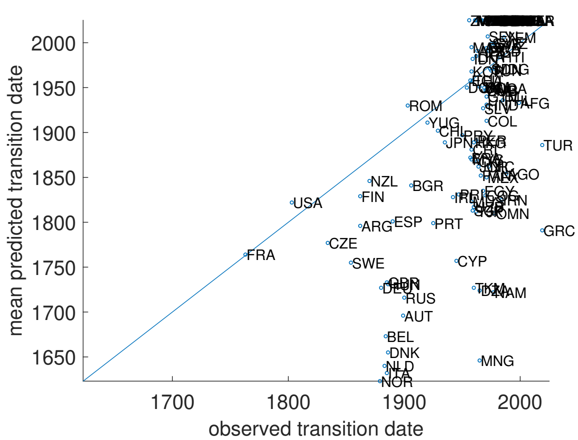
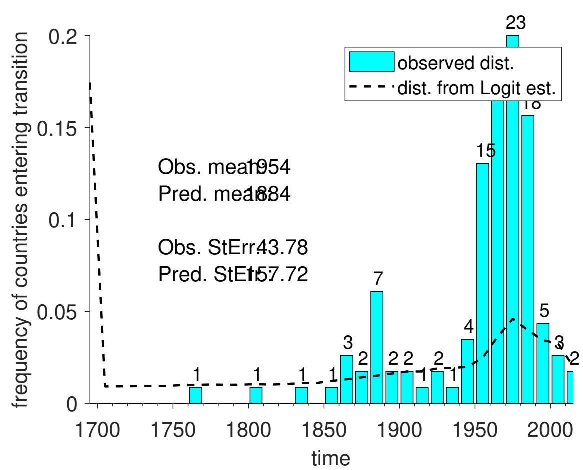


Figure 10: Distribution of Transition Dates



Finally, we assume that the distance between two countries is given by

$$g_{ij} = \exp\{\mathbf{z}'_{ij}\gamma\},$$

where $\mathbf{z}_{ij}$ is a column vector of bilateral distance measures and γ is a vector of coefficients. The parameter vectors β and γ and the parameter ψ can be estimated using log-likelihood.

5.1 Bilateral country distance measures

Equation 5 follows Melitz and Toubal (2013), who investigate the effect of each of these distances on bilateral trade volumes in the second half of the 20th century.[5] We also follow Melitz and Toubal (2013) by borrowing their data on bilateral geographic, linguistic, religious, and legal distances.

Regarding geographic distance, we employ the great-circle distance between capital cities. Regarding linguistic distance, we use Melitz and Toubal's (2013) "LP2" distance, which the authors construct using data on the distribution of spoken languages and Bakker, Müller, Velupillai, Wichmann, Brown, Brown, Egorov, Mailhammer, Grant, and Holman's (2009) calculation of linguistic similarity.[6] To reflect connections that may exist between countries for historical reasons independently of shared language, we also consider Melitz and Toubal's (2013) index of shared religion and a dummy variable for common legal origins. Table 10 displays summary statistics for these variables, and the correlation table is given in Table 11.

Table 10: Distance measures, summary statistics

Variable	sample mean	st. Dev.	N. Obs.
ln Distance, km *(ldi)*	8.7	0.8	24334
Linguistic proximity *(lp2)*	0.6	0.7	24334
Common religion *(cmr)*	0.2	0.2	24334
Common legal system *(cml)* $\in \{0,1\}$	0.2	0.4	24334

Table 11: Distance measures, correlations

	lp2	*ldi*	*cmr*	*cml*
ln Distance, km *(ldi)*	1	-0.33	-0.36	-0.27
Linguistic proximity *(lp2)*		1	0.23	0.38
Common religion *(cmr)*		0.23	1	0.21
Common legal system *(cml)* $\in \{0,1\}$				1

The linguistic, religious, and legal *proximity* measures (*lp2*, *cmr*, and *cml*) are transformed into *distance* measures by calculating *distance* = 1 - *proximity*. Missing bilateral distances are imputed to take the maximum theoretical value for that distance–1 in the case of $1 - lp2$, $1 - cmr$, and $1 - cml$, and (the natural log of) 20,015 km in the case of great-circle distance

[5] Melitz and Toubal (2013) build on a large literature in international trade that estimates gravity equations where the distance between countries considers both geographical measures and the effects of language and other related factors. Egger and Lassmann (2012) provide an overview.

[6] Melitz and Toubal (2013) construct and test several alternative measures of the degree of linguistic commonality between countries, ranging from the narrowest definition, simply recording whether the two countries share an official language or not, to more nuanced definitions based on the shares of the population in each country that speak the same or similar languages. "LP2" is comprehensive yet relatively parsimonious.

(ldi) between capital cities.[7] Finally, log geographical distance *ldi* is divided by $ln(20,015)$ so that this distance measure, too, is normalized to fall between 0 and 1.

5.2 Demographic contagion

Table 12 shows the results of the Logit regression described in the previous section. Specification (1) shows the results of the regression without including any inter-country influence. Specification (2) adds a global count of the number of countries that have begun the transition, and specification (3) adds some curvature to that sum, which is still global. The estimated value of ψ, being less than 1, implies that there are diminishing returns–the more countries have already entered the transition, the smaller the effect of each additional country on other countries' odds of entering the transition. Specifications (4) through (11) weight the influence of one transitioned country on other countries according to the inverse distance between them, as determined by various measures of distance. When included by themselves, all 4 measures of distance (geographic, linguistic, religious and legal) have highly significant estimated coefficients, with geographic distance having somewhat more explanatory power (as reflected in the log likelihood sum) than the others. Religious distance has the wrong sign, which means that it is probably correlated with some excluded factor and, thus, the coefficient does not reflect the real effect of religious distance. Specifications (9), (10), and (11) include more than one measure of distance simultaneously. Geographic distance retains a significant coefficient in all of these specifications, while linguistic and legal distance maintain positive, but not quite statistically significant point estimates.

In Figure 11, we look at the access to transitions measure implied by specification 11 (the distributions displayed in all of these figures are smoothed using a Gaussian kernel). Using the estimated parameters, access is calculated as

$$\mathcal{A}_{it} \equiv \left[\sum_{j=1}^{N} \exp[\mathcal{D}_{ij} + 0.16 \cdot \text{lp2}_{ij} + 0.04 \cdot \text{cml}_{ij}] \mathcal{I}_{j,t-1} \right]^{0.45},$$

where

$$\mathcal{D}_{ij} \equiv 2.25 \cdot \mathbf{1}\{\text{ldi}_{ij} < \ln 500\} + 1.46 \cdot \mathbf{1}\{\ln 500 \leq \text{ldi}_{ij} < \ln 1000\} + 0.56 \cdot \mathbf{1}\{\ln 1000 \leq \text{ldi}_{ij} < \ln 2000\}.$$

is the step variable for distance.

The top left panel of Figure 11 shows the distribution of this measure at different points in time. Not surprisingly, as more countries transition, this distribution moves steadily to the

[7]The circumference of the Earth is 40,030 kilometers, and so the maximum great-circle distance between any two points on the globe is approximately 20,015 kilometers (the Earth not being perfectly spherical).

Table 12: Determinants of the start of the CBR transition

cons	-23.11	-46.12	-38.89	-39.23	-35.11	-35.62	-37.00	-35.20	-31.49	-31.66	-30.35
	(7.52)	(8.85)	(8.76)	(8.99)	(9.09)	(8.48)	(8.54)	(8.88)	(8.87)	(9.06)	(8.99)
lnGDPPC	2.63	8.71	6.70	6.67	5.56	5.93	6.21	5.81	4.76	4.73	4.44
	(1.89)	(2.21)	(2.20)	(2.23)	(2.28)	(2.13)	(2.14)	(2.21)	(2.23)	(2.28)	(2.26)
lnGDPPC ^{2}	-0.04	-0.47	-0.36	-0.36	-0.29	-0.32	-0.33	-0.31	-0.25	-0.24	-0.23
	(0.12)	(0.14)	(0.14)	(0.14)	(0.14)	(0.13)	(0.13)	(0.14)	(0.14)	(0.14)	(0.14)
access		0.06	0.75	5.07	9.91	1.38	0.92	0.80	14.09	9.74	12.21
		(0.00)	(0.32)	(0.43)	(0.91)	(0.15)	(0.11)	(0.11)	(1.31)	(0.93)	(1.17)
geo dist.				4.08							
				(0.00)							
$<$ 500km					2.67				2.57	2.39	2.42
					(0.33)				(0.46)	(0.35)	(0.44)
500-1000km					1.75				1.59	1.60	1.56
					(0.34)				(0.50)	(0.34)	(0.46)
1000-2000km					0.90				0.75	0.99	0.89
					(0.32)				(0.44)	(0.30)	(0.39)
ling. dist						1.12			1.22		0.69
						(0.00)			(0.89)		(0.86)
relig dist							0.39				
							(0.18)				
legal dist								0.30		0.28	0.21
								(0.05)		(0.27)	(0.31)
ψ, curv.			0.48	0.41	0.41	0.47	0.48	0.50	0.43	0.43	0.43
			(0.06)	(0.00)	(0.10)	(0.00)	(0.00)	(0.02)	(0.08)	(0.12)	(0.09)
LLn	-707.2	-523.6	-514.2	-510.9	-491.8	-513.0	-513.9	-511.9	-490.0	-489.4	-489.0
Pseudo-R^2	0.128	0.355	0.366	0.370	0.394	0.368	0.367	0.369	0.396	0.397	0.397
N. Obs.	51720	51720	51720	51720	51720	51720	51720	51720	51720	51720	51720

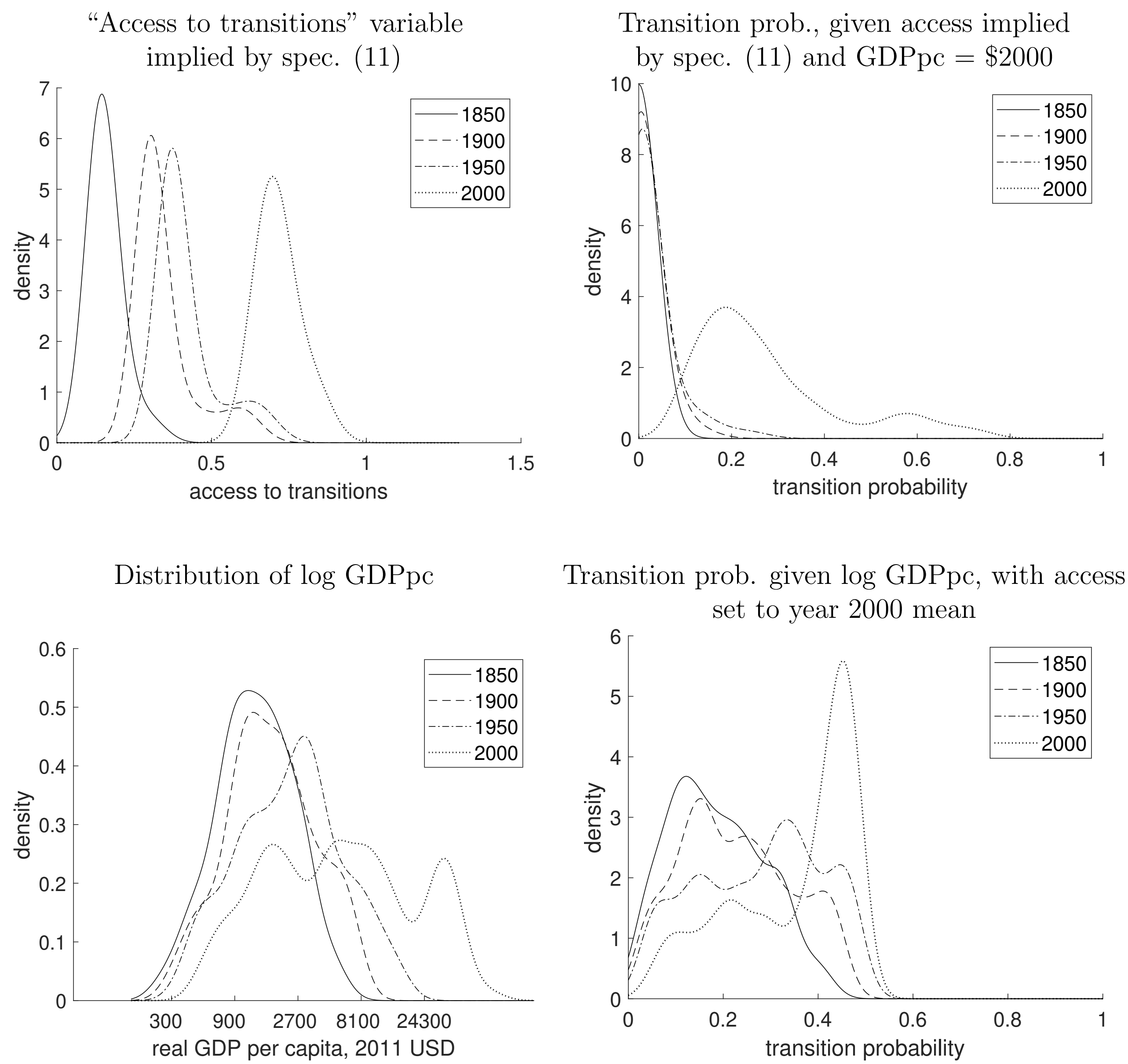


Figure 11: Demographic contagion.

right. The top right panel of Figure 11 plots the transition probabilities implied if each country is assigned its actual access to transitions value and GDP per capita equal to $2000. Here we can see that in 1850, 1900, and 1950, "Access to transitions" in the great majority of countries was such that their probability of transition at $2000 GDP per capita would have been relatively small. In the year 2000, this situation changes dramatically, and the lowest yearly probability of transition for any country with $2000 GDP per capita would be 10%.

The bottom left panel of Figure 11 shows the evolution of the distribution of GDP per capita over time. This distribution shifts right as time passes and more countries enjoy higher levels of GDP per capita. The bottom right panel of Figure 11 shows the distribution of the probability of transition, given the observed GDP per capita for each country, assuming they have the mean level of "Access to transitions" existing in the year 2000. This panel demonstrates the importance of the complementarity between a country's level of development and the influence of its neighbors. In 1850, even countries with relatively high log GDP per capita had a low transition probability. In comparison, by 2000, a country with the relatively low level of GDP per capita ($2000) has a probability of transition close to 1 if enough of their neighbors have already started the transition.

Again, in the Appendix, we repeat all the previous exercises but for the CDR. The lessons are very similar except that the neighborhood effect is weaker for mortality transitions.

5.3 A recap

In this section and the previous one, we have documented three findings. First, transitions in both fertility and mortality have been getting faster over time. Second, in spite of this increase in the speed of the transitions, there is no clear trend in the level of GDP per capita at which countries enter the fertility transition. Finally, we have found suggestive evidence for a kind of "demographic contagion," whereby a transition in one country is statistically associated with following transitions in countries which are close to it geographically and linguistically and have similar legal systems.

6 Model

In this section we build a model of endogenous fertility, education, and technology diffusion with the goal of accounting for the trends we have documented. In this model there will be a quantity-quality trade-off between how many children to have and how much to educate them, following classic work by Barro and Becker (1989). We propose an economy with a skilled and an unskilled sector, as in Acemoglu (2002). An exogenous increase in the ratio of skilled to unskilled TFP raises the skill premium and induces parents invest in a smaller number of more educated children. In order to link fertility patterns across countries, we introduce technology diffusion in a manner similar to Lucas (2009), and allow the elasticity of catch-up growth to differ between the skilled and unskilled sectors. We show that if this elasticity is higher in the skilled sector, the skill premium will rise more sharply in countries that begin converging to the frontier later, leading to faster fertility transitions.

6.1 Consumer preferences, fertility, and education decisions

Consider a world that consists of different locations. Consumers in each location i live for two periods, one as children and one as adults. As children, consumers are under the care of their parents. As adults, they work, consume and choose how many children to have, n_{it}, and how much education, e_{it}, to provide for each of them. With an exogenous probability s_{it} a child survives to the adulthood.

Each unit of children requires a time commitment of τ_1, for a total time cost of $n_{it}\tau_1$. To achieve a level of education e_{it} for each child, parents must pay a total time cost of $n_{it}e_{it}\tau_2$. The level of education that children receive will determine their level of human capital when they are adults, given by

$$h_{i,t+1} = e_{it}.$$

Adults have a total time endowment of 1. They do not value leisure, and so supply $1 - \tau_1 n_{it} - \tau_2 n_{it} e_{it}$ units of time to the labor market. The income that parents receive per unit of labor depends on the equilibrium unskilled and skilled wages, w_{it}^U and w_{it}^S, and their level of human capital, h_{it}. In exchange for each unit of labor supplied, adults receive income

$$y_{it} \equiv w_{it}^U + h_{it} w_{it}^S.$$

Parents choose c_{it}, e_{it}, and n_{it} to maximize

$$\log(c_{it} - \overline{c}_i) + \log(s_{it} n_{it}) + \beta \log y_{i,t+1},$$

subject to

$$c_{it} = (1 - n_{it}(\tau_1 + \tau_2 e_{it}))y_{it},$$

and

$$y_{it+1} \equiv w_{it+1}^U + h_{it+1}w_{it+1}^S \text{ with } h_{it+1} = e_{it},$$

where $\bar{c}_i$ is a minimum consumption requirement.

Define the skill premium at time t as $\pi_{it} \equiv \frac{w_{it}^S}{w_{it}^U}$. Then the first order conditions of this problem are given by

$$\frac{[\tau_1 + \tau_2 e_{it}]}{1 - \frac{\bar{c}_i}{y_{it}} - [\tau_1 + \tau_2 e_{it}]\, n_{it}} = \frac{1}{n_{it}},$$

for n_{ii} and by

$$\frac{\tau_2 n_{it}}{1 - \frac{\bar{c}_i}{y_{it}} - [\tau_1 + \tau_2 e_{it}]\, n_{it}} = \beta \frac{1}{\frac{1}{\pi_{i,t+1}} + e_{it}},$$

for e_{it}. With simple algebra, the optimal decisions for e_{it} and n_{it} are given by

$$e_{it} = \frac{\beta\frac{\tau_1}{\tau_2} - \frac{1}{\pi_{i,t+1}}}{1-\beta},$$

and

$$n_{it} = \frac{1}{2}\left(1 - \frac{\bar{c}_i}{y_{it}}\right)\frac{1}{\tau_1 + \tau_2 e_{it}}.$$

The human capital investment decision, e_{it}, is increasing in $\pi_{i,t+1}$ (the skill premium) and in $\tau_1$and is decreasing in τ_2. The number of children, n_{it} is decreasing in τ_1, τ_2 and e_{it}; and decreasing in $\bar{c}_i$

6.2 Production and technology diffusion

Time-t output for country i, Y_{it} is given by

$$Y_{it} = [(A_{it}S_{it})^\rho + (B_{it}[L_{it}^\omega + U_{it}^\omega]^{\frac{1}{\omega}})^\rho]^{\frac{1}{\rho}},$$

where where S_{it} represents the quantity of skilled labor employed and A_{it} represents the productivity of skilled labor, L_{it} represents the land endowment, U_{it} represents the quantity of unskilled labor employed, and B_{it} represents the productivity of the land and unskilled labor aggregate, and where $\frac{1}{1-\omega}$ represents the elasticity of substitution between land and unskilled labor and $\frac{1}{1-\rho}$ represents the elasticity of substitution between skilled labor and the land and unskilled labor aggregate.[8]

Factor shares for skilled labor and the land and unskilled labor aggregate are $\frac{A_{it}}{A_{it}+B_{it}}$ and $\frac{B_{it}}{A_{it}+B_{it}}$ respectively, and TFP $\tilde{A}_{it}$ can be defined as

$$\tilde{A}_{it} \equiv A_{it} + B_{it}.$$

Given this production technology, the skill premium is given by

$$\pi_{it} = \frac{w_{it}^S}{w_{it}^U} = \left(\frac{A_{it}}{B_{it}}\right)^{\rho} \frac{S_{it}^{\rho-1}}{[L_{it}^{\omega} + U_{it}^{\omega}]^{\frac{\rho}{\omega}-1}\frac{1}{2}U_{it}^{\omega-1}}.$$

The world is composed of 1 frontier country, indexed as country 0, and n following countries in the set $N \equiv \{1, 2, ..., n\}$. Time is discrete, indexed by $t \in \{0, 1, 2, ...\}$. The effective distance of each follower from the frontier country at each point in time, d_{it} is a function of a time-invariant geographic distance d_i^g, a time-invariant linguistic and/or cultural distance, d_i^c, and potentially time-varying idiosyncratic barriers to the diffusion of information represented by $\phi_{0i}(t)$:

$$d_{it} = \phi_{oi}(t) + \phi_1(t)d_i^g + \phi_2(t)d_i^c,$$

The parameters $\phi_l(t)$ for $l \in \{1, 2\}$ are shared across countries and may vary over time. In particular, it is assumed that these parameters decline at a constant rate from their initial values:

$$\phi_j(t+1) = \phi_j(t)(1 - g_{\phi_j}) \text{ for } j \in \{1, 2\}.$$

The idiosyncratic barriers term, $\phi_{0i}(t)$, can be thought of as reflecting how " open" or " closed" country i is in terms of its policies and other non-geographical, non-linguistic factors that might affect knowledge flows into country i.

There are frontier levels of skilled and unskilled productivity, denoted $\bar{A}_t$ and $\bar{B}_t$ respectively. These are assumed to have the constant values $\bar{A}_0$ and $\bar{B}_0$ for all periods $t \in \{..., -3, -2, -1, 0\}$. There is a frontier country, aka Great Britain, indexed as country 1, which has the lowest barriers to diffusion of the frontier levels of technology. It is assumed that they do coincide for all periods leading up to period 0, prior to the start of frontier technology growth, the technology levels in the frontier and the frontier country are the same: $A_{0t} = \bar{A}_0$ and $B_{0t} = \bar{B}_0$ for all $t \in \{..., -3, -2, -1, 0\}$.

At time 1, frontier skilled labor productivity makes an unanticipated discrete jump to $\bar{A}_1 > \bar{A}_0$, while frontier unskilled productivity retains its former value $\bar{B}_1 = \bar{B}_0$. Starting in period

[8] This production function follows the setup used in Fernandez-Villaverde (2001), with skilled and unskilled sectors as in Acemoglu (2002).

2, the growth rates for both types of productivity experience an unanticipated, discrete jump from 0 to g, such that for periods $t \in \{2, 3, 4, ...\}$,

$$\bar{A}_t = (1 + g)\bar{A}_{t-1}$$

and

$$\bar{B}_t = (1 + g)\bar{B}_{t-1}.$$

For all time periods, productivity in each country grow at a rate that depends on their distance to the frontier d_{it} and their productivity level relative to the productivity level of the frontier, in accordance with the following laws of motion, inspired by Lucas (2009):

$$A_{i,t+1} = A_{it} \left(1 + ge^{-d_{it}} \frac{\overline{A}_t}{A_{it}}\right),$$

and

$$B_{i,t+1} = B_{it} \left(1 + ge^{-d_{it}} \frac{\overline{B}_t}{B_{it}}\right)^{\theta}$$

where $\theta > 0$ represents the relative elasticity of catch-up growth in unskilled TFP to the gap to the frontier. If $\theta < 1$, then the same gap with the frontier will lead to slower growth in unskilled TFP realtive to skilled TFP. If $\theta > 1$, then the same gap with the frontier will lead to faster growth in unskilled TFP realtive to skilled TFP.

6.3 Vital statistics

Childhood survival rates are determined by the overall level of technology in a country, according to the following formula:

$$s_{it} = 1 - \frac{1 - s_i^0}{(A_{it} + B_{it})^{\zeta}}$$

where $\zeta > 0$. The CBR is given by

$$B_{it} = \frac{U_{it} n_{it}}{U_{it} + U_{it} s_{it} n_{it}} = \frac{n_{it}}{1 + s_{it} n_{it}}.$$

Similarly, the CDR is given by

$$D_{it} = \frac{U_{it} + U_{it} n_{it}(1 - s_{it})}{U_{it} + U_{it} s_{it} n_{it}} = \frac{1 + n_{it}(1 - s_{it})}{1 + s_{it} n_{it}}.$$

Finally, the population growth is given by

$$B_{it} - D_{it} = \frac{n_{it}s_{it} - 1}{1 + s_{it}n_{it}}.$$

7 A quantitative exercise

Now suppose we are in a world in which period 0 is 1775 and in which a model period lasts 25 years, and that there are 7 countries in the world: a frontier country (Great Britain), assumed to be on average effectively 50 kilometers from the notional " frontier" contained within its borders (in for example, London), a country that is 312.5 kilometers away (like Amsterdam, Netherlands from London, England), a country that is 625 kilometers away (like Geneva, Switzerland), a country that is 1250 kilometers away (like Vienna, Austria), a country that is 2500 kilometers away (like Moscow, Russia), a country that is 5000 kilometers away (like Baghdad, Iraq), and a country that is 10000 kilometers away (like Manila, Philippines).

Distances d_{it} are a function of physical distance only, i.e. we set ϕ_{0i} and ϕ_2 to zero:

$$d_{it} = \phi(t)d_i^g,$$

where d_i^g represents the physical distance in kilometers between London, United Kingdom, and the capital city of country i.

Suppose that all of these countries are initially identical in all aspects other than their distance from the frontier, and that they are all initially in a population steady state in which total births equal total deaths. In period 0, frontier technology starts growing, and the importance of distance for diffusion starts falling, in the manner described in the previous section.

Table 7 shows the parameter values. These parameters are chosen to match roughly the key features of the economic and demographic transition in the UK since 1700. They also produce a sequence of transitions, following the diffusion of technology from the UK to the rest of the world, that produces a world income distribution that is line with the data in 2000. Finally, the model economy generates demographic transitions that get faster over time. Table 8 shows how the model economy compares with the data along several dimensions.

Table 7: Parameters Values

Parameter	Description	Value
	Preferences	
β	altruism	0.8
$\bar{c}$	minimum consumption	2
τ_1	time cost of fertility	0.133
τ_2	time cost of education	0.05
	Technology	
ρ	substitutability between skilled, unskilled labor	0.8
ω	substitutability between land, unskilled labor	0.1
$\frac{\bar{A}_0}{\bar{B}_0}$	initial ratio between skilled and unskilled TFP	0.2
$\frac{\bar{A}_1}{\bar{B}_0}$	long-run ratio between skilled and unskilled TFP	0.5
s_0	initial infant mortality rate	0.5
	Growth and Diffusion	
ϕ_0	initial cost of distance	3.7
g_ϕ	rate of decline in cost of distance	0.4895
g	rate of technology growth	0.325
ζ	elasticity of mortality to technology	2
θ	elasticity of unskilled TFP growth to gap with frontier	.25

Table 8 lists 10 targeted moments, the sources that the target numbers are derived from, and the numbers produced by the model. Eight of these moments pertain to the United Kingdom. The UK's total population growth between 1700 and 2000, per capita income growth between 1700 and 2000 are compared against data from the Maddison 2010 database. The total drop in the crude birth rate and crude death rate in the UK between 1700 and 2000 is compared to the difference between the initial and final mean crude birth and death rates for the UK as estimated in Section 4 of this paper. The UK CBR and CDR in 1700 is compared against the initial mean CBR and CDR estimated in Section 4 of this paper.

The education variable e_{it} is interpreted in the following way: let $\widetilde{e}_{it}$ represent years of education, and let $\widetilde{e}_{it} = Ce_{it}$, where C is set so that $\widetilde{e}_{UK,2000} = 10.02$, the years of average education given for the UK in the year 2000 by the Barro and Lee (2013) dataset. Then the year 2000 college wage premium is calculated as the difference in total earnings between a notional agent in the UK who has 15 total years of schooling versus one who only has 12 years, which is then compared to the 30% figure produced by Walker and Zhu (2008). The total growth in education in the UK in the model between 1900 and 2000 is also compared to the same figure from Barro and Lee (2013).

Two of the moments in Table 8 are global–the population-weighted variance of log per capita GDP in the year 2000, and the rate at which the average transition length decreases over time. The population-weighted variance across the seven model countries in the year 2000 is calculated and compared with the population-weighted variance across ten major world regions in the year 2000 in the Maddison 2000 database. The slope of the transition length/time relationship is calculated as the coefficient on time of a regression of transition start date and a constant on the total length of the crude birth rate transition, in the model. The start of a model transition is defined as the point at which the crude birth rate declines by 0.5 persons per thousand from its initial level, and the end is defined as the point at which it reaches below 22 persons per thousand. This slope is compared against the slope of the linear fit line from the comparison between transition length and transition start date shown in Figure 6-B in Section 4 of this paper.

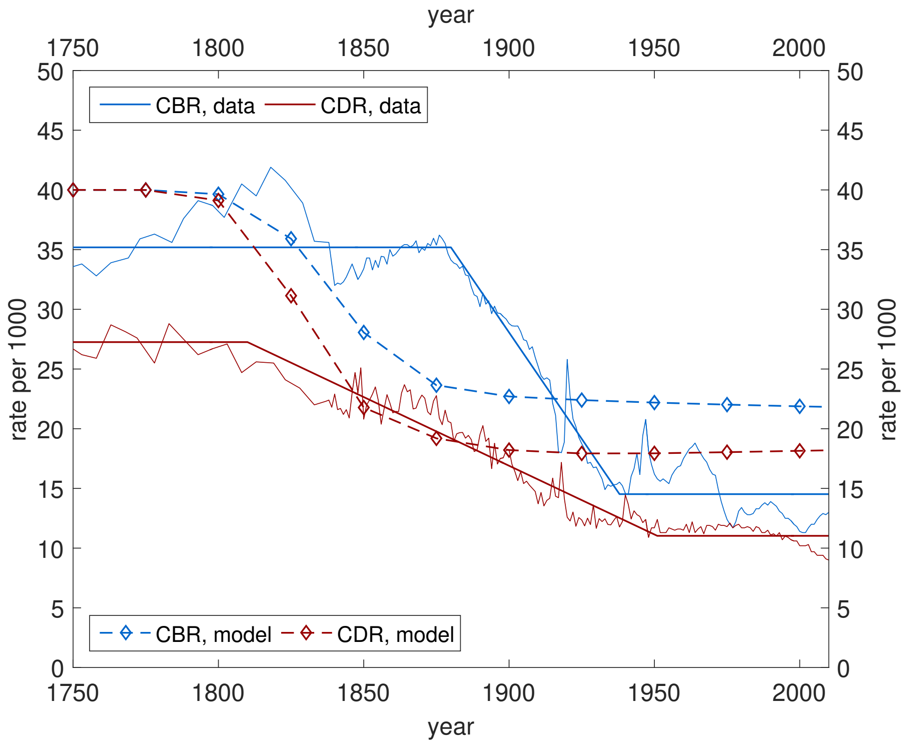
Table 8: Model versus Data

Moment	Source	Target	Model
Variance of log income, world, year 2000	Maddison 2010	0.98	0.57
UK GDP per capita growth, 1700-2000	Maddison 2010	1630%	1690%
UK population growth, 1700-2000	Maddison 2010	690%	590%
UK years of education growth, 1700-2000	Barro and Lee (2013)	260%	160%
UK year 2000 college wage premium (15 vs. 12 years)	Walker and Zhu (2008)	30%	21%
UK drop in CBR 1700-2000	Section 4	20	18.12
UK CBR in 1700	Section 4	35.2	40
UK drop in CDR 1700-2000	Section 4	15	21.85
UK CDR in 1700	Section 4	26.8	40
Slope of transition length/time relationship	Section 4	-0.75	-0.80

Figure 12 compares the vital statistics as they evolve in themodel to the raw data and fitted 3-phase transitions estimated for Great Britain.

Figure 13 plots the pattern of the evolution of technology in the frontier country described in Section 6.2, in which both types of TFP begin growing, but skilled-complementary TFP experiences an initial discrete jump. Figure 14 shows how effective distance between the frontier country and the rest shrinks over time. As can be seen in the figure, the different countries

Figure 12: Great Britain, model vs. data



become more and more similar in their levels of access to the frontier over time. Figures 15 and 16 shows the evolution of technology in two places, 625 km from London (Geneva) and 10,000 km from London (Manila). As can be seen figure, both countries initially experience no growth, even after growth has begun in the frontier. As the cost of distance falls, each country experiences a discrete growth takeoff, with the closer country taking off first. Catch-up growth induces a temporary oscillation of the ratio of skilled to unskilled TFP above its frontier, long-run level in each country. This is due to the assumption that $\theta < 1$, so that the catch-up growth is more elastic in response to the gap to the frontier in skilled than unskilled technology. In Manila, which takes off later, catch-up growth is more rapid, and this oscillation is larger and of greater duration.

As technology improves and diffuses to other countries, skill premium start to rise in each of these locations. As a result, parents choose higher and higher levels education for their children. Figure 17 plots the evolution of the skill premium in the various notional countries, and Figure 18 plots the evolution of education levels. Because of higher elasticity of catch-up growth to technological gap in the skilled sector, the skill premium rises faster in later-transitioning countries, and so the increase in education levels is also more rapid.

As parents educate their children more, they also produce fewer children overall–the classic quantity-quality tradeoff. Figure 19 shows the simulated path of the crude birth rate for the modeled countries. Because the rise in education levels is sharper in later-transitioning coun-

Figure 13: Technology Frontier

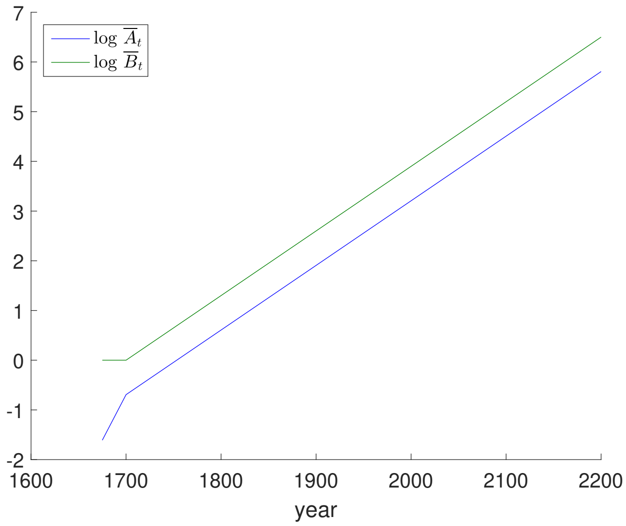


Figure 14: Distance from the Frontier

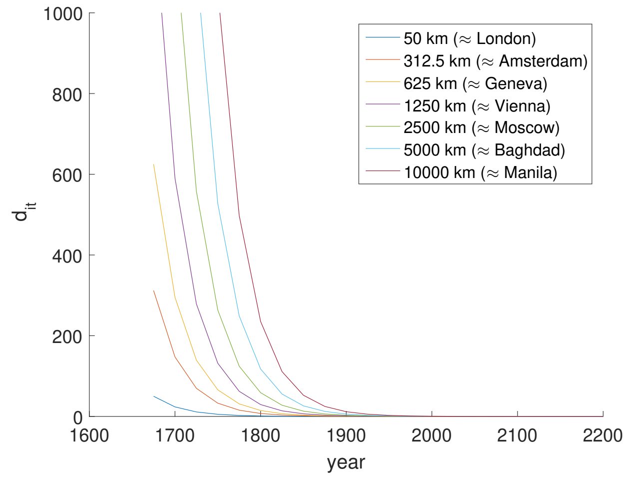


Figure 15: Technology in Geneva

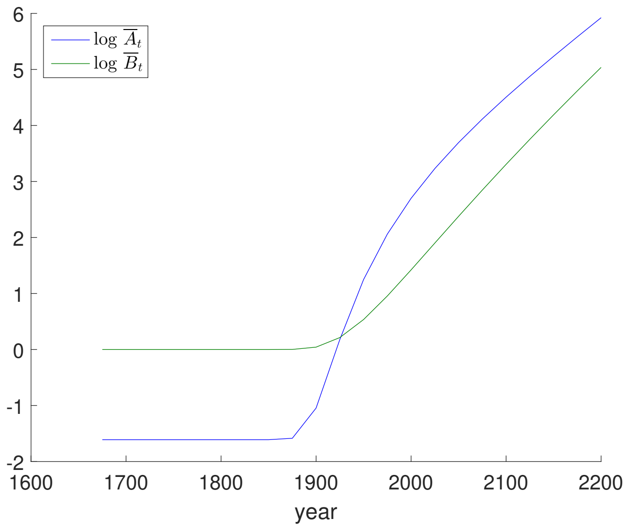


Figure 16: Technology in Manila

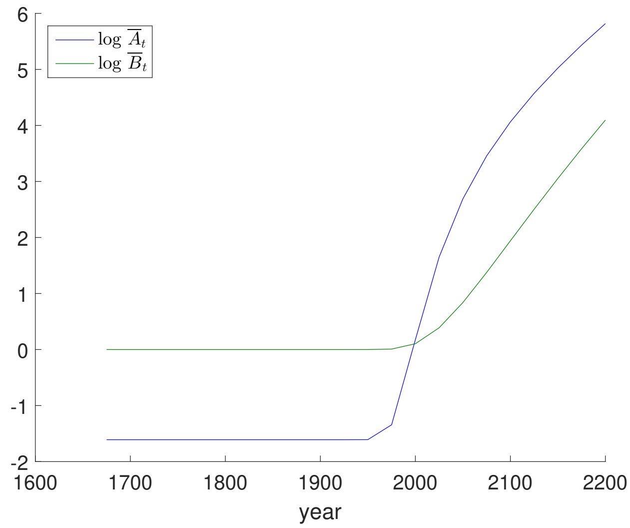


Figure 17: Skill Premium

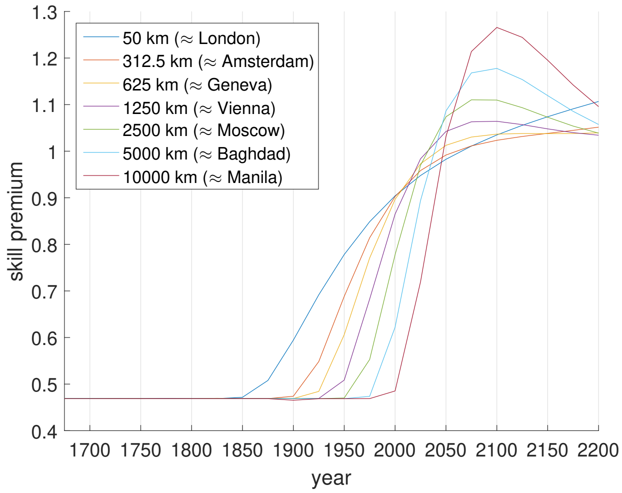


Figure 18: Education

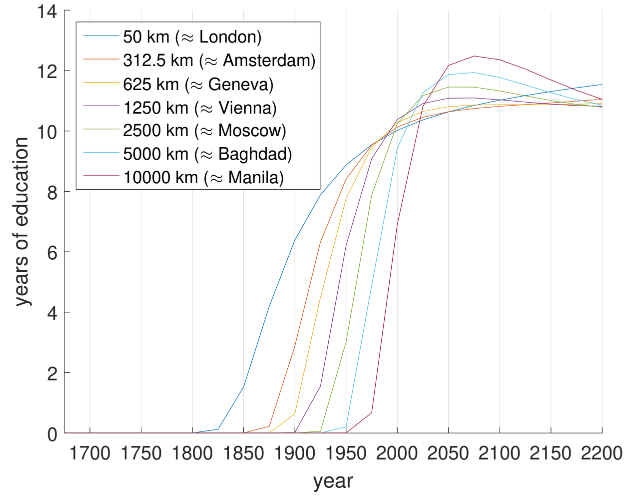


Figure 19: Fertility Transitions

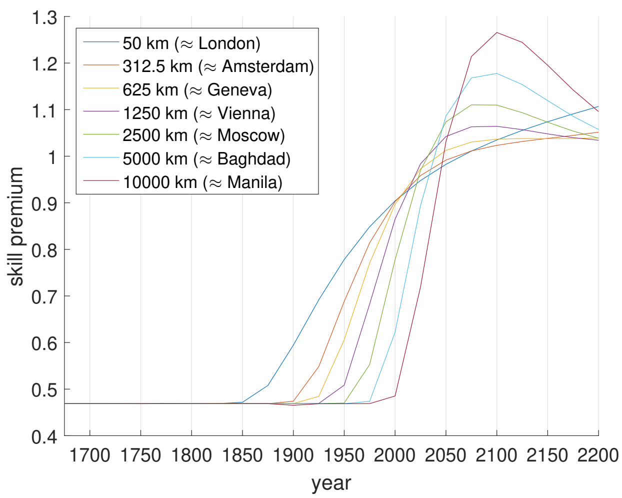
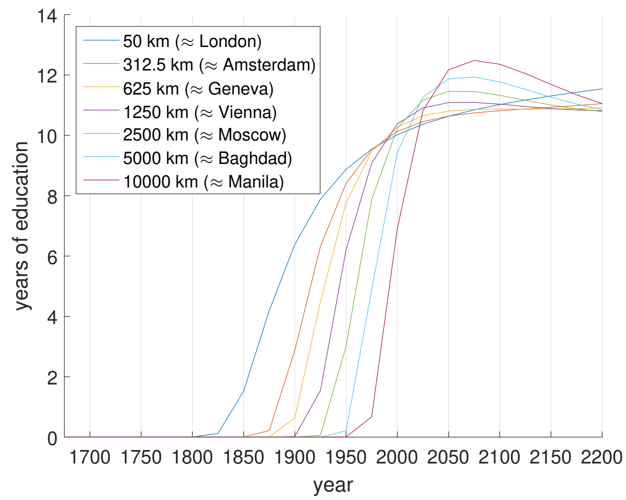


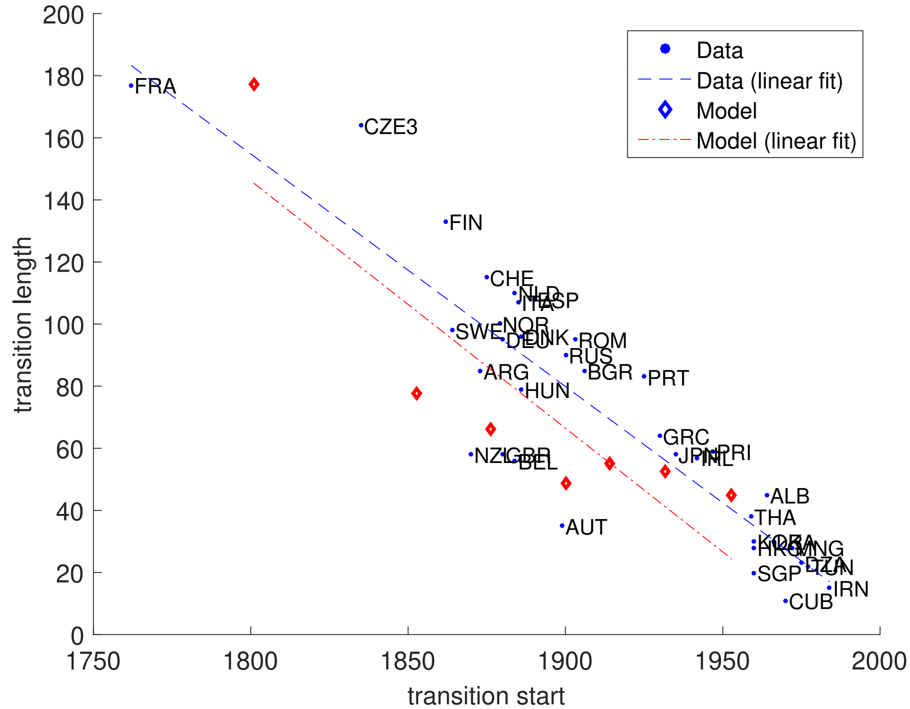
Figure 20: Transition Lengths



tries, so the fall in fertility is also more rapid, and the overall transition period shorter. Figure 20 shows the length of each simulated transition. These vary in length from more than 120 years for the frontier country, to less than 80 years for the last model country to enter the transition.

Figure 21 compares the simulated transition lengths with transition lengths observed in the data. Here we see that this quantitative exercise is able to replicate the overall trend of accelerating transitions, and is able to account for roughly half of the overall decline in transition length over the observed period.

Figure 21: Transition Lengths, Model vs. Data



8 Conclusions

In this paper we have constructed a dataset consisting of birth rates and death rates, and GDP per capita for a panel of 186 countries and spanning from 1735 until 2014. We have proposed a way of measuring demographic transitions which lets the data pick likely start and end dates for fertility and mortality transitions, and used our results to show that: 1) transitions are becoming faster, 2) the average level of GDP per capita at the start of a transition is more or less constant, and 3) an important predictor of a country's transition is the prior transition of other countries which are "close" to it in a geographical and a linguistic sense, and which have similar legal systems.

We then build a model in the tradition of Barro, Becker and Lucas that can account for these facts. In addition to the standard quantity-quality trade-off between how many children to have and how much to educate them, there is also technological diffusion between countries. We conduct a quantitative exercise to show that a simple mechanism of diffusion where skill-biased technological change travels from Britain to the rest of the world in a manner that only depends on geographic distance is able to generate sequences of demographic transitions, each happening faster than the previous one, as we observe in the data, and the account for roughly half of the observed reduction in total transition time.

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A Supplementary tables

A CDR calculated by projecting backward using the method described in Section 2 is indicated by ⋆.

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Afghanistan	1962	2008	1999	n/a
Albania	1898⋆	1977	1963	2010
Algeria	1930⋆	1993	1965	n/a
Angola	n/a	2016	1988	n/a
Argentina	1869	1945	1862	n/a
Armenia	n/a	n/a	n/a	2001
Australia	n/a	1961	n/a	1987
Austria	1881	1941	1899	1934
Azerbaijan	n/a	1988	n/a	1999
Bahamas, The	1916⋆	1967	1954	n/a
Bahrain	1923⋆	1979	1960	2011
Bangladesh	1921⋆	2004	1973	2011
Barbados	1923	1957	1954	1987
Belarus	n/a	n/a	n/a	1998
Belgium	n/a	1956	1884	1940
Belize	1912⋆	1972	1981	n/a
Benin	1947⋆	2001	1987	n/a
Bhutan	1947⋆	2004	1977	2012
Bolivia	1917⋆	2011	1969	n/a
Bosnia and Herzegovina	n/a	1964	n/a	2000
Botswana	1921⋆	1977	1971	n/a
Brazil	1864⋆	1994	1957	2010
Brunei Darussalam	1915⋆	1974	1954	2007
Bulgaria	1918	1948	1906	1991
Burkina Faso	1951	2016	1997	n/a
Burundi	1898⋆	2016	1987	n/a
Cambodia	1981	1987	1985	n/a
Cameroon	1897⋆	2016	1988	n/a
Canada	n/a	1955	n/a	2009
Cape Verde	1899⋆	2000	1984	n/a

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Central African Republic	1961	1979	1978	n/a
Chad	1953	n/a	n/a	n/a
Channel Islands	n/a	2016	n/a	2013
Chile	1921	1978	1929	n/a
China	n/a	1972	n/a	2005
Colombia	1870⋆	1990	1971	n/a
Comoros	1929⋆	1999	1980	n/a
Congo, Dem. Rep.	1904⋆	2016	2004	n/a
Congo, Rep.	1934⋆	1974	1970	n/a
Costa Rica	1883⋆	1982	1958	2008
Cote d'Ivoire	n/a	1981	1963	n/a
Croatia	n/a	n/a	n/a	2002
Cuba	n/a	1946	1970	1981
Cyprus	1922	1955	1945	2010
Czechoslovakia	1867	1951	1834	2000
Denmark	1834	1943	1886	1982
Djibouti	1939⋆	1979	1978	n/a
Dominica	1919⋆	1975	1969	1976
Dominican Republic	1916⋆	1981	1954	n/a
Ecuador	1894⋆	1992	1957	n/a
Egypt, Arab Rep.	1934	1997	1968	n/a
El Salvador	1885⋆	1996	1968	n/a
Equatorial Guinea	1950⋆	2009	1997	n/a
Eritrea	1926⋆	2015	1967	n/a
Estonia	n/a	n/a	n/a	2001
Ethiopia	1932⋆	2016	1992	n/a
Fiji	1864⋆	1976	1964	n/a
Finland	1866	1957	1862	1996
France	1740	1990	1763	1939
French Polynesia	1866⋆	1987	1956	n/a
Gabon	1961	1989	1990	n/a
Gambia, The	1955	1999	1981	n/a
Georgia	n/a	1967	n/a	2000
Germany	1880	1932	1880	1975

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Ghana	1894⋆	1996	1967	n/a
Greece	1916	1955	1930	1994
Grenada	1885⋆	1973	1957	2004
Guam	n/a	1950	1963	n/a
Guatemala	1917	1997	1971	n/a
Guinea	1949⋆	2014	1990	n/a
Guinea-Bissau	1930⋆	2012	1991	n/a
Guyana (British Guiana)	1919	1962	1971	n/a
Haiti	1925⋆	2004	1983	n/a
Honduras	1924⋆	1992	1971	n/a
Hong Kong SAR, China	1941	1947	1960	1989
Hungary	1875	1943	1886	1966
Iceland	n/a	2006	1963	n/a
India	1917	2002	1982	n/a
Indonesia	1933⋆	1983	1959	n/a
Iran, Islamic Rep.	1933⋆	1997	1984	1999
Iraq	n/a	1992	n/a	n/a
Ireland	1899	2014	1942	1999
Israel	n/a	1945	n/a	n/a
Italy	1874	1955	1885	1992
Jamaica	1920	1965	1965	n/a
Japan	1945	1951	1935	1993
Jordan	1932⋆	1980	1964	n/a
Kazakhstan	n/a	1971	n/a	1996
Kenya	1926⋆	1983	1975	n/a
Kiribati	1910⋆	1996	1962	n/a
Korea, Dem. Rep.	1952⋆	1969	1970	1980
Korea, Rep.	1950⋆	1970	1958	1996
Kuwait	1858⋆	1985	1968	n/a
Kyrgyz Republic	n/a	1992	n/a	n/a
Lao PDR	1920⋆	2012	1988	n/a
Latvia	n/a	n/a	n/a	2002
Lebanon	n/a	1972	n/a	2008
Lesotho	1927⋆	1981	1974	n/a

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Liberia	1937⋆	2016	1982	n/a
Libya	1939⋆	1983	1967	n/a
Lithuania	n/a	n/a	n/a	2004
Luxembourg	n/a	2016	n/a	1978
Macao SAR, China	n/a	1970	n/a	1969
Macedonia, FYR	n/a	1967	n/a	2005
Madagascar	1928⋆	2012	1978	n/a
Malawi	n/a	2016	1981	n/a
Malaysia	1911⋆	1975	1958	n/a
Maldives	1945⋆	2000	1986	2001
Mali	1963	2014	2003	n/a
Malta	n/a	2000	n/a	2001
Mauritania	1926⋆	1989	1962	n/a
Mauritius	1930	1965	1958	2009
Mexico	1905	1982	1971	n/a
Micronesia, Fed. Sts.	1846⋆	1986	1971	n/a
Moldova	n/a	1963	n/a	2007
Mongolia	1904⋆	2002	1965	n/a
Morocco	1918⋆	1993	1958	n/a
Mozambique	1936⋆	2016	1977	n/a
Myanmar	1929⋆	1990	1961	n/a
Namibia	1930⋆	1982	1977	n/a
Nepal	1950⋆	2004	1984	n/a
Netherlands	1869	1932	1883	1995
New Caledonia	1852⋆	1992	1968	2008
New Zealand	n/a	2016	1870	1929
Nicaragua	1911⋆	1996	1973	n/a
Niger	n/a	2016	1987	n/a
Nigeria	1911⋆	n/a	1978	n/a
Norway	n/a	1954	1879	1980
Oman	1943⋆	1991	1978	n/a
Pakistan	1923⋆	1994	1980	n/a
Panama	1856⋆	1982	1966	n/a
Papua New Guinea	1941⋆	1986	1967	n/a

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Paraguay	n/a	1994	1950	n/a
Peru	1928⋆	1989	1962	n/a
Philippines	1889⋆	1981	1985	n/a
Poland	n/a	1957	n/a	2004
Portugal	1919	1959	1925	2009
Puerto Rico	1905⋆	1961	1947	2008
Qatar	n/a	1970	n/a	2013
Romania	1902	1962	1903	1998
Russian Federation	1891	1951	1900	1990
Rwanda	1906⋆	n/a	1984	n/a
St. Lucia	1903⋆	1978	1969	2010
St. Vincent and the Grenadines	1892⋆	1977	1961	2002
Samoa	n/a	1992	n/a	n/a
Saudi Arabia	1939⋆	1988	1974	n/a
Senegal	1942⋆	2001	1972	n/a
Serbia (Yugoslavia from 1900)	1875	1958	1920	1998
Seychelles	1869⋆	1980	1965	2001
Sierra Leone	1956	n/a	1997	n/a
Singapore	1910	1961	1959	1981
Slovenia	n/a	2011	n/a	1998
Solomon Islands	1869⋆	2014	1979	n/a
Somalia	1927⋆	2016	2004	n/a
South Africa	n/a	1972	n/a	n/a
Spain	1890	1960	1890	1999
Sri Lanka	1935	1962	1962	n/a
Sudan	1877⋆	2010	1974	n/a
Suriname	n/a	1985	1963	n/a
Swaziland	1932⋆	1982	1978	n/a
Sweden	1710	1958	1854	1969
Switzerland	n/a	1953	n/a	1996
Syrian Arab Republic	1923⋆	1985	1975	n/a
Taiwan	n/a	1966	1955	n/a
Tajikistan	1835⋆	2012	1962	n/a
Tanzania	1889⋆	2016	1966	n/a

Calculated Transition Start and End Dates				
	CDR		CBR	
Country	Start	End	Start	End
Thailand	1909⋆	1979	1959	1999
Togo	1937⋆	1987	1975	n/a
Tonga	1797⋆	1974	1963	n/a
Trinidad and Tobago	1897	1966	1961	2002
Tunisia	1882⋆	1999	1975	1999
Turkey	1927	1990	1958	2006
Turkmenistan	1876⋆	1992	1960	n/a
Uganda	1863⋆	2016	2001	n/a
Ukraine	n/a	n/a	n/a	1999
United Arab Emirates	n/a	1977	n/a	2010
United Kingdom	1794	1958	1885	1937
United States	n/a	1954	1803	1980
Uruguay	n/a	1939	n/a	1941
Uzbekistan	1867⋆	1995	1960	n/a
Vanuatu	n/a	1998	n/a	n/a
Venezuela, RB	1915	1975	1973	n/a
Vietnam	1928⋆	1981	1962	2005
Yemen, Rep.	n/a	1996	1986	n/a
Zambia	1850⋆	2016	1971	n/a
Zimbabwe	1934⋆	1968	1956	n/a

B Imputation of GDP per capita in 1500 CE

Table B1: Year 1500 GDPpc Imputations

Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Afghanistan	Iran, Islamic Rep.	1950	0.50	612
Albania	Germany	1950	0.23	527
Algeria	Spain	1970	0.73	1074
Angola	France	1975	0.25	438
Argentina	Chile	1950	1.71	1271
Armenia	Turkey	1980	0.65	546
Australia	(self)	1820		941
Austria	Germany	1850	0.99	2297
Azerbaijan	Iran, Islamic Rep.	1980	0.81	993
Bahamas, The	(Not in Maddison 2018 dataset)	2010		
Bahrain	(Excluded: First GDP per capita observation influence by natural resource boom.)			
Bangladesh	India	1950	1.36	1433
Barbados	Cuba	1950	0.71	303
Belarus	Finland	1980	0.35	429

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Belgium	(self)	1500		2407
Belize	(Not in Maddison 2018 dataset)			
Benin	Egypt, Arab Rep.	1950	0.41	492
Bhutan	(Not in Maddison 2018 dataset)			
Bolivia	Peru	1950	0.82	760
Bosnia and Herzegovina	Germany	1960	0.14	331
Botswana	Egypt, Arab Rep.	1950	0.24	288
Brazil	(self)	1800		1123
Brunei Darussalam	(Not in Maddison 2018 dataset)			
Bulgaria	Turkey	1925	1.43	1204
Burkina Faso	Egypt, Arab Rep.	1950	0.15	184
Burundi	Egypt, Arab Rep.	1950	0.17	198
Cambodia	Vietnam	1950	0.49	378
Cameroon	Egypt, Arab Rep.	1950	0.46	553
Canada	United States	1820	0.74	660
Cape Verde	Egypt, Arab Rep.	1950	0.46	544
Central African Republic	Egypt, Arab Rep.	1950	0.40	479

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Chad	Egypt, Arab Rep.	1950	0.31	369
Channel Islands	(Not in Maddison 2018 dataset)			
Chile	(self)	1810		744
China	(self)	1661		1083
Colombia	(self)	1800		937
Comoros	India	1950	0.87	921
Congo, Dem. Rep.	Egypt, Arab Rep.	1950	0.49	581
Congo, Rep.	Egypt, Arab Rep.	1950	0.85	1015
Costa Rica	Mexico	1920	0.83	564
Cote dIvoire	Egypt, Arab Rep.	1950	0.77	921
Croatia	Germany	1960	0.45	1033
Cuba	(self)	1690		429
Cyprus	Greece	1950	0.95	1332
Czech Countries (Czechoslovakia 1900-1986, Czech Republic 1987-...)	Germany	1850	0.70	1624
Denmark	Sweden	1820	1.53	2843

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Djibouti	Egypt, Arab Rep.	1950	0.99	1179
Dominica	Cuba	1950	0.39	167
Dominican Republic	Cuba	1950	0.62	267
Ecuador	Peru	1870	0.50	461
Egypt, Arab Rep.	(self)	1500		1190
El Salvador	Mexico	1920	0.68	463
Equatorial Guinea	Egypt, Arab Rep.	1950	0.28	330
Eritrea	(Not in Maddison 2018 dataset)			
Estonia	Finland	1980	0.51	618
Ethiopia	Egypt, Arab Rep.	1950	0.16	192
Fiji	(Not in Maddison 2018 dataset)			
Finland	(self)	1600		1209
France	(self)	1500		1748
French Polynesia	(Not in Maddison 2018 dataset)			
Gabon	(Excluded: First GDP per capita observation influence by natural resource boom.)			
Gambia, The	Egypt, Arab Rep.	1950	0.36	425
(continued on next page)				

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Georgia	Iran, Islamic Rep.	1980	0.86	1056
Germany	(self)	1500		2315
Ghana	Egypt, Arab Rep.	1980	0.33	392
Greece	(self)	1		1400
Grenada	(Not in Maddison 2018 dataset)			
Guam	(Not in Maddison 2018 dataset)			
Guatemala	Mexico	1920	0.64	436
Guinea	Egypt, Arab Rep.	1950	0.21	254
Guinea-Bissau	Egypt, Arab Rep.	1950	0.15	184
Guyana (British Guiana)	(Not in Maddison 2018 dataset)			
Haiti	Cuba	1950	0.65	278
Honduras	Mexico	1920	0.76	519
Hong Kong SAR, China	(self)	1820		961
Hungary	Germany	1870	0.71	1655
Iceland	United Kingdom	1950	0.72	826
India	(self)	1600		1055
(continued on next page)				

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Indonesia	(self)	1815		875
Iran, Islamic Rep.	(self)	1		1225
Iraq	(self)	1150		1190
Ireland	United Kingdom	1930	0.69	787
Israel	(self)	1		1225
Italy	(self)	1500		3125
Jamaica	Cuba	1950	0.67	288
Japan	(self)	1450		829
Jordan	(self)	1		1225
Kazakhstan	Iran, Islamic Rep.	1980	1.20	1474
Kenya	Egypt, Arab Rep.	1950	0.46	553
Kiribati	(Not in Maddison 2018 dataset)			
Korea, Dem. Rep.	(self)	1820		245
Korea, Rep.	(self)	1820		462
Kuwait	(Excluded: First GDP per capita observation influence by natural resource boom.)			
Kyrgyz Republic	Iran, Islamic Rep.	1980	0.43	525

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Lao PDR	Vietnam	1950	0.84	651
Latvia	Finland	1980	0.56	675
Lebanon	Iran, Islamic Rep.	1820	1.43	1749
Lesotho	Egypt, Arab Rep.	1950	0.12	144
Liberia	Egypt, Arab Rep.	1950	0.31	372
Libya	Egypt, Arab Rep.	1950	0.92	1100
Lithuania	Finland	1980	0.61	733
Luxembourg	Belgium	1950	1.38	3313
Macao SAR, China	(Not in Maddison 2018 dataset)			
Macedonia, FYR	Greece	1960	0.65	915
Madagascar	Egypt, Arab Rep.	1950	0.60	710
Malawi	Egypt, Arab Rep.	1950	0.15	175
Malaysia	(self)	1820		1120
Maldives	(Not in Maddison 2018 dataset)			
Mali	Egypt, Arab Rep.	1950	0.19	224
Malta	Greece	1950	0.43	603

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Mauritania	Egypt, Arab Rep.	1950	0.33	387
Mauritius	Egypt, Arab Rep.	1950	0.84	1005
Mexico	(self)	1550		683
Micronesia, Fed. Sts.	(Not in Maddison 2018 dataset)			
Moldova	Turkey	1980	0.82	696
Mongolia	China	1950	2.89	3133
Morocco	(self)	1820		703
Mozambique	Egypt, Arab Rep.	1950	0.11	128
Myanmar	(self)	1820		594
Namibia	Egypt, Arab Rep.	1950	1.28	1527
Nepal	(self)	1820		621
Netherlands	(self)	1500		2617
New Caledonia	(Not in Maddison 2018 dataset)			
New Zealand	Australia	1850	0.53	494
Nicaragua	Mexico	1920	0.96	654
Niger	Egypt, Arab Rep.	1950	0.30	353
Nigeria	Egypt, Arab Rep.	1950	0.61	725

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Norway	Sweden	1820	1.74	3248
Oman	Iran, Islamic Rep.	1950	0.73	889
Pakistan	Iran, Islamic Rep.	1950	0.26	322
Panama	Mexico	1910	1.13	770
Papua New Guinea	(Not in Maddison 2018 dataset)			
Paraguay	Chile	1940	0.63	466
Peru	(self)	1595		930
Philippines	(self)	1820		1094
Poland	(self)	1500		1036
Portugal	(self)	1530		1284
Puerto Rico	Cuba	1950	1.23	530
Qatar	(Excluded: First GDP per capita observation influence by natural resource boom.)			
Romania	Turkey	1923	0.95	801
Russian Federation	Finland	1960	0.89	1075
Rwanda	Egypt, Arab Rep.	1950	0.19	222

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
St. Lucia	Cuba	1950	0.50	213
St. Vincent and the Grenadines	(Not in Maddison 2018 dataset)			
Samoa	(Not in Maddison 2018 dataset)			
Saudi Arabia	Iran, Islamic Rep.	1820	1.57	1920
Senegal	Egypt, Arab Rep.	1950	0.55	657
Serbia (Yugoslavia from 1900)	Germany	1870	0.29	664
Seychelles	Australia	1950	0.33	306
Sierra Leone	Egypt, Arab Rep.	1950	0.28	338
Singapore	Hong Kong SAR, China	1950	1.30	1249
Slovak Republic	(Excluded: First GDP per capita observation influence by natural resource boom.)			
Slovenia	Germany	1960	0.42	974
Solomon Islands	(Not in Maddison 2018 dataset)			
Somalia	(Not in Maddison 2018 dataset)			
South Africa	Egypt, Arab Rep.	1820	1.11	1317
Spain	(self)	1500		1477
(continued on next page)				

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Sri Lanka	(self)	1820		799
Sudan	Egypt, Arab Rep.	1950	0.60	711
Suriname	(Not in Maddison 2018 dataset)			
Swaziland	Egypt, Arab Rep.	1950	0.29	340
Sweden	(self)	1500		1864
Switzerland	(self)	1950		1050
Syrian Arab Republic	Iran, Islamic Rep.	1820	0.33	403
Taiwan	(Not in Maddison 2018 dataset)			
Tajikistan	Iran, Islamic Rep.	1980	0.48	593
Tanzania	Egypt, Arab Rep.	1950	0.36	434
Thailand	(self)	1820		795
Togo	Egypt, Arab Rep.	1950	0.33	396
Tonga	(Not in Maddison 2018 dataset)			
Trinidad and Tobago	Cuba	1950	1.13	484
Tunisia	(self)	1820		718
Turkey	(self)	1500		844

(continued on next page)

Year 1500 GDPpc Imputations (continued)				
Country	Comparison Country	Comp. Year	Comp. Mult.	Imputed GDPpc
Turkmenistan	Iran, Islamic Rep.	1980	0.78	953
Uganda	Egypt, Arab Rep.	1950	0.33	394
Ukraine	Turkey	1980	1.59	1343
United Arab Emirates	(Excluded:			
United Kingdom	(self)	1500		1142
United States	(self)	1650		897
Uruguay	Chile	1820	2.71	2020
Uzbekistan	Iran, Islamic Rep.	1980	0.48	594
Vanuatu	(Not in Maddison 2018 dataset)			
Venezuela, RB	Colombia	1800	1.29	1210
Vietnam	(self)	1820		778
Virgin Islands (U.S.)	(Not in Maddison 2018 dataset)			
Yemen, Rep.	Iran, Islamic Rep.	1950	0.30	369
Zambia	Egypt, Arab Rep.	1950	0.62	734
Zimbabwe	Egypt, Arab Rep.	1950	0.36	427

C Auxiliary Rules for Model Selection

C.1 Auxiliary Rules of Transition Starts

A statistically-detected Crude Death Rate transition start date is removed, moving from Case I to Case II, or Case III to Case IV, if one or more of the following conditions holds:

1. Estimated initial CDR level of less than 25, less than 20 years after the start of the series.
2. Estimated initial CDR level of less than 15, regardless of timing.
3. Estimated initial CDR level more than 20 points below the initial level of CBR, regardless of timing.

A Crude Death Rate transition start date is added, moving from Case II to Case I, or Case IV to Case III, if both of the following conditions holds:

1. Estimated initial CDR level greater than 35.
2. CDR start date has not been previously removed by the first set of rules.

A statistically-detected Crude Birth Rate transition start date is removed, moving from Case I to Case II, or Case III to Case IV, if one or more of the following conditions holds:

1. Estimated initial CBR level of less than 30, less than 20 years after the start of the series.
2. Estimated initial CBR level of less than 20, regardless of timing.

A Crude Birth Rate transition start date is added, moving from Case II to Case I, or Case IV to Case III, if both of the following conditions holds:

1. Estimated initial CBR level greater than 50.
2. CBR start date has not been previously removed by the first set of rules.

C.2 Auxiliary Rules of Transition Ends

A statistically-detected Crude Death Rate transition end date is removed, moving from Case I to Case III, or Case II to Case IV, if one or more of the following conditions holds:

1. Estimated final CDR level of greater than 20, less than 20 years after the start of the series.
2. Estimated initial CDR level greater than 25, regardless of timing.

A Crude Death Rate transition end date is added, moving from Case III to Case I, or Case IV to Case II, if both of the following conditions holds:

1. Estimated final CDR level less than 12.
2. CDR end date has not been previously removed by the first set of rules.

A statistically-detected Crude Birth Rate transition start date is removed, moving from Case I to Case III, or Case II to Case IV, if one or more of the following conditions holds:

1. Estimated initial CBR level of greater than 20, less than 20 years after the start of the series.
2. Estimated initial CBR level of greater than 25, regardless of timing.

A Crude Birth Rate transition start date is added, moving from Case III to Case I, or Case IV to Case II, if both of the following conditions holds:

1. Estimated final CBR less than 12.
2. CBR end date has not been previously removed by the first set of rules.

D An empirical analysis of CDR transitions

Table B1: GDPpc and CDR transition, Logit results

Variable	Estimates
Cons	0.75
	(19.21)
lnGDPPC	-3.64
	(5.12)
lnGDPPC ^{2}	0.37
	(0.34)
LLn	-259.9
Pseudo-R^2	0.071
N	16062

Table B1 reports the Logit estimation for CDR when the only explanatory variable is log GDP per capita. As shown in Figure 22, this specification replicates well the distribution of log GDP per capita at the start of the CDR transition. This specification does not perform well, however, in replicating the distribution of CDR transition starts over time or in predicting transition start dates for individual countries, as seen in Figures 23 and 24.

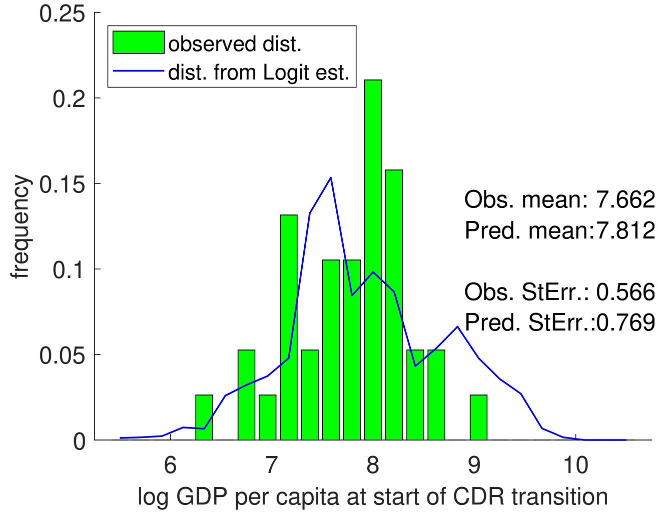


Figure 22: Distribution of log GDPpc at the start of the CDR transitions

Figure 23: Within Sample Predictions

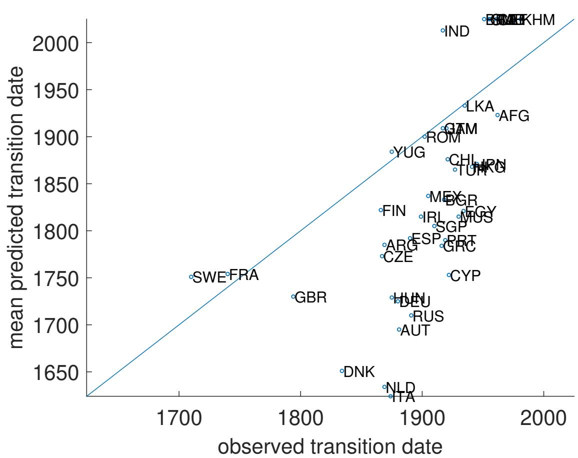
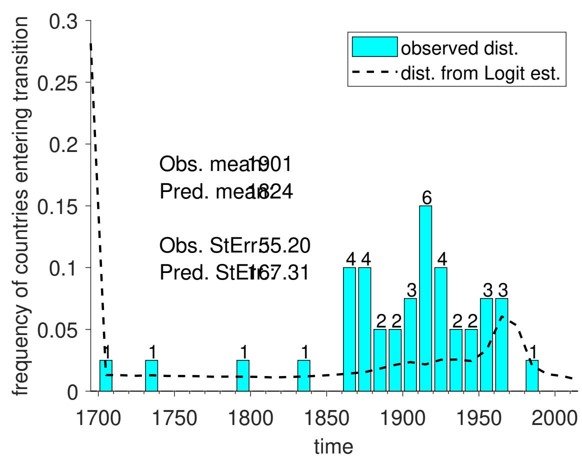


Figure 24: Distribution of Transtion Dates



D.1 Demographic contagion for CDR

Table B2 shows the results of the Logit regression described in Section 5 for CDR. Specification (1) shows the results of the regression without including any inter-country influence. Specification (2) adds a global count of the number of countries that have begun the transition, and specification (3) adds some curvature to that sum, which is still global. The estimated value of ψ, being less than 1, implies that there are diminishing returns–the more countries have already entered the transition, the smaller the effect of each additional country on other countries' odds of entering the transition. Specifications (4) through (11) weight the influence of one transitioned country on other countries according to the inverse distance between them, as determined by various measures of distance. When included by themselves, all 4 measures of distance (geographic, linguistic, religious and legal) have highly significant estimated coefficients, with geographic distance having somewhat more explanatory power (as reflected in the log likelihood sum) than the others. Religious distance has the wrong sign, which means that it is probably correlated with some excluded factor and, thus, the coefficient does not reflect the real effect of religious distance. Specifications (9), (10), and (11) include more than one measure of distance simultaneously. Geographic distance retains a significant coefficient in all of these specifications, while linguistic and legal distance maintain positive, but not quite statistically significant point estimates.

In Figure 11, we look at the access to transitions measure implied by specification 11 (the distributions displayed in all of these figures are smoothed using a Gaussian kernel). Using the estimated parameters, access is calculated as

$$\mathcal{A}_{it} \equiv \left[\sum_{j=1}^{N} \exp[\mathcal{D}_{ij} + 0.16 \cdot \mathrm{lp2}_{ij} + 0.04 \cdot \mathrm{cml}_{ij}] \mathcal{I}_{j,t-1} \right]^{0.45},$$

where

$$\mathcal{D}_{ij} \equiv 2.25 \cdot \mathbf{1}\{\mathrm{ldi}_{ij} < \ln 500\} + 1.46 \cdot \mathbf{1}\{\ln 500 \leq \mathrm{ldi}_{ij} < \ln 1000\} + 0.56 \cdot \mathbf{1}\{\ln 1000 \leq \mathrm{ldi}_{ij} < \ln 2000\}.$$

The top left panel of Figure 25 shows the distribution of this measure at different points in time. Not surprisingly, as more countries transition, this distribution moves steadily to the right. The top right panel of Figure 25 plots the transition probabilities implied if each country is assigned its actual access to CDR transitions value and GDP per capita equal to $2000. Here we can see that in 1850 and 1900 "Access to CDR transitions" in the great majority of countries was such that their probability of transition at $2000 GDP per capita would have been relatively small. In 1950 and the year 2000, the distributions shift outward somewhat. In each of these two years, there are still some countries that would have zero probability of transition at $2000 GDP per capita, and the majority of countries have less than 20% yearly probability of transition at this income level. would be 10%.

The bottom left panel of Figure 25 shows the evolution of the distribution of GDP per capita over time. This distribution shifts right as time passes and more countries enjoy higher levels of GDP per capita. The bottom right panel of Figure 25 shows the distribution of the probability of CDR transition, given the observed GDP per capita for each country, assuming they have the mean level of "Access to CDR transitions" existing in the year 2000. This panel demonstrates the importance of the complementarity between a country's level of development and the influence of its neighbors. In 1850, even countries with relatively high log GDP per capita had a low transition probability. In comparison, by 2000, a country with the relatively low level of GDP per capita ($2000) has a greater than 40% probability of starting the CDR transition if enough of their neighbors started before them.

Table B2: Determinants of the start of the CDR transition

cons	0.75	-15.89	-18.85	-23.47	-35.75	-9.53	-15.49	-25.78	-45.02	-31.05	-37.71
	(19.21)	(22.45)	(21.86)	(21.94)	(24.04)	(20.92)	(22.76)	(21.71)	(25.01)	(23.16)	(24.22)
lnGDPPC	-3.64	0.67	1.33	2.84	6.15	-0.75	0.54	3.07	8.27	4.73	6.28
	(5.12)	(6.03)	(5.86)	(5.92)	(6.41)	(5.65)	(6.13)	(5.78)	(6.61)	(6.17)	(6.39)
lnGDPPC ^{2}	0.37	0.06	0.01	-0.11	-0.34	0.12	0.05	-0.10	-0.46	-0.23	-0.32
	(0.34)	(0.40)	(0.39)	(0.40)	(0.43)	(0.38)	(0.41)	(0.39)	(0.44)	(0.41)	(0.42)
access		0.14	1.18	7.01	4.03	3.58	1.88	1.17	2.20	2.10	0.69
		(0.01)	(0.71)	(2.76)	(0.53)	(0.52)	(0.38)	(0.28)	(0.35)	(0.32)	(0.14)
geo dist.				4.31							
				(1.29)							
$<$ 500km					0.82				1.12	0.17	-0.74
					(0.38)				(0.50)	(0.29)	(0.30)
500-1000km					1.88				2.30	1.83	2.16
					(0.29)				(0.21)	(0.20)	(0.09)
1000-2000km					0.27				0.69	-0.11	0.15
					(0.37)				(0.29)	(0.31)	(0.18)
ling. dist						2.95			-2.43		-1.64
						(0.00)			(0.70)		(0.41)
relig dist							1.65				
							(0.53)				
legal dist								0.46		0.21	0.21
								(0.09)		(0.16)	(0.06)
ψ, curv.			0.46	0.63	0.66	0.63	0.56	0.52	0.56	0.69	0.63
			(0.16)	(0.74)	(0.00)	(0.00)	(0.03)	(0.05)	(0.00)	(0.00)	(0.00)
LLn	-259.9	-203.4	-200.0	-194.1	-186.4	-196.4	-195.1	-196.8	-185.4	-185.6	-185.2
Pseudo-R^2	0.071	0.273	0.285	0.306	0.334	0.298	0.303	0.297	0.337	0.337	0.338
N. Obs.	16062	16062	16062	16062	16062	16062	16062	16062	16062	16062	16062

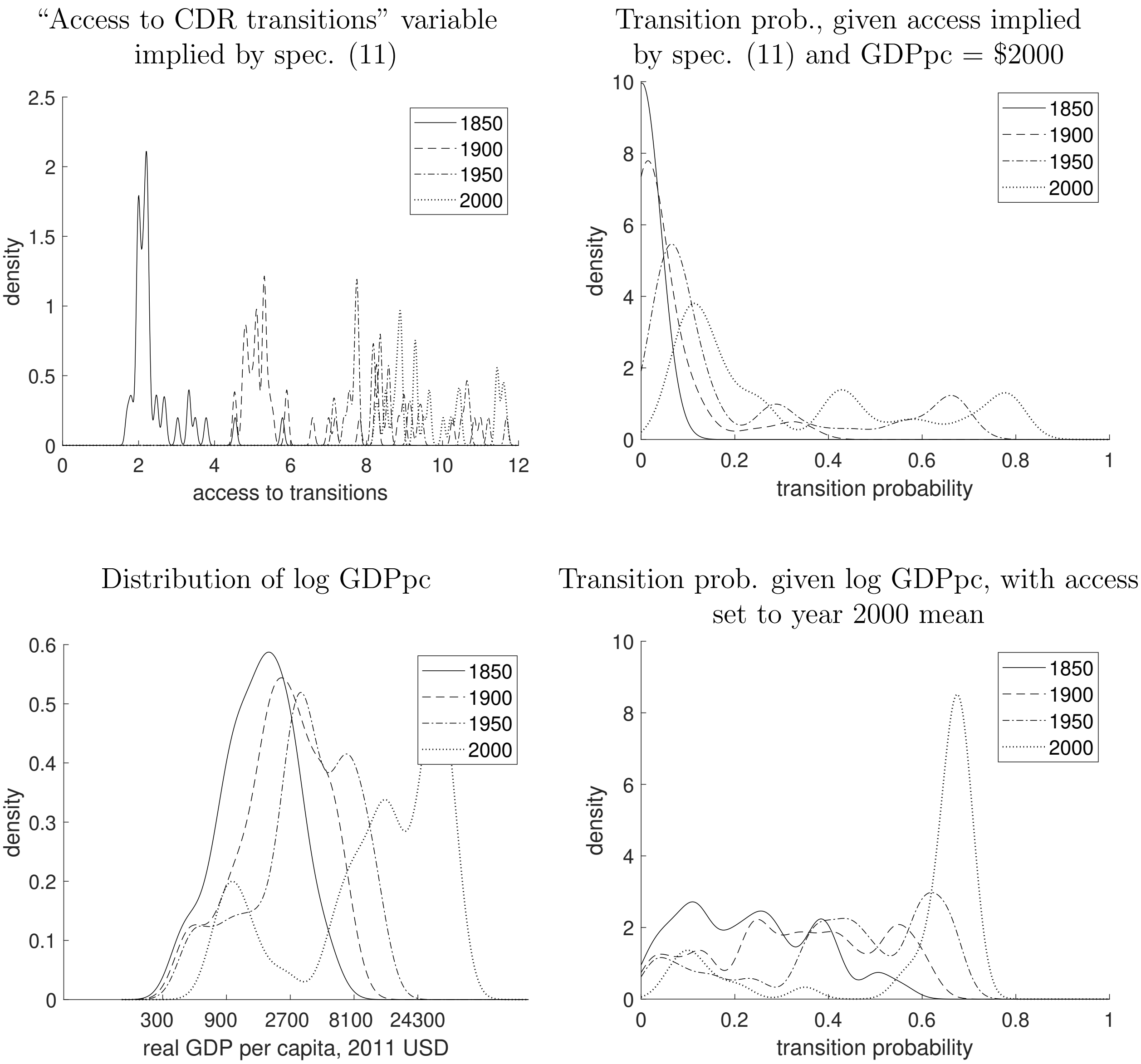


Figure 25: Demographic contagion.