Demography and Development Redux

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Abstract

The effects of population growth on long-term economic development are obviously important. Existing studies, notably Kremer [40], argue that population growth spurs technological change. This paper introduces previously untested growth predictions of Kremer’s [40] model, and assesses the sensitivity of existing findings using numerous alternative data sources, empirical specifications, and sample periods. I find that excluding modern data reverses existing time series conclusions. Inferences drawn from the melting of the ice caps are also reversed when appropriate controls are taken into account. A leapfrogging model is briefly discussed as a competing framework to study demographic and technological change.

Keywords: Population growth; technological change; Malthus and Boserup.

JEL classification: J10, O40.

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1 Introduction

The relationship between population growth and economic development is contentious. Social scientists are broadly divided between Malthusians, who see population growth as a barrier to economic development, and Boserupians, who see population growth as a driver of technological change. Global environmental sustainability, Africa’s demographic momentum, and the emergence of below-replacement fertility in developed countries are among the many current issues confronted by this perennial debate. Through a synthesis of Malthusian and Boserupian views, Kremer [40] provided evidence relevant for assessing these views of population growth. Based on long time series population data and a natural experiment, the geographic isolation of populations following the last glaciation, Kremer [40] argued that the long-term history of population growth is consistent with a view whereby population growth spurs technological change.

This paper seeks to further Kremer’s [40] discussion. I introduce several previously untested population growth predictions from Kremer’s [40] model and reassess existing findings using alternative global, regional, and local demographic data. The findings largely differ from those of Kremer [40]. I find, for example, that the theory’s time series tests are reversed when recent observations are excluded. The theory predicts a positive association between population growth and population size. In samples that end after the 1970s, population growth and size are strongly positively associated, even for regional and local data not examined by Kremer [40]. But if recent observations are omitted, data as recent as those based on post-1900 observations, the results become insignificant and often display a “wrong” (e.g., negative) sign.

Existing assessments based on the melting of the ice caps are also likely biased. The last glaciation isolated the Old and the New Worlds, as well as Australia and other smaller regions. Suppose, as in Kremer [40], that populations were randomly allocated between the Old and New Worlds, and that population densities were the same in both regions some 12 thousand years ago (12KYA). The theory predicts that the New World’s smaller initial population size (a consequence of its smaller area, since densities are assumed equal) would generate a technological disadvantage relative to the Old World when these
two regions were reunited. Existing tests, however, ignore regional differences in factor endowments and biogeography. This is problematic because the importance assigned to initial population size could simply be due to geographic differences, which, according to Diamond [21], favored an early origin of agriculture and an easier diffusion of post-agricultural technologies such as metallurgy and weaponry in the Old World. A careful selection of a control group or the inclusion of appropriate control variables in an econometric specification suggest that differences in initial population sizes played no significant role in the demography of these regions at the time of the European expansion.

The findings primarily highlight the transient nature of modern population growth. Particularly, the sharp divide between pre-modern and modern demographic regimes. In pre-modern samples, for example, population exhibits mean reversion, as a stationary Malthusian equilibrium would predict.\textsuperscript{1} Moreover, exogenous determinants of demographic and technological change (i.e., arable land and biogeographic endowments) influence population growth in opposite ways in modern and pre-modern samples. These reversals contradict the continuity in demographic conditions in Kremer [40] and in unified growth models such as Galor and Weil [25]. (A leapfrogging model, i.e., Brezis et al., [9], may actually fit the empirical patterns of population growth much better than an ideas-based model.) The findings thus caution against overgeneralizing long-term relationships based on modern observations.\textsuperscript{2} The experience of developed countries during the eighteenth and nineteenth centuries, and the current experience of most of the developing world, clearly contradict the Malthusian theory. This contradiction does not necessarily mean support for Boserupian views of the relationship between population growth and economic development.

\textsuperscript{1}This paper, however, is not a test for Malthusian dynamics. In contrast to Ashraf and Galor [4], for example, the analysis does not focus exclusively on the pre-modern period. This paper, in fact, provides a clear illustration of the breakdown of Malthusian theory. This paper lacks direct data on technological differences across space and time. Comin et al. [15] assembled a dataset on the adoption of technology during pre-modern times. The concluding section establishes consistency with their findings.

\textsuperscript{2}The fragility of Kremer’s [40] findings was also discussed by Ravallion [49], but in a different context. Ravallion [49] noted that Kremer’s [40] model has a spacing implication: longer time periods between observations imply higher growth rates. Ravallion [49] showed that the global data contradicts the spacing implication. The analysis presented here complements Ravallion [49]. For example, I examine different predictions and consider additional sources of data; specifically, data with evenly spaced observations.
The findings also have a practical significance. Renewed interest in global environmental change has made negative population externalities due to congestion, market imperfections, and natural-resource base constraints central to the literature; see, e.g., Acemoglu et al. [1], Baland and Robinson [5], Bohn and Stuart [7], Bongarts [8], Cohen [14], Dasgupta [18], Ehrlich et al. [22], Kelly and Kolstad [36], and Lee and Miller [42]. Yet empirical assessments of the long-term effects of population growth (even in reduced-form) have not advanced much beyond Kremer’s [40] initial discussion. In addition, while economic growth theory has moved away from scale effects in population size, population growth is still the ultimate determinant of technological change in ideas-based models; see, e.g., Jones [34], Kortum [39], and Segerstrom [55].

Despite the synchronized timing and pace of modern economic and demographic changes in the spotlight since at least Kuznets [41], empirical assessments of the relationship between population growth and economic growth are generally inconclusive and contradictory, even when there are no serious measurement problems. This paper suggests that these contradictions arise because modern and pre-modern demographic and economic regimes are too dissimilar to produce a stable long-term relationship between population growth and economic growth.

The paper unfolds as follows. Section 2 provides some background for the empirical tests of the paper; Section 3 presents tests that use modern population data; Section 4 discusses tests based on the melting of the ice caps; and Section 5 concludes.

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3 Kuznets [41] and Simon [56] emphasized, but did not quantify, positive population externalities. Johnson [32] and Jones [33] discussed population externalities in the production of knowledge in a long-term perspective. Pryor and Maurer [47] and Lee [42] are earlier syntheses of Malthus and Boserup with predictions that are similar to those of Kremer [40]. Curiously, the (positive) relationship between population growth and population size was first studied in the 1960s in the context of fatalistic “doomsday” models; see, e.g., Foerster et al. [24] and Umpleby [59].

4 The empirical literature that examines modern samples has found positive, negative, and zero effects of population growth on postwar economic growth; see, e.g., Headey and Hodge [28], Kelley [35], and Pritchett [48]. Anthropologists have also examined the relationship between population size and technological complexity in hunter-gatherer societies; see, e.g., Collard et al. [16], Henrich [29], Kline and Boyd [38], and Read ([50], [51]), as well as in the transition from hunter-gathering to agriculture; see, e.g., Harlan [26] and Fagan [23]. These assessments are usually inconclusive partly because of small sample sizes and omitted considerations.
2 Some theoretical background

This section closely follows Kremer [40] and Klasen and Nestmann [37], but it explicitly allows for exogenous determinants of demographic and technological change. Let $N(t)$ and $A(t)$ represent population size and the level of technology at date $t = 0$, with $N(0) = N_0 > 0$ and $A(0) = A_0 > 0$. The aggregate production function is $Y(t) = A(t)N(t)^\eta T^{1-\eta}$ with $0 < \eta < 1$, where $T$ is land, in fixed supply. Technological change satisfies

$$\dot{A}(t) = \lambda A(t)^\phi N(t)^\gamma,$$

(1)

where $\phi$, $\gamma$, and $\lambda$ are positive and fixed parameters: $\phi$ measures the returns to scale to knowledge, $\gamma$ captures the influence of population on the production of knowledge, and $\lambda$ represents exogenous influences on technological change; $\phi$ and $\gamma$ are associated with the “standing on shoulders” and “fishing out” knowledge externalities; see Jones [34]. If $\phi = 1$ and $\gamma = 0$, technology would grow exogenously at a rate $\lambda$.

Output per capita is $y(t) = A(t)(N(t)/T)^{\eta-1}$. There is an invariant “subsistence level” $\bar{y}$ with $y(t) = \bar{y}$ so that

$$\frac{\dot{N}(t)}{N(t)} = \frac{1}{1-\eta} \frac{\dot{A}(t)}{A(t)},$$

(2)

which, once combined with (1), yields

$$\dot{N}(t) = \theta N(t)^\alpha,$$

(3)

with $\theta \equiv \lambda \bar{y}^{\phi-1} T^{(\eta-1)(\phi-1)/(1-\eta)}$ and $\alpha \equiv (1-\eta)(\phi-1) + \gamma$.

The composite parameter $\alpha$ is central to the theory. This parameter captures the race between Malthusian and Boserupian effects: if $\alpha < 1$ because $\gamma < 1 + (1-\eta)(1-\phi)$, Malthusian effects dominate: population growth and size will be negatively related. If $\alpha > 1$ because $\gamma > 1 + (1-\eta)(1-\phi)$, Boserupian effects dominate: population growth and size will be positively related. Expression (3) implies that:

(i) If $\alpha > 1$, population growth is an increasing function of population size.
The solution of the Bernoulli differential equation (3), when $\alpha > 1$, is

$$\ln [N^*(t; \theta, N_0)] = \frac{\ln[\theta(1-\alpha)t + N_0^{1-\alpha}]}{1-\alpha},$$  \hspace{1cm} (4)$$
defined for $t < t^* \equiv N_0^{1-\alpha}/\theta(\alpha - 1) > 0$. In terms of the solution $N^*(t; \theta, N_0)$, expression (4) implies that:

If $\alpha > 1$, population growth increases with: (ii) time, $t$; (iii) exogenous factors, $\theta$; and (iv) initial population size, $N_0$.

Kremer [40] focused on (i) and (iv). Predictions (ii) and (iii) have not been previously examined but they seem equally useful for assessing the previous theory.\footnote{Ravallion [49] interpreted the time index $t$ as the length between observations. Accordingly, a longer time period between observations implies higher growth rates. Differences in the spacing between observations are specially relevant during the early part of the sample in Kremer [40]. I do not focus on spacing because the data sources used here are roughly evenly spaced. Notice also that (iii) relates exogenous variables to population growth. Malthusian theory would associate these exogenous variables to population levels, not to growth rates; see, e.g., Ashraf and Galor [4].} Through $\theta$, for example, (3) and (4) predict a positive effect of exogenous technological factors $\lambda$ and arable land $T$ on the growth rate of population. That is, exogenous factors are predicted to have growth effects and not just level effects on population size, as typically considered in say Malthusian analyses; e.g., Ashraf and Galor [3]. In fact, in the limit as $\alpha \to 1$, the model yields exponential growth at an exogenous rate $\theta$. Notice also that all the previous predictions are reduced-form. Ideally, one would like to examine the structural equations (1) and (2) to identify $\eta$, $\phi$, and $\gamma$ separately instead of the composite term $\alpha$; this is not feasible due to the lack of data for $A(t)$.$^6$

Klasen and Nestmann [37] augmented Kremer’s [40] model by considering population density as an argument in the production of knowledge, e.g., (1) becomes

$$\dot{A}(t) = \lambda A(t)^\phi N(t)^\gamma (N(t)/T)^\varsigma,$$  \hspace{1cm} (5)$$

\footnote{\vspace{1cm}6For example, it is not possible to separately test for “scale effects” (e.g., $\gamma = 1$ and $\phi = 0$) and “market size effects” (e.g., $\gamma < 1$ and $\phi < 1$). Madsen [44] used patents and R&D data for OECD economies to examine Schumpeterian and semi-endogenous versions of the knowledge production function. These tests require data that is not available for pre-modern times.}
with $\sigma > 0$. In this case, $\theta \equiv \lambda \gamma^{\phi-1} T^{(\eta-1)(\phi-1)-\sigma} / (1-\eta)$ and $\alpha \equiv (\phi-1)(1-\eta)+\gamma+\sigma$. Thus including population density in (1) enhances the relationship between population size and growth in $\alpha$, but weakens the positive relationship between arable land and population growth. It is not possible to separately identify the different factors determining $\alpha$ and $\theta$. I will, however, empirically study the effect of arable land on population growth.

Kremer [40] and Klasen and Nestmann [37] rely on the (Malthusian) assumption that technological change augments population size. Such assumption is less problematic for the pre-modern epoch; see, e.g., Ashraf and Galor [4]. The most serious concern is the following. In (3) and (4), population grows due to exogenous factors, captured by $\theta$, and endogenous ones, captured by $\alpha$. Thus, to properly identify the relative strength of Boserupian or Malthusian effects (i.e., $\alpha$), one must control for potentially confounding influences (i.e., $\theta$). Section 4 discusses this identification problem in more detail in the context of prediction (iv).

3 Tests with modern population data

This section examines predictions (i) to (iii) using modern data. The next section examines (iv) using pre-modern data. The first part of this section briefly discusses data issues; additional remarks are available in Appendix A. The next sub-sections present the empirical estimates and sensitivity analyses.

**Data.** To examine prediction (i), Kremer [40] used population estimates taken from Deevey [19] and complemented them with modern sources such as McEvedy and Jones [45]. Figure 1 plots population size and the population growth rate from 1MYA through 2010 based on global data from Deevey [19], Kremer [40], and Ravallion [49]. Two points are important about this figure. First, population growth and size are positively related, especially in Deevey’s [19] data which ends in the 1960s. Second, this positive relationship seems heavily influenced by the modern demographic transition. On one side, data prior to 1600 are dwarfed in Figure 1 so one needs a smaller scale to make any pre-1600 pattern visible, as in Figure 2 below. On the other side, post-1960 data show a negative association
instead of a positive relationship like the one visible between 1600 and 1960.\(^7\)

Pre-modern population data in Kremer [40] is heavily influenced by the Deevey’s [19] estimates. Deevey’s ([19], p. 195) estimates are available “from the inception of the hominid line one million years ago,” but his population data is so speculative that Deevey ([20], p. 248) himself remarked: “my own treatment of this, published some years ago in *Scientific American*, was not very professional.” Deevey’s [19] data is especially problematic because it is biased toward accepting Kremer’s hypotheses (i) to (iii). The source of the bias lies in Deevey’s [19] assumption that population density within each area populated by humans increased at an increasing rate from 1 million years ago (1MYA) onwards. This faster-than-exponential growth in population densities implies that population growth and size would be positively related *by construction*. This assumption seems counterfactual. Post-agricultural times clearly feature increasing population densities (i.e., in the form of denser cities), as Deevey [19] assumes. It is unclear, however, that Deevey’s [19] assumption holds in the long pre-agricultural era. There are no archeological records to establish the population size or density of hunter-gatherers in the past, and there seems to be no useful alternative estimate of the human population size before agriculture to substitute Deevey’s [19] estimates.\(^8\)

Since Deevey’s [19] data is problematic, I consider numerous alternative sources. Several authors have provided longitudinal estimates of regional populations in post-agricultural times. I rely on McEvedy and Jones [45] and Biraben [6] to study changes within world regions or countries and Whitmore et al. [60] to focus on particular agricultural centers. None of the available sources are direct measures, and it is recognized

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7 Ravallion [49] updated Kremer’s [40] global population data for 2000, 2005, and 2010, and showed that adding these observations drastically weakens the performance of the model, a point anticipated by Kremer [40].

8 Although these populations are very selected, I was not able to find statistical differences in the sizes and densities of current hunter-gatherers in the Standard Cross-Cultural Survey, an ethnographic atlas of pre-industrial societies. (The empirical analysis of the current hunter-gatherers is available upon request.) Human genetic history; see Ashraf and Galor [4], suggests an origin date of modern humans of about 150KYA. Clark ([13], p. 62), who provided one of the earliest longitudinal estimates of regional populations and some remarks about prehistoric population size, noted that “[s]o far as biologists can judge, the human race has existed in this world for something like a million years ago. However, the evidence on which this statement is based seems to be very uncertain, and some biologists are so casual that one wonders if they have even got the correct number of zeros.”
that population data are highly uncertain; see, e.g., Caldwell and Schindlmayr [10] for a
critical assessment of past population estimates. McEvedy and Jones [45] and Biraben
[6] are independent sources that cover a large number of geographic areas: McEvedy and
tains 12 regions, and population data from 400 BC to 1970. Whitmore et al. [60] provide
archeological reconstructions for agricultural centers. I use data from local agricultural
centers primarily for sensitivity purposes.

**Prediction (i): population growth and population size.** Let $n_{i,t}$ be the geo-
metric average growth rate of the population for region $i$, between periods $t - 1$ and $t$.
(The geometric average is more appropriate than the arithmetic average for describing
population growth.) I consider the following simple econometric model:

$$n_{i,t} = \beta_0 + \beta N_{i,t-1} + \delta_i + \varepsilon_{i,t},$$  \hspace{1cm} (6)
where $N_{i,t-1}$ denotes the population size of region $i$ in period $t - 1$, and $\delta_i$ denotes an 
unobserved region-specific component that influences population growth. I consider both 
random and fixed effects. (The findings are invariant to the choice of specification.) The 
error term, $\varepsilon_{i,t}$, captures all other omitted factors, and $\beta_0$ is a constant term.

Prediction (i) requires $\beta > 0$. Table 1, Panel A, estimates equation (6) for the entire 
sample and the three global population data, using OLS. Column (1) reproduces the 
estimates in Kremer [40]. Column (2) uses data from McEvedy and Jones [45], and 
Column (5), data from Biraben [6]. For all data sources, the point estimates for $\beta$ are 
positive and significant. The point estimates in columns (2) and (5) are actually greater 
than those that rely on Kremer’s [40] data (column (1)).

Columns (3) and (4) in Table 1, Panel A, present estimates of equation (6) using 
regional data from McEvedy and Jones [45]. Columns (5) and (6) present the same 
estimates using data from Biraben [6]. Columns (3) and (5) consider random effects, and 
columns (4) and (6), fixed effects. The point estimates in these specifications are pos-
itive, statistically significant, and virtually identical across data sets and specifications.
The point estimates for the regional data are greater than those for the world popu-
lation. These estimates show that global and regional population growth rates are strongly 
correlated with population size, as predicted by (i).

The previous estimates speak about the value of $\alpha$ in equation (3) only as an ap-
proximation, e.g., one can approximate (3) as $n(t) \approx \theta(1 - \alpha) + \alpha \theta N(t)$. The relevant 
reduced-form elasticity $\alpha$ can be more directly obtained using a log-log specification in 
equation (3):

$$\ln n_{i,t} = \rho_0 + \rho \ln N_{i,t-1} + \delta_i + \varepsilon_{i,t}. \quad (7)$$

This log-log specification, however, is inconsistent with zero or negative population 
growth. In the world population estimates in Kremer ([40], Table 1), there is only one 
instance of a population decline, namely the Black Death. Past population estimates are 
usually biased towards positive growth because paleo-demographic methods are better 
suited to find population increases rather than population crashes; see Schacht [54] and 
Petersen [46]. To deal with nonpositive growth rates, I first estimate (7) using positive
growth rates only and treat $1+\rho$ as an upper bound for $\alpha$.\footnote{I re-scaled the growth rates so that all values of the normalized population growth rates are positive. The results are sensitive to the normalization I used. I do not present these results here, but as expected, $\rho$ is an upper bound. I also considered a non-linear OLS estimation of the model in the form of (4) but the estimates did not converge or were too sensitive to the initial guess to be of any value.} Then, as part of the sensitivity analysis, I will assess the bias in $\rho$ relative to $\alpha$ using long-term demographic data based on archeological reconstructions for well-defined agricultural centers in which these biases are less likely to be present; see Whitmore et al. [60].

Table 1, Panel B, presents the estimates for equation (7) under the same specifications as in Panel A once all nonpositive growth rates are dropped from the samples. All point estimates are positive and significant. A point estimate of $\hat{\rho} = 1$ implies that population growth is directly proportional to population size. Global data suggest that this might not be a bad approximation. For example, with Kremer’s [40] data, $\hat{\rho} = 0.80$. Using regional data, the relevant elasticity, $\hat{\alpha}$, is around 1.5. Using data from Deevey [19] yields $\hat{\rho} = 0.86$ (s.e. 0.07). This point estimate, as expected, is indistinguishable from the one obtained using Kremer’s data.

**Sensitivity analysis.** I first examine if the estimates reported in Table 1 are driven by any particular set of observations. A variety of diagnostics can be used to detect influential observations; see Chatterjee and Hadi [12]. High-leverage diagnoses atypical observations. Leverage also determines the Cook’s distance diagnostic, which measures the influence of a given observation on the point estimates. For Table 1, Panel A, the post-1900 observations in McEvedy and Jones [45] and Biraben [6] and the post-1940 observations in Kremer [40] are high-leverage points. That is, the population size values during these periods are atypical compared to the majority of the sample. The Cook’s distances also suggest that the point estimates in equation (6) are sensitive to the removal of observations from these periods.\footnote{An observation is considered high leverage if its leverage exceeds $4/N_{\text{obs.}}$; see, Chatterjee and Hadi ([12], p. 100). All of Cook’s distances ($D$) should be roughly equal. A relatively large Cook’s distance indicates an influential observation. I use the cut-off values based on $D > F(0.5, 2, N_{\text{obs.}} - 2)$; see, Chatterjee and Hadi ([12], p. 119). Influential observations are not necessarily outliers, but their inclusion is likely to bias the estimation of the regression coefficients. For example, because OLS minimizes square deviations, the estimates place a relatively heavy weight on atypical observations. I also computed the previous diagnostics for regional data. Leverage and the Cook’s distance show a significant positive time trend. This indicates that recent observations are more influential than pre-modern observations.}
Figure 2: World population size and its growth rate, 1MYA to 1650.

How sensitive are the point estimates in Table 1? Recall from Table 1, Panel A, that the point estimate from Kremer [40] is 5.08 (s.e. 0.5). This point estimate declines to 4.22 and 4.56 if post-1900 and post-1800 observations are excluded, respectively. These estimates are still significant. If post-1700 observations are excluded, however, \( \beta \) declines to 2.60 (s.e. 1.14) and becomes only marginally significant; in fact, if post-1600 observations are excluded, \( \beta \) declines to 1.75 (s.e. 1.14) and is no longer significant.

This lack of significance in the relationship between population growth and size is due to a large decline in the point estimate for \( \beta \), not only to an increase in the standard errors. Figure 2 illustrates the fragility of the point estimates. This figure includes pre-modern data from Kremer [40] and Deevey [19], as well as their respective linear trends. The trend in Deevey’s pre-modern data is positive by construction, as I noted previously; see also Appendix A. This trend is also more positive than in Kremer’s data partly because there
are no negative growth rates in Deevey [19]. (There are also some minor discrepancies discussed in Appendix A.) In general, the relationship between population growth and size in Figure 2 is considerably weaker than in Figure 1. In effect, the trend in Kremer’s [40] data in Figure 2 is not statistically significant.

One can question the relevance of a sensitivity analysis for Kremer’s [40] data because the degrees of freedom in the global samples are considerably reduced; also, the small global sample makes influential observations more likely to occur naturally. A decline in the point estimates of β, however, is evident even in the regional data. Table 2 presents estimates of (6) for alternative sample periods. Excluding post-1900 observations has a dramatic impact on the point estimates for regional data. All point estimates, with the exception of the fixed effects in Biraben [6], which is only marginally significant, become insignificant. Excluding post-1800 observations has a similar effect. Only the fixed effects estimate in McEvedy and Jones [45] is significantly different from zero in both tables. Finally, no point estimate is significant if post-1700 observations are excluded. In these samples, the estimates of β have the “wrong” (negative) sign. That is, these estimates suggest that population growth and size are negatively rather than positively associated. If one excludes post-1600 observations, some of these negative estimates actually become significant.

As in the global sample, the decline in the significance of the point estimates is not primarily due to an increase in the standard errors, but to a decline in the point estimates themselves. This fact is important because the most recent data is likely to be of the highest quality hence one would expect precision to be lost if these observations are removed.11 As Table 2 shows, this is not the case: the point estimates are not becoming more “imprecise.” A positive relationship between population growth and size, instead, is

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11An alternative way to examine the sensitivity of the results is to focus only on modern observations. To save space, I only discuss the post-1600 estimates of equation (6) for the global data and the fixed effects regional estimates in McEvedy and Jones [45], where more data is available. For the global data, β = 7.52 (s.e. 0.70). For the fixed effects estimates, β = 42.60 (s.e. 11.70). These estimates are positive, significant, and larger than the estimates for the entire sample. These results and Table 2 show that the strong positive relationship in the recent samples drives the results in Table 1.
mostly a feature of the modern epoch.

Figure 3: Local population size and growth rates.

Finally, Table 3 considers the sub-samples in Table 2, but uses the log-log specification (7). The general pattern for regional data is consistent with Table 2. In Table 3, the estimates of $\rho$ also decline, although the significance is not always lost. If post-1600 data is excluded, the upper bound estimate $\rho$ is reduced in half.

Local demographic data.— This subsection briefly presents an additional perspective of the relationship between population growth and size based on data from demographic reconstructions in local areas where archaeological material covers a long span of time; see
Whitmore et al. [60]. The local areas are the Tigris-Euphrates lowlands, the Egyptian Nile Valley, the basin of Mexico, and the central Maya lowlands. Two of these areas are located in the Old World and two in the New World thus producing a general geographic coverage. A local perspective does not intend to substitute the previous discussion based on global and regional data but to complement it with less speculative population measurements for more homogeneous regions and longer periods of time. For instance, aggregation might make relevant local patterns irrelevant at the aggregate level, especially if the timing of populations expansions and declines in local areas tend to covary negatively. Kremer’s [40] theory is also specifically designed to examine global data so its predictions for local populations are not fully specified.

Figure 3 reproduces Figures 1 and 2 using data for the previous four local areas. Each panel of the figure presents one region and three linear trends. The baseline trend uses all data points and the entire sample period. The second trend (positive growth only) omits nonpositive growth rates, as a way to assess the bias in $\rho$ relative to $\alpha$, and the third trend uses only pre-1900 data, as a way to assess the sensitivity of the estimate to changes in the end of the sample.

The patterns of population in Figure 3 are considerably more diverse than in the global and regional data. With the exception of panel (d), all figures show a baseline positive association between population size and growth; panel (b) actually shows a stronger association between population size and growth in the pre-1900 sample. (In the Whitmore et al. [60] data, the Nile valley experienced a sharp population decline between 1420 AD and 1600 AD and rapid surge afterwards. This “cycle” is likely the reason for the steeper pre-1900 trend in Figure 3(b).) The Mayan lowlands, panel (d), have experienced a steady population decline since 800 AD to the point that this region has not yet reached a population size near its peak during the pre-modern era. Panels (a) and (c) roughly agree with the global and regional patterns in the sense that recent observations are the main reason for the baseline positive association between population size and growth. In these panels, for example, once post-1900 data is omitted, the association between these variables becomes significantly negative.
Figure 3 also shows numerous episodes of negative growth. The magnitude of the bias in $\rho$ relative to $\alpha$ depends on the frequency of negative growth rates in the data. Panels (a) and (b) feature relatively small negative growth rates and therefore they suggest a relatively small bias in the log-log specification. In contrast, panel (c) features large negative growth rates of population and therefore a large bias. The Basin of Mexico in panel (c), in fact, shows that the relationship between population size and its growth rate is very sensitive to the sample examined and the econometric specification.

Overall, the time series relationship between population growth and size is not stable. Using alternative sample periods results in substantively different estimates of $\beta$ and $\rho$. In global and regional samples, estimates of $\beta$ lose significance even when a few observations are dropped. In local data for key agricultural centers in the Old and New Worlds, there are more varied patterns of population growth but recent observations also tend to have a disproportionate influence on the relationship between population growth and size. The findings in this sub-section thus imply that the positive association between population growth and size in Kremer [40] is heavily influenced by the growth acceleration during the early stages of the modern demographic transition. (More to this point, the post-1960 period features a negative relationship between population growth and size; Figure 1.) As the next sub-sections will show, the sensitivity of existing findings is not unique to prediction (i); the empirical findings for predictions (ii) and (iii) are also sensitive to changes in the sample.

**Prediction (ii): population growth and time.** Predictions (ii) and (iii) rely on time series observations but use the solution equation (4). This expression implies a time trend in the growth rate of population, not in the level of population, as normally considered in Malthusian analyses; e.g., Ashraf and Galor [3]. This more “mechanical” relationship between population growth and time provides a complementary test of Kremer’s [40] model. In this test, time itself is used as a substitute for the level of population.

To estimate a linear time trend, $\tau$, I consider:

$$ n_{i,t} = \tau_0 + \tau \text{Time} + \delta_i + \varepsilon_{i,t}. \quad (8) $$

15
Table 4 presents the estimates for equation (8) for alternative sample periods and data from McEvedy and Jones [45] and Biraben [6]. The first panel includes the entire sample period. In this panel, and for both data sources, the growth rate of population exhibits a positive time trend. The point estimates for $\tau$ are similar across specifications and sources, and between the global and regional samples. The second and third panels consider samples that end in 1800 and 1600, respectively.

There are two notable features in Table 4. First, the point estimates for $\tau$ decline uniformly across the samples. Second, the decline is shared by the estimates based on global and regional data. The significance of the point estimates also declines as the end point of the sample is reduced. In Biraben [6], no single estimate is significantly different from zero if post-1600 data are excluded. In McEvedy and Jones [45], the regional estimates remain significant, but the findings do not show any trend in world population. Finally, as in Tables 2 and 3, the decline in significance is not due to an increase in the estimated standard errors.\(^{12}\)

**Prediction (iii): exogenous determinants of demographic and technological change.** Recall from equation (4) that exogenous factors associated with technological change and arable land influence population growth, not the level of population, as normally considered in Malthusian analyses. These relationships have not been previously examined by the literature, but accounting for the growth effects of exogenous factors is important as an alternative testable prediction of the theory.

As in equations (6) and (8), I consider the following econometric model:

$$n_{i,t} = \varphi_0 + \varphi \theta_i + \varphi_x X_{i,t} + \varepsilon_{i,t}, \quad (9)$$

where $\theta_i$ denotes time-invariant exogenous factors, and $X_{i,t}$ denotes the control variables. More specifically, I use time, $t$, and population size, $N_{i,t-1}$, as control variables. Since $\theta_i$...
is time-invariant, I cannot rely on fixed-effects. Instead, I present pooled OLS estimates. (The random effects estimates are virtually identical, so to save space, I do not report them.) For these estimates, population size controls for regional-specific factors. Furthermore, since I assume that global arable land and other exogenous factors remain constant, I am only able to examine regional data. Finally, I examine McEvedy and Jones [45], as their data contains a larger number of regions and thus permits a better matching with additional sources.

I follow two different approaches. First, I examine the relationship between population growth and arable land, as reported in McEvedy and Jones [45]. Second, I examine biogeographical variables, such as those emphasized by Diamond [21] and coded (at the regional/country level) by Hibbs and Olsson [30]. Country boundaries are endogenous, so arable land is not necessarily exogenous; biogeography is more likely to be so.

Population growth and arable land.— Table 5, panel A includes log-arable land as a predictor of population growth. (Total land yields similar results.) Column (1) includes no other controls, column (2) includes a time trend, and column (3) controls for population size. I consider the complete sample first. The point estimate in column (1) is $\varphi = 9.7$, which is statistically significant. The inclusion of time or population size only changes the value of $\varphi$ marginally, without lowering its statistical significance. (Population and time are strongly correlated and hence I do not include both factors simultaneously.) These findings show that population grew at a faster rate in larger geographical areas, as predicted by the theory.

The findings in the alternative sub-samples, however, provide a different view. In the sample ending in 1800, arable land is no longer significant, with or without a time trend or population controls. Once again, this diminished significance is not primarily due to larger standard errors or higher imprecision. Moreover, in the sample ending in 1600, the estimate of $\varphi$ has the “wrong” (negative) sign, and it is significant. This finding implies that before the modern epoch, population growth was actually slower in larger geographical areas.

Population growth and biogeography.— Table 5, Panel B, presents a complementary
strategy. I matched the regions in McEvedy and Jones [45] with the biogeographic information coded by Hibbs and Olsson [30]. Table 5, Panel B, examines the influence of the number of plants, which is the average numbers of locally available wild plants suited for domestication 12K YA in various parts of the world, and the number of animals, which is the number of species of wild terrestrial herbivore and omnivore mammals suitable for domestication in various parts of the world. I consider a specification without a time trend, as well as two other specifications, one with a time trend and one with a population control.\textsuperscript{13}

Column (1) shows that the number of plants has no predictive power for population growth. The number of animals, however, is negative and significant. Instead of yielding higher population growth, a large number of domesticable animals lowers population growth in the complete sample. The variation of the point estimates across the sub-samples is the same as in Panel A. In the sample ending in 1800, none of the biogeographic variables is significant, whereas in the sample ending in 1600, the signs are reversed; that is, in the pre-1600 sample, animals have a positive influence on population growth. As in Panel A, adding a time trend or population size as a control does not alter the previous conclusions.

The previous tests document an inherently unstable relationship between exogenous factors and population growth. Predictions relating population growth to arable land are supported in the data but only in the samples that include modern observations. Biogeography is unimportant in the modern data, but there is a strong association between biogeographic variables and population growth during the pre-modern epoch. The most significant point in this subsection is that the estimated coefficients for the relationship between arable land and population growth, and biogeography and population growth, change signs in the pre-modern samples. These reversals emerge because the fastest pre-1900 population growth took place in European and Neo-European regions. These areas were not populous at the onset of the modern demographic transition. Likewise, the post-

\textsuperscript{13}The number of domesticable plants and the number of animals are highly correlated in the sample (the correlation coefficient is 0.87). I included the continental axis of orientation from Hibbs and Olsson [30] as an alternative specification. The results are similar to Panel B, and are available upon request.
1900 demographic transition of populous countries explains the positive effect of arable land on population growth in the complete sample. The reversal in the role of biogeography can be similarly explained. The rapid pre-1900 population growth in European and Neo-European regions cannot be a consequence of favorable biogeographic conditions. These regions (i.e., North America and Australia) lacked the conditions for settled agriculture and yet they were able to industrialize before highly-advanced agricultural areas such as China and the near East. Reversals on the role of biogeographic endowments on the growth rate of population are consistent with the reversal of fortune experienced by European colonies, documented by Acemoglu et al. [1]. Note, however, that the findings presented here have a broader scope as they hold across all world regions.

4 Tests based on a natural experiment

The empirical analysis has so far focused on the time series of population growth. This section provides a causal assessment of equation (4), or prediction (iv), using a natural experiment, namely the melting of the ice caps that divided the continents following the last glaciation. The ideal experiment to test prediction (iv) would randomly divide human populations into two groups which only differ in terms of their population size and remain isolated for a very long period of time. In theory, one should then see over time a lower level of technological sophistication in the group with the smallest initial population size.

The melting of the ice caps shares many features with the ideal experiment. In particular, the land bridges that connected the New World with Asia and New Guinea with Australia (also Tasmania and Flinders Island) disappeared some 12KYA, leaving certain populations geographically isolated. Geographic isolation thus created relevant differences in population sizes across various regions in the world. Moreover, one can arguably claim, as in Kremer [40], that populations were randomly allocated between the different geographic areas, and that population densities were the same in all regions of the world prior to the melting of the ice caps. There were no agricultural centers before 12KYA so these assumptions can be justified since hunter-gathering was the common mode of production.
at that time.

But there is a critical limitation in the implementation of tests based on the melting of the ice caps. To assess the effect of population growth on long-term development, one needs a control and a treatment group with similar pre-treatment characteristics or one might otherwise obtain biased inferences. Formally, let \( n^*(t|\theta, N_0) \equiv d \ln [N^*(t|\theta, N_0)] / dt \) denote the growth rate of population; see (4). Population growth depends on exogenous factors \( \theta \) (i.e., arable land and biogeography) and the initial population size \( N_0 \). Consider two regions that differ along these dimensions. The difference in growth rates is

\[
n^*(t|\theta', N'_0) - n^*(t|\theta, N_0) = [n^*(t|\theta', N'_0) - n^*(t|\theta, N'_0)] + [n^*(t|\theta, N'_0) - n^*(t|\theta, N_0)], \tag{10}
\]

where \((\theta', N'_0)\) represents the exogenous factors and initial population size of the treatment group; the control group is described by \((\theta, N_0)\).

To test prediction (iv), one needs geographic areas with different initial population sizes \( N_0 \), but the same exogenous factors \( \theta \), i.e., \( n^*(t|\theta, N'_0) - n^*(t|\theta, N_0) \). Expression (10) includes this relevant difference but also the contribution of exogenous factors \( n^*(t|\theta', N'_0) - n^*(t|\theta, N'_0) \) as an omitted variable. Tests that do not account for differences in exogenous factors \( \theta \) that foster population growth are biased in favor of prediction (iv). Suppose that \( \alpha = 1 \) as \( \phi = 1 \) and \( \gamma = 0 \).14 Boserupian effects are ruled out in theory since technological change is independent of population size. Empirically, however, (10) still sides with prediction (iv). That is, initial population sizes are irrelevant for population growth, \( n^*(t|\theta, N'_0) = n^*(t|\theta, N_0) = \theta \), but one still obtains a significant difference in (10), \( n^*(t|\theta', N'_0) - n^*(t|\theta, N_0) = \theta' - \theta \).

A case study. To make the previous points more tangible, consider the New World as the treatment group (i.e., the group with the smallest initial population) and take the Old World as the control group. Since densities are assumed to be equal, the New World’s smaller area translates into a smaller population size prior to the melting of the

\[14\] The use of \( \alpha = 1 \) is only for illustrative purposes. In general, as (4) and Appendix C make clear, exogenous factors in \( \theta \) have a positive effect on population growth: \( d \ln [n^*(t|\theta, N_0)] / d \ln N_0 > 0 \) if \( \alpha > 1 \), and \( d \ln [n^*(t|\theta, N_0)] / d \ln \theta = (\alpha - 1)^{-1} d \ln [n^*(t|\theta, N_0)] / d \ln N_0 > 0 \) if \( \alpha > 1 \), and \( d \ln [n^*(t|\theta, N_0)] / d \ln \theta = 1 \) if \( \alpha = 1 \).
ice caps. The New World was less sophisticated and less densely populated around 1500. This comparison thus suggests that a smaller initial population size limited the New World’s long-term development. But this comparison is likely biased, as (10) suggests. In particular, large geographic areas do not only have larger human populations but also have larger numbers of animals and plants suitable for domestication; see Diamond [21]. Since geographic factors are relevant determinants of population growth (both in theory; see, e.g., expression (4), and in practice; see, e.g., Table 5), the Old World does not serve as a valid control group for the isolation of the New World.

A suitable control group should only differ with the isolated societies in the New World in terms of initial population sizes; exogenous determinants of technological and demographic change should be the same. There is no “pure” comparison, but it is possible to argue that sub-Saharan Africa may be as close as possible to a suitable control group for the isolation of societies in tropical America. Consider the following reasons:

(a) Sub-Saharan Africa and tropical America have similar geographies. In both, axes run mostly from North to South; see Diamond ([21], p. 177), and the total area of each continent is relatively the same; see McEvedy and Jones [45]. Indeed, according to McEvedy and Jones [45], population sizes in 400 BC were similar for these two regions; see Appendix B. Moreover, the respective climates are similar since sub-Saharan Africa and tropical America are the only large areas that cross the equator.

(b) Agriculture originated in both regions at a much later date than in the Near East or China (both in Eurasia), but roughly at the same time, about 4 KYA; see Smith [57]. This late origin also had a common cause. In neither region were there many domesticable animals; see Diamond ([21], Table 9.2). Likewise, the number of large-seeded grass species needed for agriculture is similar for both areas; see Diamond ([21], Table 8.1).

(c) Finally, sub-Saharan Africa was integrated with the rest of the Old World. Regular contact between Eurasia and Africa existed via the Nile River in connection with the ancient Egyptian civilization, via the Sahara in connection with the Arab trade from the seventh century AD, and via the East African trade by ways of the Indian ocean during Medieval times; see, e.g., Connah [17] and Appendix B.
Tropical America and sub-Saharan Africa are similar in size, orientation, climate, and biogeography. Populations in sub-Saharan Africa, however, had contact with Eurasia’s larger initial population size. Prediction (iv) thus implies that one should expect more advanced demographic and technological conditions in Africa around 1500. I study this comparison in some detail in Appendix B. In general, the existing evidence fails to convincingly demonstrate that, at that time, sub-Saharan Africa had more advanced economic conditions than tropical America. There is no standard measure of pre-modern sophistication, but the urbanization rate, a common proxy for pre-modern sophistication (e.g., Acemoglu et al., [1]), was lower in sub-Saharan Africa than in tropical America in 1500. Estimates of income per capita in 1500 are also lower in sub-Saharan Africa than in tropical America. Even in a casual sense, the tributary empires in sub-Saharan Africa (i.e., Mali, the Great Zimbabwe, and the Swahili coastal states) do not appear to be larger or more sophisticated than the Incas and Aztecs in the New World.

Many other regions remained isolated from the Old World until the European expansion. Could other regions yield “purer” inferences? Consider Australia and Tasmania (even Flinders Island), which were also cut off from the rest of the Old World when the Bassian plain flooded. The size of their land areas is considerably different so one should expect differences in their initial population sizes some 12KYA. One should also expect significant differences in the level of technology between these regions around 1500. Kremer ([40], p.709) and Diamond ([21], p. 313) describe some technological differences that have been systematically studied by anthropologists. None of these areas, however, relied on agriculture for subsistence at the time of the European expansion because there were no animals or plants suitable for domestication. This suggests that technological

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15 The difference in sizes is actually larger than the difference between the Old and New Worlds. The land ratio between the Old and New Worlds is 2:2:1 whereas the ratios between Australia and Tasmania, and Australia and Flinders Island are 113:1 and 1130.1:1, respectively; see Kremer ([40], Table VII).

16 Henrich [29] proposed an analytical model of knowledge accumulation and diffusion much in line with Boserupian ideas and used demography to account for Tasmania's technological conditions during pre-modern times. Read [50] provides a critical assessment of Henrich's [29] theory and finds population to be a second-order influence. The analytical and empirical relationship between population/group size and cultural complexity in hunter-gather societies is the subject of a considerable literature in anthropology; see, e.g., Collard et al. [16], Kline and Boyd [38], and Read [51]. Existing empirical findings seem heavily constrained by small samples and by the fact that hunter-gatherers face different environments that require different technological adaptations and risk strategies.
differences during the pre-modern era were largely dominated by nondemographic factors such as geography.

**Some econometric estimates.** This sub-section complements the previous discussion. In this sub-section, I examine the growth of regional populations in pre-modern samples, or samples ending in 1500. Under the assumption that populations were randomly assigned across regions, the following econometric model is an alternative assessment of the previous *natural experiment*:

\[
\ln[N_{i,t}] = \pi_0 + \pi_1 \ln[N_{i,0}] + \pi_2 \text{Time} + \pi_3 \{\ln[N_{i,0}] \times \text{Time}\} + \pi_x X_{i,t} + \delta_i + \varepsilon_{i,t}, \tag{11}
\]

where \(\ln[N_{i,0}]\) is the log of population in area \(i\) at time \(t = 0\), during the first period in the sample. (I use this variable as a proxy for population size prior to the melting of the ice caps. As a robustness check, later on I replace this variable with arable land.) The term \(\{\ln[N_{i,0}] \times \text{Time}\}\) is the cross-product of the initial population and time. As before, \(\delta_i\) is a region-specific unobserved component capturing invariant characteristics in the various regions, and \(X_{i,t}\) are additional control variables.

In expression (11), \(\pi_1\) captures how initial differences in population size yield differences in final population size; \(\pi_2\) captures the time trend in population, and \(\pi_3\) captures the double difference between time and the initial population size. The double-difference estimates whether or not areas with larger initial populations grew at faster rates than areas with smaller initial populations. To be consistent with (4), \(\pi_3\) should be positive.

Table 6 presents the results using data from McEvedy and Jones [45] and Biraben [6], under three specifications: pooled OLS, random effects, and fixed effects, all with alternative sets of controls. I also present two strategies aimed at accounting explicitly for a possible correlation across the error term due to geographic isolation. I consider robust standard errors and clustering at the continental level. Clustering implies that unobserved shocks during the initial period will have a common spillover in each continent during the remaining periods.

Column (1) includes the interaction term \(\ln[N_{i,0}] \times \text{Time}\) with no other covariates. In column (1), \(\pi_3\) is positive, significant, and virtually identical across data sets. Columns
(2) and (3) include a time trend and the initial population size of the region as controls. Time trends have little impact on the point estimates (the reason being that there was little sustained population growth at that time). As Panel A, column (3), shows, however, \( \pi_3 \) is no longer positive once initial population size is included as a control; \( \pi_3 \) is negative and significant. In Panel B, column (3), \( \pi_3 \) also switches signs.

Column (4) includes continental controls for Africa, America, Asia, Europe, and Australia. The point estimates for \( \pi_3 \) remain virtually unchanged, although (as expected due to the control for geographic region) the clustered standard errors yield a reduced significance compared to the robust standard errors. Columns (5) and (6) present the random effects estimates, and column (7) the fixed effects estimates. In these specifications, \( \pi_3 \) is also negative and statistically significant.\(^{17}\)

Table 7 reproduces Table 6 for alternative specifications, for the McEvedy and Jones [45] data. First, I use 1 AD (or year 1) as the starting date rather than 200 BC, because there are fewer observations for this earlier sample. The pattern across specifications is the same as in Table 6. Second, I use arable land instead of initial population as the proxy for initial conditions.\(^{18}\) In specifications using arable land, \( \pi_3 \) is also positive in the absence of controls, and negative (though insignificant) once the basic controls are added.

Table 8 reproduces Table 6 for alternative specifications, for the Biraben [6] data. I consider two additional starting dates, 200 BC and 1 AD. In both cases, the pattern seen in Tables 6 and 7 is also present in Table 8. Finally, it may be useful to discriminate across regions given that respective pre-1500 developments were independent. I have estimated specification (7) from Table 6 separately for the Old World and the New World. (The fixed effects estimates are representative of all other specifications.) In order to maximize the number of observations, I use \( t_0 = 1 \) AD. The estimates are \( \pi_3^{\text{Old World}} = -2.1 \) (s.e. 0.3) and \( \pi_3^{\text{New World}} = 0.4 \) (s.e. 0.4). For regions in the Old World, \( \pi_3^{\text{Eurasia}} = -2.0 \) (s.e.

\(^{17}\)I also added dummy controls for the Black Death and the Mongol invasions to specification (7) in Table 6. The point estimates for these events are negative, but they do not alter the estimate of \( \pi_3 \).

\(^{18}\)Population in 200 B.C. may be an inadequate proxy for the population size prior to the melting of the ice caps. In 200 B.C., the large centers of agricultural production in Asia were consolidated, and may have faced relatively stagnant conditions. Arable land may be a better proxy for the size of pre-treatment populations.
0.4) and $\pi^\text{Africa}_3 = -2.7$ (s.e. 1.0). The only positive but not significant estimate of the interaction term is for the New World, which also contradicts the idea of that areas with larger initial populations have faster population growth.

In pre-modern samples, and in the absence of any control variable, there is a positive association between population growth and initial population size, as predicted by (iv). This association, however, is reversed once controls for systematic differences across the various world regions are included. As in the case study previously discussed, omitting systematic differences across regions leads to confounding results that attribute to Boserupian forces influences that are more likely to be Malthusian. A positive estimate of $\pi_3$ suggests momentum dynamics consistent with Boserupian effects. A negative estimate of $\pi_3$ suggests mean-reverting dynamics consistent with Malthusian effects. Mean reversion implies that population movements tended to be transitory and self-correcting. These estimates are therefore consistent with the tendency of populations to return to some stationary Malthusian equilibrium value after positive or negative deviations. In samples that include modern population data, populations do not exhibit mean reversion. This is yet another contrast between the pre-modern and the modern samples.19

5 Some final remarks

This paper introduced and assessed several previously untested population growth predictions from Kremer’s [40] well-known model of long-term population growth; it also assessed the sensitivity of existing findings using numerous alternative data sources, empirical specifications, and sample periods. In general, and especially outside of the modern epoch, the findings provide a limited support for the hypothesis that population growth spurs technological change. In particular, I found that the conclusions one can draw about the model’s performance are very sensitive to the sample period: the sign and statistical significance of the relationships between population growth and size, population growth

19For example, regressing $\ln[N_{i,t}]$ on $\ln[N_{i,t-1}]$ in the full sample for McEvedy and Jones [45] yields a fixed effects point estimate of 1.030 (s.e. 0.016). Since this point estimate exceeds one, the estimates suggest “divergence” across regions. For the reasons discussed in the previous section, this divergence appears to be a transitory event associated with the demographic transition.
and time, and population growth and exogenous factors are reversed when recent observations are excluded. Findings based on the geographic isolation of populations following the last glaciation, i.e., the melting of the ice caps, are also sensitive to the controls used, and are typically reversed when confounding influences are taken into account.  

The findings suggest a sharp contrast between pre-modern and modern economic and demographic regimes. Pre-modern population data, for example, exhibit mean reversion consistent with the notion of a stationary Malthusian equilibrium. The influence of biogeography and arable land on population growth is also reversed further contradicting the idea of continuity in demographic conditions. The central issue is that in ideas-based growth models such as Kremer [40], past technological sophistication and population size reinforce technological change. For example, integrating equation (1) gives

\[ A(t) = A_0 \left[ \lambda(1 - \phi)^{-1}X(t) \right]^{1/(1-\phi)}, \text{ where } X(t) = \int_0^t N(s)^\gamma ds, \tag{12} \]

which represents accumulated “experience” with a given mode of production, which affects \( A(t) \) positively.

Continuity is inconsistent with the main findings of this paper. Consider an alternative leapfrogging view; see, e.g., Brezis et al. [9]. Suppose, for example, that the pre-modern epoch is characterized by technological change, \( \hat{A}(t) \), determined exclusively by biogeography and similar exogenous variables emphasized by Diamond [21]. Let \( \hat{A}(t) = \hat{A}_0 \exp\{\lambda t\} \), which represents equation (12), with \( \phi = 1 \) and \( \gamma = 0 \). Suppose also that a new technology that satisfies equation (12) becomes available. Since \( \gamma > 0 \), population growth

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20 It is probably interesting to contemplate another natural experiment to study the role of population on long-term development. Cecelia Holland [31] examined a counterfactual as part of a series of “what if’s” in human history. She considered the fate of Europe if Ogadai Khan had not died on the eve of the Mongol siege of Vienna in 1242 and estimated the impact using Bagdad as a “control.” After destroying the Christian armies of Poland and Hungary, the Mongols were poised to siege Vienna when the death of Ogadai Khan prompted Batu Khan to return to Karakoram to elect a new Khan. The Mongols never returned and Europe was fortuitously saved from depopulation.

According to Holland ([31], p. 93), if European cities had experienced the massive destruction of Bagdad following the Mongol’s siege, Europe would have replaced learning with religious prejudice and would have fallen into the fundamentalism that the Islamic world experienced after the Mongol invasions; “[t]he Dark Ages were pure light compared to what could have happened to Europe if, in the thirteenth century, it had been overrun by the Mongols.” Interestingly enough, the Black Death visited Europe a century after the Mongol’s retreat thus Ogadai’s death may have only saved Europe temporarily.
positively influences this modern technology. Under a leapfrogging view, the less sophisticated and less populous economies (i.e., economies without much experience with $\hat{A}(t)$) will be the first to adopt this “radical” technology. As these backward economies overtake the population size and technological sophistication of more advanced regions, one observes reversals such as those documented here.

In contrast to ideas-based models (e.g., Jones [33]), an Industrial Revolution is not inevitable in a leapfrogging framework. A leapfrogging framework can also reconcile the positive association between population size and growth during the modern epoch and its reversal previously documented. For example, a leapfrogging view is consistent with the persistence in technological sophistication between 1000 BC, 0 AD, and 1500 AD, documented by Comin et al. ([15], Tables 7A and 7B) and with the absence of any significant effect of technological sophistication during 1000 BC and 0 AD on current economic and technological conditions; see, e.g., Comin et al. ([40], Table 8A). Persistence is natural during “normal” times because knowledge within any one particular mode of production is cumulative. Technological leadership is irrelevant during “radical” technological changes.21 The irrelevance of past technological conditions is notable in Europe’s industrialization, as Diamond ([21], pp. 409-410) noted:

“A historian who had lived at anytime between 8500 B.C. and 1450 A.D., and who had tried then to predict future historical trajectories, would surely have labeled Europe’s eventual dominance as the least likely outcome, because Europe was the most backward of those three Old World regions for most of those 10,000 years. [...] Until the proliferation of water mills after about A.D. 900, Europe west or north of the Alps contributed nothing of significance to Old World technology or civilization.”

There are obviously many statistical caveats in the interpretation and analysis of long-term population data. The data sources are not ideal and segmentation of the data will

21 Other examples may be relevant. Archaeologists and prehistorians have long debated the role of population pressure in the origin of agriculture. Views based on population pressures were first proposed in the mid-1970s, but they are less favorable nowadays; see, e.g., Harlan [26]. Alternative views emphasize global climatic change; see, e.g., Fagan [23], due to the synchronized adoption of farming across separate regions of the world; see Smith [57].
likely exacerbate measurement biases. Confirmation bias is also important because none of the sources here rely on direct measurements of population size. As discussed by Kremer ([40], pp. 699-700), the basic assumption behind the existing estimates of past population sizes appears to be a Malthusian assumption that associates an increase in population with exogenous technological changes. The statistical analyses also omit many social, economic, and political influences that cannot be measured given the scope of the paper. Likewise, the comparisons within the tropics lack a sense of statistical significance, as they are not based on traditional statistical testing. Despite their importance, it is quite unlikely that one can overcome the data limitations in the short term.22

There are also many economic caveats in the interpretation offered here. Particularly, the historical record suggests that earlier periods are characterized by small and infrequent discrete technological changes. The current tests only rely on post-400 BC data. Thus the tests do not necessarily discriminate against very gradual technological change, which perhaps was the norm prior to the Industrial Revolution. This means that Boserupian effects may be harder to detect given the shorter span of data considered here, or it might be that settled agriculture introduced a Malthusian mechanism into an otherwise Boserupian process. Similarly, the theory’s focus is on global demographic and technological changes and not on the dynamics of countries or regions. The difficulty is that without reliable data it is nearly impossible to examine the presence of Boserupian effects in early human demography at a global level. One can read the present findings simply as a call for caution in interpreting the existing empirical evidence. The findings also show the need for further theoretical and empirical investigations of the long-term relationship between demography and development.

22 There are few alternative data sources for examining pre-modern conditions. Anthropological analyses of genetic diversity in current populations have been able to shed light on the demography of past populations; see, e.g., Relethford ([53], [52]). In economics, a growing literature has started using genetic information to examine current and past differences in economic development; see, e.g., Spolaore and Wacziarg [58] and Ashraf and Galor [3].
References


6 Appendix A: Population in the very long run

The purpose of this Appendix is to discuss some shortcomings in Deevey [19] estimates of the world population that critically limit the applicability of this data source to test prediction (i) of Kremer’s [40] model. Table A1 reproduces Deevey’s [19] population and density estimates. These estimates and Hassan [27] follow a similar principle; they assume that the area inhabited by humans has increased over time and that the population densities within each of these areas has also increased since 1MYA.

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<th>Year</th>
<th>Population density (per square km.)</th>
<th>Growth rate (percent)</th>
<th>Population size (millions)</th>
<th>Growth rate (percent)</th>
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<tr>
<td>1650</td>
<td>3.7</td>
<td>0.281297</td>
<td>545</td>
<td>0.289935</td>
</tr>
<tr>
<td>1750</td>
<td>4.9</td>
<td>0.471737</td>
<td>728</td>
<td>0.438435</td>
</tr>
<tr>
<td>1800</td>
<td>6.2</td>
<td>0.574993</td>
<td>906</td>
<td>0.576606</td>
</tr>
<tr>
<td>1900</td>
<td>11</td>
<td>0.801971</td>
<td>1610</td>
<td>0.801665</td>
</tr>
<tr>
<td>1950</td>
<td>16.4</td>
<td>2.084141</td>
<td>2400</td>
<td>1.939178</td>
</tr>
<tr>
<td>2000</td>
<td>46</td>
<td>-</td>
<td>6270</td>
<td>-</td>
</tr>
</tbody>
</table>

The critical issue is that in Deevey’s [19] estimates, the rate of change of population density is itself increasing over time. As a consequence of this assumption, population size and population growth will be (mechanically) positively related. In fact, Table A1, column (2), shows that the positive trend in population density is the main reason for the changes in the growth rate of population in Deevey [19]: the correlation between the growth rate of population density, Column (2), and the growth rate of population size, Column (4), is
0.99. As a useful contrast, the correlation between the growth rate in occupied area, the other determinant of population growth in Table A1, and the growth rate of population in Table A1 is negative, $-0.57$.

The correlation between population growth and size would be zero if population densities increase at a constant rather than at an increasing rate. The proof is simple. Let the inhabited area at date $t$ be $T(t)$ and let population density be $d(t) \equiv N(t)/T(t)$. Assume that $T(t) = T_0 \exp\{g_T t\}$, and $d(t) = d_0 \exp\{g_d(t) t\}$, with $\partial g_d(t)/\partial t > 0$. Then, population size satisfies $N(t) \equiv d(t)T(t) = N_0 \exp\{[g_T + g_d(t)]t\}$, which yields an increasing population growth rate due to the effect of time on $g_d(t)$. If $g_d(t) = g_d$, population size, population density, and occupied area will grow at different but constant rates. In this case, the growth rate of population would be constant $\dot{N}(t)/N(t) = g_T + g_d$, so its correlation with population size would be zero.

Deevey’s [19] data, by construction, features a positive association between population growth and population size. This association is evident in Figure 1 but less so in Figure 2 since the density estimate of 25KYA equals that of 10KYA, and the estimate of 6KYA equals that of the year 1; see Table A1. The trend is also steeper than in Kremer [40] because post-agricultural observations in Kremer [40] are taken primarily from McEvedy and Jones [45]; there are also more episodes of zero and negative growth in Kremer [40]. Both figures use estimates of population sizes in hunter-gatherer societies for which it is difficult to document an increasing growth rate of population densities. Increasing densities are easier to document in agricultural societies since higher densities take the form of larger cities. Most of these density changes are available in the sources used in the text, i.e., in the local agricultural data from Whitmore et al. [60]. Overall, since the underlying assumption of increasing growth rates in population densities is difficult to substantiate, and since this assumption introduces a bias for prediction (i), the text discarded Deevey’s [19] estimates all together.
7 Appendix B: Sub-Saharan Africa as a “control”

In this Appendix, I use sub-Saharan Africa as a control region and examine the isolation of tropical America along the lines described in the text. I treat North Africa (including ancient Egypt) as part of Eurasia because biogeographically it is closer to Eurasia than to sub-Saharan Africa; see Diamond ([21], p. 161). I focus on South and Central America because in terms of biogeography these regions and the West Indies conform a single Neotropical region. (North America is part of the Nearctic zone.) Communication between South and Central America was far more common than between Central and North America.

Table B1. Estimated pre-modern population in Africa and the Americas.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>400 BC  AD 1000 1500</td>
<td>AD 1000 1500</td>
</tr>
<tr>
<td>Africa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>2</td>
<td>10  14  9  9</td>
<td>8  11  8</td>
</tr>
<tr>
<td>Sub-Saharan</td>
<td>25</td>
<td>7   12  30 78</td>
<td>8  22  38</td>
</tr>
<tr>
<td>The Americas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>20</td>
<td>1   2   2  3</td>
<td>0.4  0.7  1.3</td>
</tr>
<tr>
<td>South and Central</td>
<td>20</td>
<td>7   10  16 39</td>
<td>4  8  13</td>
</tr>
<tr>
<td>Indian subcontinent</td>
<td>5</td>
<td>30  46  40 95</td>
<td>34  77  100</td>
</tr>
<tr>
<td>World population</td>
<td>153</td>
<td>252 253 461</td>
<td>170 265 425</td>
</tr>
</tbody>
</table>

Notes: Population in millions. Area (mill. km$^2$) from McEvedy and Jones [45]. North Africa includes the Maghreb, Libya and Egypt. The area in North Africa does not include the Sahara. North America includes the US, Canada, and the Caribbean.

The idea in (10) is to compare the economic conditions of the treatment region, i.e., tropical America, with those of the control region, i.e., sub-Saharan Africa. Since sub-Saharan Africa had contact with Eurasia during the post-agricultural period, one should expect higher technological sophistication than in tropical America. There is no standard
measure of development or technological sophistication in pre-modern societies but Table B1 presents estimates of regional population sizes from the sources in the text; it also includes land area which serves as a proxy for pre-treatment differences in population sizes under the assumption of equal population densities some 12KYA or so. For both data sources in Table B1, population in sub-Saharan Africa in 1500 was larger than in South and Central America. In this sense, and since pre-treatment population sizes are roughly the same, Table B1 agrees with prediction (iv).

<table>
<thead>
<tr>
<th>Year</th>
<th>North Africa</th>
<th>Middle Nile and Ethiopia (indigenous)</th>
<th>Rest</th>
<th>Total</th>
<th>North America</th>
<th>South America</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1000</td>
<td>13</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>1200</td>
<td>18</td>
<td>6</td>
<td>2</td>
<td>12</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1300</td>
<td>18</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>1400</td>
<td>18</td>
<td>8</td>
<td>2</td>
<td>9</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>1500</td>
<td>19</td>
<td>13</td>
<td>3</td>
<td>24</td>
<td>1</td>
<td>16</td>
</tr>
</tbody>
</table>

Source: Chandler ([11], 39-57). The indigenous cities in sub-Saharan Africa cover mostly Ghana, Zimbabwe and the Bantus. The middle Nile corresponds to Dongola (modern Sudan) and Kaffa. North Africa includes cities in the Mediterranean (i.e., Arabian, Egypt, Spanish Africa, and Aloa) and the Maghreb.

Table B2 present an alternative assessment based on urbanization. Using urbanization as a proxy for differences in economic prosperity during pre-industrial periods contradicts Table B1 and prediction (iv).23 Table B2 lists the number of cities in Africa and the Americas. The inventory of cities with sizes over 20 and 40 thousand inhabitants is from

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23Cities are a complex form of organization that often result from advances in agricultural productivity or incentives given by external or internal trade. Physical evidence on the existence of cities also tends to be well preserved; see Acemoglu et al. ([1], Section 2) for a related discussion in support of this view.
Chandler [11]. Table B2 reports different time periods as the influence of Eurasia differed over time and divides sub-Saharan Africa in three sub-regions. The cities in regions with high Arab influence are coded as Muslims while the Middle Nile and Ethiopia are regions with influence from trade through the Indian ocean and North Africa. The rest of sub-Saharan Africa can be consider as indigenous formation.

Before the 1500s, the Islamic world was the main Eurasian influence in sub-Saharan Africa. Around the time Islam spread into Africa, after the seventh and eighth centuries, there was a total of 5 cities with more than 20 thousand inhabitants in Africa. In the Americas, in 800 AD, there were twice as many cities, 10. In 800 AD, the number of large cities, cities with more than 40 thousand inhabitants, was also twice as large in the Americas. In 1500 there were 13 cities in regions with Arab influence. The number of non-Arab cities in sub-Saharan Africa increased from 5 to 11 between 800 and 1500, but the number of cities with more than 20 thousand inhabitants in South and Central America was still larger in 1500. The total number of cities with more than 40 thousand inhabitants was the same in sub-Saharan Africa as in the Americas. Of the 6 large cities in sub-Saharan Africa, 2 have an African origin and the rest were primarily the result of direct Eurasian influence. The 6 large cities in the Americas were indigenous.

Based on Tables B1 and B2, it is possible to construct the difference in urbanization rates between sub-Saharan Africa and tropical America. Multiply the number of cities at each size by the cut-off size to obtain a total estimate of urban populations. For the Americas this number in 1500 is $10 \times 20,000 + 6 \times 40,000 = 440,000$. If the Muslim cities are counted as part of Africa, the same estimate for sub-Saharan Africa gives 600,000. If Muslim cities are excluded, the size of the urban population is 260,000. Using the population size from Biraben [6] as the denominator gives urbanization rates for Africa that are 68 percent the rate in the Americas (or 30 percent if Arab cities are excluded). Using the population size from McEvedy and Jones [45] gives estimates that are 47 and 20 percent the rate in the Americas. In all cases, the urbanization rate in sub-Saharan Africa is lower than in tropical America.

The lower urbanization rate in Africa clearly contradicts prediction (iv). Moreover, the
empirical relationship between urbanization and GDP per capita is positive and robust. In particular, Acemoglu et al. ([1], Table 2) find a coefficient of 0.038 (s.e. 0.006 and $R^2 = 0.69$) between urbanization rates and log income per capita. This value holds for a cross section estimate in 1913 as well as for a cross-country regression in 1995. If the value of 0.038 is assumed stable, the range of urbanization rates suggest that income per capita in tropical America was between 5 to 20 percent higher than in sub-Saharan Africa, a contradiction of prediction (iv).
Appendix C: Comparative statics

Prediction (i) in Section 2 follows from (3), by construction. Predictions (ii) to (iv) follow from the differentiation of (4). To verify these results, notice that the population growth rate is $n^*(t|\theta, N_0) \equiv d\ln[N^*(t|\theta, N_0)]/dt = \theta/[(\theta(1 - \alpha)t + N_0^{1-\alpha})]$. Since $N(t)$ is endogenous, it is necessary to relate population growth to its determinants in $N^*(t|\theta, N_0)$:

$$\frac{dn^*(t|\theta, N_0)}{dt} = \frac{d^2 \ln[N^*(t|\theta, N_0)]}{dtdt} = \frac{\theta(\alpha - 1)}{[(\theta(1 - \alpha)t + N_0^{1-\alpha})]^2} > 0,$$  \hspace{1cm} (C1)

$$\frac{dn^*(t|\theta, N_0)}{d\theta} = \frac{d^2 \ln[N^*(t|\theta, N_0)]}{dtd\theta} = \frac{N_0^{1-\alpha}}{[(\theta(1 - \alpha)t + N_0^{1-\alpha})]^2} > 0,$$  \hspace{1cm} (C2)

$$\frac{dn^*(t|\theta, N_0)}{dN_0} = \frac{d^2 \ln[N^*(t|\theta, N_0)]}{dtdN_0} = \frac{\theta(\alpha - 1)N_0^{-\alpha}}{[(\theta(1 - \alpha)t + N_0^{1-\alpha})]^2} > 0.$$  \hspace{1cm} (C3)