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Population and development redux

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Abstract The effects of population growth on long-term economic development are obviously important. This paper introduces new predictions from a general Malthus-Boserup model of population growth and ideas-based technological change. It also tests these predictions using numerous data sources, empirical specifications, and sample periods. Time series tests reveal that the empirical associations that hold true in the modern era are completely reversed in pre-modern samples. Inferences drawn from the pre-modern population growth of geographically isolated populations are also reversed when relevant controls are taken into account. While there is a clear break with Malthusian theory, in general, and especially outside of the modern era, there is no unequivocal evidence supporting Boserupian views. An alternative model consistent with transitional demographic patterns is briefly discussed.

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. The nature of this relationship has important implications for a range of issues in economics. Global environmental sustainability, sub-Saharan Africa's demographic momentum, the emergence of below-replacement fertility in developed countries, and demographic policies such as China's one-child policy are among the many current issues confronted by this perennial debate.

Since the earlier empirical assessments of this relationship in the 1960s and 1970s (see Kuznets (1960) among many others), there has been a general understanding that the modern era has not met the dismal predictions of the Malthusian model: population growth during the modern demographic transition did not bring global poverty. Although living standards have diverged in ways consistent with lingering Malthusian effects, assessments of the relationship between population growth and economic growth during the modern era have been generally inconclusive; see, e.g., Kelley (1988) and Pritchett (1996). As succinctly stated by Headey and Hodge (2009, p. 221) in their recent meta-study of the macro-literature, "a stylized fact in the macroeconomic literature on population growth is the absence of a robust effect of total population growth on economic growth."

Modern technological change has been able to accommodate a much larger global population size than Malthusian theory predicted. With the demise of Malthusian ideas, a disconnection between population growth and technological change gained acceptance. This disconnection was so entrenched that population growth and technological change were made into exogenous and independent variables by neoclassical growth theorists. Population growth was not banished from growth theory but, for the most part, studies of the relationship between population and economic growth went into hibernation. (There are, of course, many important exceptions. Assuming an exogenous population growth turned out to be critical, for example, for the stability of economic growth models with exhaustible resources; see Cigno (1981).)

Endogenous growth theories awakened the debate between Malthusians and Boserupians. Kremer (1993), in particular, added several new elements to the debate. He proposed a synthesis of Malthusian and Boserupian views. In this synthesis, as well as in more general models of endogenous growth, technological change is not passive; as in Boserup (1981), it actively responds to population size or the growth rate of population, depending on specific functional form assumptions. Kremer (1993) also provided novel and relevant empirical evidence 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 (1993) argued that the long-term history of population growth, a history dating back to 1 million years ago (1 MYA), is consistent with a view whereby population growth spurs technological change.[1]

This paper presents some new evidence on the long-term economic effects of population growth. I introduce several new population growth predictions from a slightly more general model than Kremer (1993) and Klasen and Nestmann (2006). I assess these predictions and reassess some of the current findings using alternative demographic data. The findings largely differ from those in the literature in all possible dimensions. The model, for example, predicts population *growth effects* from exogenous factors such as arable land and biogeographic endowments. This testable prediction is a novel way to set Boserupian and Mathusian views apart. Malthusian theory, for instance, predicts *level effects* but no growth effects from exogenous variables; see, e.g., Ashraf and Galor (2011). I find that biogeographic variables and arable land are strongly associated with population growth. I also find, however, that the sign of this association is the opposite in modern and pre-modern data.

The model also 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 in data not previously examined. But tests of this prediction are also completely reversed when recent observations are excluded. If recent observations are omitted, data as recent as those based on post-1900 observations, the findings display a "wrong" (e.g., negative) sign.

Finally, the model predicts a positive effect of initial population size on the growth rate of population in geographically isolated populations. The melting of the ice caps provided a *natural experiment* upon which this prediction can be tested; see, e.g., Kremer (1993). The last glaciation isolated the Old and the New Worlds, as well as Australia. If population densities were the same some 12 thousand years ago (12 KYA), one should expect that a smaller initial population size (a consequence of its smaller area, since densities are assumed equal) would generate a technological disadvantage for small areas circa 1500 AD. This comparison, however, disregards differences in factor endowments and biogeography. This omission is problematic because the importance assigned to initial population size could simply be due to geographic differences, which, according to Diamond (1997), favored an early origin of agriculture and an easier diffusion of post-agricultural technologies such as metallurgy and weaponry in the Old World. Once systematic differences are taken into account, I find no effect of initial population size on population growth rates.

[1] Kuznets (1960) and Simon (1977) emphasized, but did not quantify, positive population externalities such as those advocated by endogenous growth theorists. Johnson (2000) and Jones (2005) also discussed population externalities in the production of knowledge in a long-term perspective. Pryor and Maurer (1982) and Lee (1988) are earlier syntheses of Malthus and Boserup with predictions that are similar to those of Kremer (1993). 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., von Foerster et al. (1960) and Umpleby (1987).

The main lesson one can draw from the present exercises is that pre-modern and modern demographic regimes are so different that the implied long-term relationship between population growth and technological change cannot be satisfactorily interpreted using a Boserupian perspective. In general, the empirical associations that hold true in the modern era are contradicted in pre-modern samples. For example, in pre-modern samples, population exhibits *mean reversion*, as a stationary Malthusian equilibrium would predict.[2] There is no support for Malthusian predictions in the modern era; in modern samples, there is no mean reversion in population. Likewise, population size and biogeographic endowments influence population growth in *opposite ways* in modern and pre-modern samples.

The sharp contrast between pre-modern and modern demographic regimes runs against traditional unified growth models and ideas-based models of technological change.[3] In these models, long-run economic growth depends on population dynamics; see, e.g., Galor and Weil (2000), Jones (2005), Kremer (1993), Kortum (1997), and Segerstrom (1998).[4] The absence of Boserupian effects aligns with recent tests of semi-endogenous growth models that find no effects of population growth on post-1870 productivity in industrialized countries, on England's post-1620 productivity growth, and on recent Asian growth miracles; see Madsen (2008), Madsen et al. (2010), and Ang and Madsen (2011). The previous conclusions also agree with the limited influence of demographic variables on the technological complexity of hunter-gatherer societies and the transition from hunter-gathering to agriculture; see Collard et al. (2013), Fagan (2005), Harlan (1992), Henrich (2004), Kline and Boyd (2010), Read (2006, 2012), and Smith (1995).

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 pre-modern data and differences in initial population sizes; Section 5 proposes a simple analytical framework to account for the empirical patterns uncovered in the paper; Section 6 briefly concludes.

[2]This paper, however, is not a test for Malthusian dynamics. In contrast to Ashraf and Galor (2011), 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. (2010) assembled a dataset on the adoption of technology during pre-modern times. The concluding section establishes consistency with their findings.

[3]The findings are also relevant due to the renewed interest in global environmental change and population externalities; see, e.g., Acemoglu et al. (2012), Baland and Robinson (2002), Bohn and Stuart (2015), Cohen (1995), Dasgupta (2000), and Lee and Miller (1990).

[4]Ravallion (2010) previously discussed the fragility of Kremer's (1993) findings, but in a different context. Ravallion (2010) noted that Kremer's (1993) model has a *spacing implication*: longer time periods between observations imply higher growth rates. Ravallion (2010) showed that the global data contradicts the spacing implication. The analysis presented here complements Ravallion (2010). For example, I examine different predictions and consider additional sources of data; specifically, data with evenly spaced observations.

2 Some theoretical background

This section extends some earlier models of population growth and technological change; particularly, Kremer (1993) and Klasen and Nestmann (2006). I explicitly allow for exogenous determinants of demographic and technological change in order to introduce a competing mechanism into these models; I also derive several new testable predictions.

Let $N(t)$ and $A(t)$ represent population size and the level of technology at date $t \geq 0$, 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

$$\dot{A}(t) = \lambda A(t)^{\phi} N(t)^{\gamma}, \tag{1}$$

where ϕ, γ, and λ are positive and fixed parameters: ϕ measures the returns to scale to knowledge, γ captures the influence of population on the production of knowledge, and λ represents exogenous influences on technological change; ϕ and γ are associated with the "standing on shoulders" and "fishing out" knowledge externalities; see Jones (2005). (Later, in Section 5, I revisit the formulation of "fishing out" externalities to consider a more general setting.) If $\phi = 1$ and $\gamma = 0$, technology would grow exogenously at a rate λ.

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

$$\frac{\dot{N}(t)}{N(t)} = \frac{1}{1-\eta}\frac{\dot{A}(t)}{A(t)}, \tag{2}$$

which, once combined with Eq. 1, yields

$$\dot{N}(t) = \theta N(t)^{\alpha}, \tag{3}$$

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

The composite parameter α 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 and the economy will converge to a steady-state with constant population size. If $\alpha > 1$ because $\gamma > 1 + (1-\eta)(1-\phi)$, Boserupian effects dominate: population growth and size will be positively related and the economy will exhibit increasing population growth. Note also that since $N(t)$ is endogenous, to test the theory, one needs to solve Eq. 3 to find the "exogenous" determinants of population. Expression (3) is a Bernoulli differential equation. Let $N^*(t|\theta, N_0)$ denote its solution as a function of exogenous factors. Then,

$$\ln\left[N^*(t|\theta, N_0)\right] = \frac{\ln\left[\theta(1-\alpha)t + N_0^{1-\alpha}\right]}{1-\alpha}, \tag{4}$$

defined for $t < t^* \equiv N_0^{1-\alpha}/\theta(\alpha - 1) > 0$ when $\alpha > 1$. Let $n^*(t|\theta, N_0)$ denote the growth rate of population along the solution path,

$$n^*(t|\theta, N_0) \equiv \frac{d \ln\left[N^*(t|\theta, N_0)\right]}{dt} = \frac{\theta}{\left[\theta(1-\alpha)t + N_0^{1-\alpha}\right]}. \tag{5}$$

Expressions (3) and (5) yield the following testable predictions:

(i) If $\alpha > 1$, population growth is an increasing function of population size. Moreover, along the solution path, population growth $n^*(t|\theta, N_0)$ increases with: (ii) exogenous factors, θ; (iii) time, t; and (iv) initial population size, N_0.

Predictions (i) and (iv) were previously examined by Kremer (1993). Prediction (ii) has not been previously formulated or tested in the literature. Through θ, for example, Eqs. 3 and 5 predict a positive effect of exogenous technological factors λ 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. Malthusian theory, in contrast, associates exogenous variables to population levels but not to growth rates; see, e.g., Ashraf and Galor (2011). In the limit as Malthusian and Boserupian effects perfectly cancel each other, i.e., $\alpha \to 1$, the model yields exogenous exponential growth $n^*(t|\theta, N_0) = \theta$, which is independent of time and the initial population N_0. In this special case discussed below, all population growth differences will be the result of differences in exogenous factors.

Prediction (iii) has been previously examined but in a very different context. Ravallion (2010) examined spacing, which is an aspect somewhat related to prediction (iii). Ravallion (2010) interpreted the time index t as the length between observations. Accordingly, a longer time period between observations implies higher population growth rates. Differences in the spacing between observations are specially relevant for very early data in which uneven spacing is prevalent; see, e.g., Kremer (1993, Table 1). I do not focus on spacing because the data sources used here are roughly evenly spaced. Prediction (iii) might seem mechanical. The growth rate of population, however, is predicted to change significantly over time. In particular, population size and the growth rate of population should approach infinity in finite time, i.e., $\lim_{t \uparrow t^*} N^*(t|\theta, N_0) = \lim_{t \uparrow t^*} n^*(t|\theta, N_0) = \infty$ in Eqs. 4 and 5, so one should see a rapid acceleration in growth rates as time advances.

The previous predictions also apply to the more general framework of Klasen and Nestmann (2006). Klasen and Nestmann (2006) considered population density as an argument in the production of knowledge, e.g., Eq. 1 becomes $\dot{A}(t) = \lambda A(t)^{\phi} N(t)^{\gamma} (N(t)/T)^{\sigma}$, with $\sigma > 0$. In this case, $\theta \equiv \lambda \bar{y}^{\phi-1} T^{(1-\eta)(1-\phi)-\sigma}/(1-\eta)$ and $\alpha \equiv (\phi - 1)(1 - \eta) + \gamma + \sigma$. Including population density in Eq. 1 enhances the relationship between population size and growth in α, but weakens the relationship between arable land and population growth.

The testable predictions are reduced-form so it is not generally possible to discriminate between the different versions of the knowledge production function. Ideally, one would like to examine the structural equations to identify η, ϕ, σ, and γ separately instead of the composite term α; this is not feasible due to the lack of data for $A(t)$. For instance, it is not possible to test for specific values of the parameters γ and ϕ, which are important for setting competing endogenous growth theories apart.[5] The value of σ is also useful to discriminate between the previous versions of $\dot{A}(t)$. Although it is not possible to separately identify the different factors determining α and θ, I will empirically study the effect of arable land on population growth.

The previous predictions rely on the (Malthusian) assumption that technological change augments population size and leaves income per capita at some subsistence level. Such assumption is less problematic for the pre-modern era since there are several indications of support for the Malthusian model; see, e.g., Ashraf and Galor (2011). Another perhaps more serious concern is the following. In Eqs. 3 and 5, population grows due to exogenous factors, captured by θ, and endogenous ones, captured by α. Thus, to properly identify the relative strength of Boserupian or Malthusian effects based on differences in initial population sizes N_0, one must control for potentially confounding influences in the form of differences in θ. Section 4 discusses this problem in the context of prediction (iv).

3 Tests based on modern population data

This section examines several versions of predictions (i) to (iii) using some well-established data that covers the pre-modern and modern eras. The next section examines prediction (iv) using pre-modern data. I separate these tests because (iv) relies on the isolation of different world regions before the European expansion.

I generally focus on modern population data since existing population estimates for the distant past are severely limited. (I discuss some data concerns in an Appendix *not* for publication.) Several authors have provided longitudinal estimates of national populations in post-agricultural times. I rely on McEvedy and Jones (1985) and Biraben (1979) to study changes within world regions or countries. I use Whitmore et al. (1990) to examine particular agricultural centers. None of the available sources are census measures, and it is recognized that population data are highly uncertain; see, e.g., Caldwell and Schindlmayr (2002) for a critical assessment of past population estimates.[6] McEvedy and Jones (1985) and Biraben (1979), however, are independent sources that cover a large number of geographic areas: McEvedy and Jones (1985) contains 73 separate countries, and data from 200

[5]For 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 (2008) 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. Madsen et al. (2010) implemented tests for the shape of the knowledge production function during the Industrial Revolution, with data that cannot be extended far back in time. See also Ang and Madsen (2011) for similar tests in high performing Asian economies.

[6]There are multiple alternative estimates of past population sizes including Clark (1967), Bairoch (1988), and more recently Maddison (2001). Caldwell and Schindlmayr (2002) discusses in detail the connections between these alternative estimates and the sources used here.

BC to 1975. Biraben (1979) contains 12 regions, and population data from 400 BC to 1970. In both sources, spacing is more or less even although the frequency of observations increases slightly at the end of the sample. For convenience, I will refer to the world regions in Biraben (1979) simply as countries. Whitmore et al. (1990) provide archeological reconstructions for agricultural centers. I use data from local agricultural centers primarily for sensitivity purposes.

3.1 Tests of prediction (i)

Population growth and population size. Let $n_{i,t}$ be the geometric average growth rate of the population for country 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:

$$n_{i,t} = \beta_0 + \beta N_{i,t-1} + \delta_i + \varepsilon_{i,t}, \tag{6}$$

where $N_{i,t-1}$ denotes the population size of country i in period $t-1$, and δ_i denotes an unobserved country-specific component that influences population growth. The error term, $\varepsilon_{i,t}$, captures all other omitted factors, and β_0 is a constant term. I consider both random and fixed effects but I only report the fixed effects (FE) estimates since the findings are invariant to the choice of specification.

Prediction (i) requires $\beta > 0$. I first display the resulting tests graphically. Figure 1 plots population size and the population growth rate from 1 MYA through 2010 based

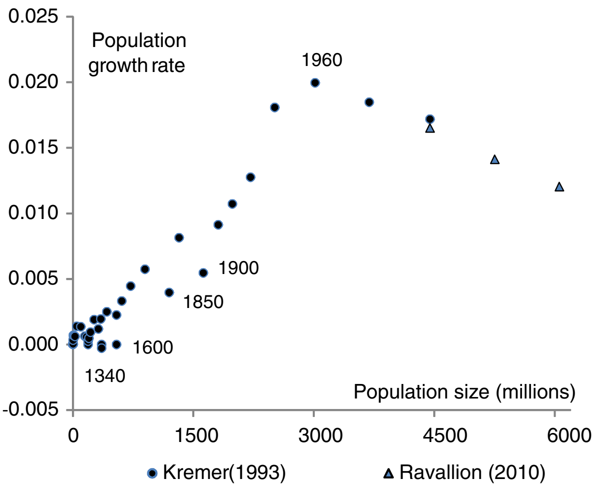

Fig. 1 World population size and its growth rate, 1 MYA to 2010

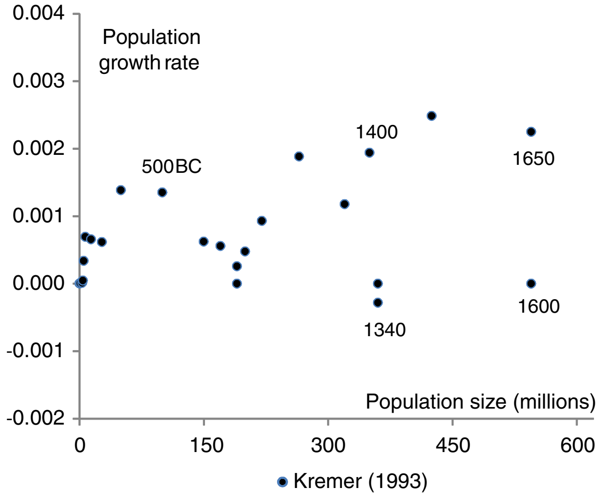

Fig. 2 World population size and its growth rate, 1 MYA to 1650

on global data from Kremer (1993) and Ravallion (2010).[7] Two points are important about this figure. First, population growth and size are positively related in the complete sample. Second, this positive relationship seems heavily influenced by the modern demographic transition: data prior to 1600 are dwarfed in Fig. 1 so one needs a smaller scale to make any pre-1600 pattern visible, as in Fig. 2 below; and, post-1960 data, updated by Ravallion (2010), show a negative association between population growth and size.

In terms of point estimates for β, Table 1, panel A, estimates Eq. 6 for the entire sample and the three global population data, using OLS. Column (1) reproduces the estimates in Kremer (1993). Column (2) uses data from McEvedy and Jones (1985), and Column (4), data from Biraben (1979). For all data sources, the point estimates for β are positive and significant. Indeed, since the data used to produce the point estimates in (2) and (4) covers a more recent sample, one should expect their point estimates to exceed those of column (1). As expected, the point estimates in columns (2) and (4) are marginally greater than those that rely on data that begins 1 MYA (column (1)).

The previous estimates are based on global samples. Column (3) in Table 1, Panel A, presents estimates of Eq. 6 using country data from McEvedy and Jones (1985). Column (5) presents the same estimates using country data from Biraben (1979). I

[7]There are very few alternatives sources to estimate the human population in the distant past; see, e.g., Hassan (1981). Deevey (1960) is a common source to most estimates. Deevey's (1960, 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 (1968, p. 248) himself remarked: "my own treatment of this, published some years ago in *Scientific American*, was not very professional." Deevey's (1960) data is especially problematic because it is biased toward accepting hypotheses (i) to (iii). I discuss this point in an Appendix not for publication.

only report the fixed effects estimates; random effects estimates are available upon request. The point estimates of β in these specifications are positive, statistically significant, and virtually identical across data sets and specifications. Thus, while the theoretical framework applies on a global scale, the empirical findings hold on a much more disaggregated setting. In fact, the point estimates for β in columns (3) and (5) are orders of magnitude greater than those for the world population. The fixed-effects estimates, for instance, are about five times larger than those in (2) and (4). To the extent that fixed-effects controls for omitted variables, one should prefer the country-level estimates over the global OLS estimates. (This difference between the global and country-level sample is somewhat surprising because fixed-effects estimators typically produce lower estimates than OLS. The country-level estimates are larger here because the timing of the modern demographic transition differed across countries. Differences in timing imply a lower covariance between population growth and population size in global samples, but a higher covariance between these variables at the country level.)

Overall, Table 1, Panel A, shows that population growth rates are strongly correlated with population size, as predicted by (i). If anything, the correlations in country-level data and alternative specifications are actually stronger that those previously documented in the literature.

Log-population growth and log-population size The OLS estimates of Eq. 6 speak about the value of α in Eq. 3 only as an approximation, e.g., one can approximate (3) by $n(t) \approx \theta(1-\alpha) + \alpha\theta N(t)$. The relevant reduced-form elasticity α can be more directly estimated using a log-log specification from Eq. 3:

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

This log-log specification, however, is inconsistent with zero or negative population growth. In the world population estimates in Kremer (1993, Table 1), there is only one instance of a population decline, namely the Black Death, but several instances of zero growth. To deal with nonpositive growth rates, I first estimate Eq. 7 using positive growth rates only and treat $1+\rho$ as an *upper bound* for α.[8] Then, as part of the sensitivity analysis, I will assess the bias in ρ relative to α using long-term demographic data based on archeological reconstructions for well-defined agricultural centers with documented negative growth rates; see Whitmore et al. (1990).

Table 1, Panel B, presents the estimates for Eq. 7 under the same specifications of Panel A, once all nonpositive growth rates are dropped from the samples. All point estimates are positive and significant. As a useful benchmark, a point estimate of $\hat{\rho} = 1$ implies that population growth is directly proportional to population size, i.e., $\hat{\alpha} = 2$ in (3). Global data suggest that $\hat{\rho} = 1$ might not be a bad approximation. For example, with Kremer's (1993) data, $\hat{\rho} = 0.80$ which implies that $\hat{\alpha} = 1.8$. The

[8] 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, ρ is an upper bound. I also considered a nonlinear 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.

Table 1 Population growth and population size

	I. Kremer (1993) 1 MYA to 1990	II. McEvedy and Jones (1985) 200 BC to 1975		III. Biraben (1979) 400 BC to 1970	
	World population OLS (1)	World population OLS (2)	Country data FE (3)	World population OLS (4)	Country data FE (5)
A. Dependent variable is population growth					
$N_{i,t-1}$	5.08***	7.06***	36.3***	6.99***	39.3 ***
	(0.55)	(0.57)	(7.99)	(0.68)	(6.98)
Obs.	37	20	679	25	300
Countries	–	–	73	–	12
R^2	0.90	0.93	0.05	0.87	0.11
B. Dependent variable is log-population growth					
$\ln N_{i,t-1}$	0.80***	1.30***	0.46***	1.48***	0.57 ***
	(0.06)	(0.10)	(0.04)	(0.31)	(0.06)
Obs.	33	16	566	21	176
Countries	–	–	73	–	12
R^2	0.86	0.90	0.16	0.52	0.45

Robust standard errors are in parentheses. $N_{i,t-1}$denotes population for country i in period $t-1$. Panel B dropped the non-positive growth rates. Point estimates and standard errors in Panel A are multiplied by 10^5 to aid visually with the presentation of the results. *** and **denote significance at the 1 and 5 percent levels.

global estimates obtained with McEvedy and Jones (1985) and Biraben (1979) are larger than in Kremer (1993) because these samples start at later dates. Table 1, Panel B, also shows that the country-level estimates of ρ are generally lower than the global estimates. Using country data, the relevant elasticity is $\hat{\alpha} = 1.5$, a value still larger than one. (Although several observations are lost in country-level samples, the log transformation stabilizes the variance of demographic data and that is a likely reason for the differences between country and global estimates in Table 1, Panel B.)

Sensitivity analyses Table 1 shows that the point estimates for β and ρ increase as the initial sample date increases. I next examine changes in these estimates when recent observations are excluded from the sample. The logic behind these exercises is simply that recent observations are likely to be very influential. A variety of diagnostics can be used to detect influential observations; see Chatterjee and Hadi (1988). *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 (1985) and Biraben (1979) and the post-1940 observations in Kremer (1993) 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 Eq. 6 are sensitive to the removal of observations from these periods.[9]

How much would the point estimates for β change if more recent observations are excluded from the samples in Table 1? Recall from Table 1, Panel A, that the point estimate from Kremer (1993) 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, β declines to 2.60 (s.e. 1.14) and becomes only marginally significant; in fact, if post-1600 observations are excluded, β declines to 1.75 (s.e. 1.14) and is no longer significant. As Table 2 shows the estimates for β in the alternative global samples of McEvedy and Jones (1985) and Biraben (1979) are also insignificant if post-1800 observations are excluded.

The lack of significance in the relationship between population growth and size in global samples is due to a large decline in the point estimate for β, not only to an increase in the standard errors. Figure 2 shows, for example, that there is no systematic relationship between population growth and size in pre-modern samples.

One can question the relevance of a sensitivity analysis for global 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 country data analyzed in Table 2. Excluding post-1900 observations has a dramatic impact on the point estimates for country data. All point estimates, with the exception of the fixed effects in Biraben (1979), which is only marginally significant, become insignificant. Excluding post-1800 observations has a similar effect. Only the fixed effects estimate in McEvedy and Jones (1985) is significantly different from zero. 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: i.e., $\hat{\beta} = -29.80$ (s.e. 15) in Biraben (1979).

As in the global sample, the decline in the significance of the point estimates for the country data 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. As Table 2 shows, this is not the case: the

[9] An observation is considered high leverage if its leverage exceeds 4 /N.obs; see, Chatterjee and Hadi (1988, 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 $D > F(0.5, 2, \text{N.obs} -2)$; see, Chatterjee and Hadi (1988, p. 119). Influential observations are not necessarily outliers, but their inclusion is likely to influence 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 country 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.

Table 2 Population growth and population size. Alternative sample periods

	World pop. OLS (1)	Country data FE (2)	World pop. OLS (1)	Country data FE (2)	World pop. OLS (1)	Country data FE (2)	World pop. OLS (1)	Country data FE (2)
I. McEvedy and Jones (1985)								
	200 BC to 1900		200 BC to 1800		200 BC to 1700		200 BC to 1600	
$N_{i,t-1}$	6.06***	12.90	5.38***	20.10**	2.24	−2.90	3.93	−7.18
	(0.61)	(9.24)	(1.59)	(9.75)	(2.13)	(10.50)	(3.01)	(16.00)
Obs.	18	533	16	404	14	346	12	302
Countries	–	68	–	63	–	63	–	63
II. Biraben (1979)								
	400 BC to 1900		400 BC to 1800		400 BC to 1700		400 BC to 1600	
$N_{i,t-1}$	5.13***	13.50*	4.06**	4.29	0.82	−19.40	−0.34	−29.80*
	(0.64)	(7.42)	(1.66)	(10.30)	(2.68)	(11.80)	(3.91)	(15.40)
Obs.	23	276	21	252	19	228	18	216
Countries	–	12	–	12	–	12	–	12

The dependent variable is population growth. $N_{i,t-1}$ denotes population for country i in period $t-1$. The specifications are the same as in Table 1. Robust standard errors in parentheses. Point estimates and standard errors multiplied by 10^5 to aid visually with the presentation of the results. ***, **, and *denote significance at the 1, 5, and 10 percent level.

point estimates are not becoming more "imprecise". A positive relationship between population growth and size, instead, is mostly a feature of the modern era.[10] Finally, I have considered changes to β, but the point estimates for ρ in the log-log specification (7) change qualitatively in similar ways as in Table 2. Estimates available upon request show that $\hat{\rho}$ declines considerably, although the significance is not always lost. The fact that some of the point estimates of ρ remain significant has to be taken with a grain of salt because nonpositive growth rates have been excluded. In general, if post-1600 data is excluded, the upper bound estimate ρ is reduced in half or more.

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. (1990). 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

[10]Focusing only on modern observations, an alternative way to examine the sensitivity of the results, agrees with the findings of Table 2. To save space, I only discuss the post-1600 estimates of Eq. 6 for the global data and the fixed effects regional estimates in McEvedy and Jones (1985), where more data is available. For the global data, $\beta = 7.52$ (s.e. 0.70). For the fixed effects estimates, $\beta = 42.60$ (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.

thus producing a general geographic coverage. The population data in these areas begins at about 6 KYA (for some local areas), and this considerably extends the sample period. A local perspective does not intend to substitute the previous discussion based on global and country data, but to complement it with less speculative population measurements for more homogeneous areas and longer periods of time. Since the theory is designed to examine global data, its predictions for local populations are not fully specified. For instance, aggregation might make relevant local patterns irrelevant at the aggregate level, especially if the timing of population expansions and declines in local areas tends to covary negatively. To counter this concern, notice that the reconstructions are done for some of the most technologically advanced societies of the pre-modern era.

Figure 3 reproduces Figs. 1 and 2 using data for the previous four local areas. I only examine the local data graphically, but include regression estimates in the relevant figures. Each panel of the figure presents one local area 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 ρ relative to α, 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 Fig. 3 are considerably more diverse than in the global and country 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. (1990) data, the Nile valley experienced a sharp population decline between 1420 AD and 1600 AD and a rapid surge afterwards. This "cycle" is likely the reason for the steeper pre-1900 trend in Fig 3b.) 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 country-level 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 ρ relative to α 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.

Overview There is a positive association between population growth and size in global and country-level samples. This association, however, is unstable. Point estimates for β lose significance when recent observations are excluded from the sample. In local data for key agricultural centers in the Old and New Worlds, there are more

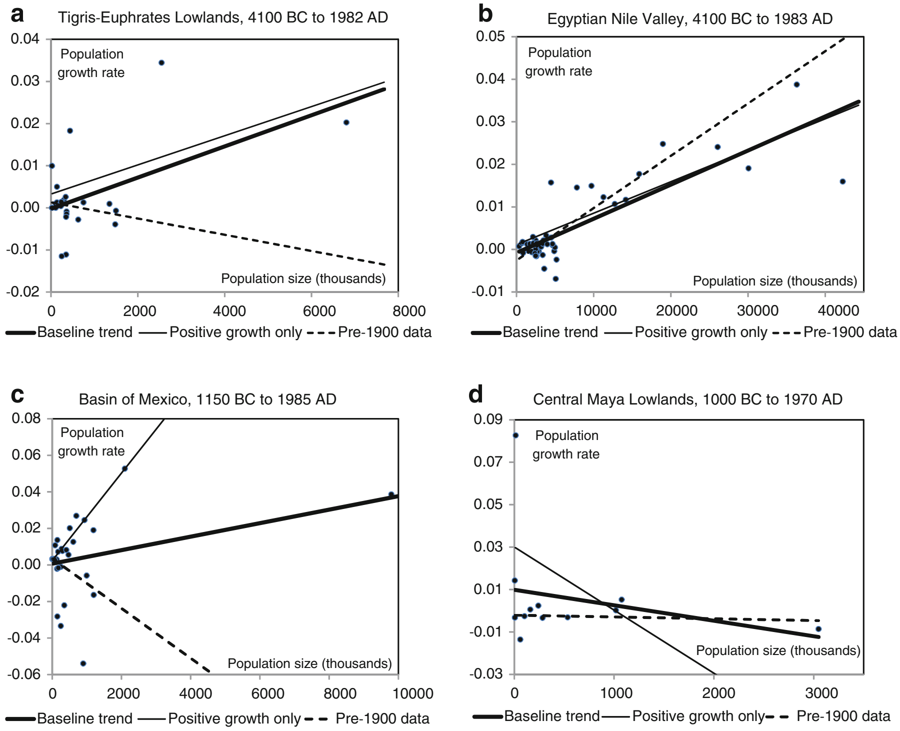

Fig. 3 Local population size and growth rates

varied patterns of population growth but recent observations also have a disproportionate influence on the relationship between population growth and size. The instability in the relationship between population growth and size is due to the transient acceleration in population growth during the modern demographic transition. This instability is thus evidence against an underlying long-term Boserupian influence. Indeed, the 1960s marked the end of the demographic transition for most developed countries. In post-1960 samples, the relationship between population growth and size is negative (Fig. 1).

3.2 Tests of prediction (ii)

Recall from Eq. 4 that exogenous factors associated with technological change and arable land influence population growth. These growth effects have not been previously examined by the literature, although there is a clear (Malthusian) connection between technological conditions and the level of population across world regions during the pre-modern era; see, e.g., Ashraf and Galor (2011).

To test for growth effects, I consider the following econometric model:

$$n_{i,t} = \varphi_0 + \varphi_\theta \theta_i + \varphi_x X_{i,t} + \varepsilon_{i,t}, \tag{8}$$

where θ_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 θ_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 and time-varying 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 (1985), as their data contains a larger number of regions and thus permits a better matching with additional sources.

In a long-term perspective, it is difficult to find "exogenous" variables; it is also difficult to justify time-invariance in θ_i. I follow two different approaches. First, I examine the relationship between population growth and arable land. Arable land, as reported in McEvedy and Jones (1985), represents potentially cultivable land. Land is measured in modern times and excludes primarily desert, inland water, and tundra. (I also use total land but the results are unchanged so I do not report these estimates.) Second, I examine biogeographical variables, such as those emphasized by Diamond (1997) and coded (at the regional/country level) by Hibbs and Olsson (2004). Country boundaries are endogenous so arable land is not necessarily exogenous. Concerns with the endogeneity of country boundaries, however, can be minimized because there is a high degree of spatial correlation in economic and demographic patterns. Biogeographic variables are often taken as exogenous, although they likely experienced temporal changes due to extinctions, for example. Since there are no longitudinal estimates of biogeographic conditions, I assume that θ_i is time invariant.

Population growth and arable land To provide a more specific context for the point estimates of φ_θ in Eq. 8, consider the special case of $\alpha = 1$, when population grows exogenously at a rate $n^*(t|\theta, N_0) = \lambda \bar{y}^{\phi-1} T^{(1-\eta)(1-\phi)}/(1-\eta)$; see Eq. 5. The growth rate of population can be approximated by $n^*(t|\theta, N_0) \simeq (1-\eta)(1-\phi)\ln T + \ln[\lambda \bar{y}^{\phi-1}/(1-\eta)]$. The point estimate for the relationship between population growth and log-land is $\hat{\varphi}_\theta \equiv (1-\eta)(1-\phi)$. If $\alpha = 1$, then some simple substitutions imply that $\hat{\varphi}_\theta = \gamma - 1$, whose sign is informative about the role of population size on the knowledge production function (1). In particular, $\hat{\varphi}_\theta > 0$ is consistent with Boserupian effects.

Table 3, Panel A, includes log-arable land as a predictor of the growth rate of population. (Total land yields similar results and for convenience I do not present those results. Since population and time are strongly correlated, I do not include both factors simultaneously as controls.) 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 $\hat{\varphi}_\theta = 9.7$, which is statistically significant. As I just noted, this point estimate suggests positive (and large) effects of population size on the production of knowledge. Moreover, the inclusion of time or population size only changes the value of φ_θ marginally, without lowering its statistical significance. In column (3), the point estimate is $\hat{\varphi}_\theta = 10.66$, which is not different from the one in column (1).

Table 3 Population growth, land, and biogeography. Alternative sample periods

	200 BC to 1970			200 BC to 1600		
	(1)	(2)	(3)	(1)	(2)	(3)
A. Pooled OLS: Arable land (in km^2)						
Log arable land	9.70***	6.31***	10.66***	−1.53**	−1.68**	−1.90**
	(2.21)	(1.95)	(2.45)	(0.69)	(0.69)	(0.83)
Time trend	No	Yes	No	No	Yes	No
Population	No	No	Yes	No	No	Yes
Obs.	679	679	679	302	302	679
B. Pooled OLS: Biogeography						
Number of plants	−0.33	0.17	0.60	−3.32**	−3.85***	−0.61***
	(0.36)	(0.33)	(0.42)	(1.44)	(1.49)	(0.17)
Number of animals	−12.88***	− 9.19***	−13.81***	2.18**	2.99 ***	3.16***
	(1.91)	(1.86)	(2.04)	(0.88)	(0.94)	(0.96)
Time trend	No	Yes	No	No	Yes	No
Population	No	No	Yes	No	No	Yes
Obs.	573	573	573	270	270	270

The dependent variable is population growth. All specifications are pooled OLS. Robust standard errors are in parentheses. Point estimates and standard errors for arable land are multiplied by 10^3 to aid visually with the presentation of the results. ***, ** , and *denote significance at the 1, 5, and 10 percent levels.

Panel A shows that in the complete sample, population grew at faster rates in larger geographical areas, as predicted by (ii). The findings in the alternative sub-samples, however, provide a very different view. In the sample ending in 1800 (which I do not report for convenience), arable land is no longer significant, with or without a time trend or population controls. In the sample ending in 1600, which is reported in Table 3, the estimate of φ_θ has the “wrong” (negative) sign, and it is stable and significant. The point estimates in these specifications are statistically the same. The reversal in the point estimate of φ_θ implies that up until 1600, population growth was slower in larger geographic areas. In the special case of $\alpha = 1$, a negative point estimate implies that population size had a *negative* effect on the production of knowledge during the pre-modern era.

Population growth and biogeography Table 3, Panel B, presents a complementary strategy. I matched the countries in McEvedy and Jones (1985) with the biogeographic information coded by Hibbs and Olsson (2004). Table 3, Panel B, examines the influence of the *number of plants*, which is the average numbers of locally available wild plants suited for domestication 12 KYA in various parts of the world, and the *number of animals*, which is the number of species of wild terrestrial herbivore

Table 4 Trends in population growth. Alternative sample periods

	World population OLS (1)	Country data FE (2)	World population OLS (1)	Country data FE (2)	World population OLS (1)	Country data FE (2)
I. McEvedy and Jones (1985)						
	200 BC to 1970		200 BC to 1800		200 BC to 1600	
Time	4.09**	5.01***	1.34**	1.42***	0.74	0.80 ***
	(1.51)	(0.49)	(0.51)	(0.22)	(0.47)	(0.24)
Obs.	20	679	18	404	12	302
Countries	–	73	–	63	–	63
II. Biraben (1979)						
	400 BC to 1975		400 BC to 1800		400 BC to 1600	
Time	3.52***	4.07***	1.00	0.60**	0.37	0.11
	(1.43)	(0.58)	(6.14)	(0.30)	(0.69)	(0.31)
Obs.	25	300	21	252	18	216
Countries	–	12	–	12	–	12

The dependent variable is population growth. t denotes calendar time. The specifications are the same as in Table 1. Robust standard errors are in parentheses. Point estimates and standard errors are multiplied by 10^5 to aid visually with the presentation of the results. ***, **, and *denote significance at the 1, 5, and 10 percent levels.

and omnivore mammals suitable for domestication in various parts of the world. I consider the same specifications as in Panel A.[11]

Column (1) shows that the number of plants has no predictive power for population growth in the complete sample. The number of animals is negatively and significantly associated with population growth; a large number of domesticable animals lowers population growth in the complete sample. The important observation is that the variation of the point estimates across sub-samples is the same as in Panel A. In the sample ending in 1800 (not displayed), none of the biogeographic variables is significant whereas in the sample ending in 1600, displayed in Table 3, Panel B, the signs of the point estimates $\hat{\varphi}_\theta$ are completely reversed. In the pre-1600 sample, domesticable animals have a positive and significant association with population growth and the number of plants has a negative and significant association with population growth. As in Panel A, adding a time trend or population size as a control does not alter the previous conclusions.

[11]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 (2004) as an alternative specification. The results are similar to Panel B and are available upon request.

Overview The relationship between population growth and exogenous factors such as arable land and biogeography is also unstable. Predictions relating population growth to arable land support Boserupian views but only in the samples that include modern observations; in pre-modern observations, the relationship between these variables displays a "wrong" (e.g., negative) sign. Biogeography is unimportant in the modern data, but there is a strong association between biogeographic variables and population growth during the pre-modern era. Importantly, as in the case of arable land, the estimated coefficients for the relationship between population growth and biogeography switch signs in the pre-modern samples.

Differential timing for the demographic transition rationalizes the reversals in the relationship between population growth and exogenous factors. The more recent and rapid demographic transition of large developing countries such as India and China would induce a positive effect of arable land on population growth in the complete sample. In contrast, European and Neo-European regions experienced an early onset of the demographic transition. These regions were not large or populous at that time. Differences in timing and initial population size thus imply that one should see a negative association between land and population growth in the pre-modern sample and a positive association when recent observations are included. The reversal in the role of biogeography can be similarly explained. The rapid early 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. Yet, their populations transitioned before those of highly-advanced agricultural areas such as China and the near East.

Reversals on the role of biogeographic endowments and arable land on the growth rate of population are consistent with the *reversal of fortune* experienced by European colonies, documented by Acemoglu et al. (2002). The findings presented here, however, hold across all countries and apply to population growth rates not to population densities or the rate of urbanization, which are the outcomes studied by Acemoglu et al. (2002).

3.3 Tests of prediction (iii)

Prediction (iii) implies a time trend in the growth rate of population. For completeness, Table 4 presents estimates of a linear time trend in the global and country samples. As before, I consider alternative sample periods and specifications. 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, as expected from prediction (iii). The point estimates for the linear trend are similar across specifications and sources, and between the global and country-level 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 the trend decline uniformly across the samples. Second, the decline is shared by the estimates based on global and country-level data. The significance of the point estimates also declines as the end point of the sample is reduced. In Biraben (1979), no single estimate is significantly different from zero if post-1600 data are excluded. In McEvedy and Jones (1985), the country estimates remain significant, but the findings do not show any trend in world population. Finally, notice that as in Tables 2 and 3, the decline in significance for the time trend is not due to an increase in the estimated standard errors.

4 Tests based on initial population sizes

The empirical analysis has so far focused on the time series of population growth. This section provides an assessment of Eq. 4, or prediction (iv), using the melting of the ice caps that divided the continents following the last glaciation.

The nature of the test The ideal experiment to test prediction (iv) would randomly divide human populations into two groups. These groups would only differ in terms of their initial population size and their populations would remain isolated for a very long period of time. In theory, one should then see 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. The land bridges that connected the New World with Asia and New Guinea with the Australian mainland (also Tasmania and Flinders Island) disappeared some 12 KYA, leaving certain populations geographically isolated. Geographic isolation thus created relevant differences in population sizes across various regions in the world; see, e.g., Kremer (1993).

There is, however, a critical limitation. For this natural experiment to provide an unbiased test, one needs the two groups to be similar in terms of exogenous characteristics represented by θ. Failure to account for differences in exogenous factors will bias tests of prediction (iv). Consider, for example, a comparison between the New and the Old Worlds. Pre-isolation population densities are assumed to be equal so the New World's smaller area translates into a smaller initial population. The New World was less sophisticated and less densely populated around 1500 AD. This comparison thus suggests that a smaller initial population size hindered the New World's long-term development. The critical limitation is that large geographic areas also have larger numbers of animals and plants suitable for domestication; see, e.g., Diamond (1997). Since biogeography determines population growth (both in theory; see, e.g., expression (4), and in practice; see, e.g., Table 3), a comparison that fails to control for these exogenous differences will incorrectly favor prediction (iv).

Many other regions remained isolated from the Old World until the European expansion. Their technological differences, however, seem largely dominated by non-demographic factors. Mainland Australia and Tasmania (even Flinders Island) 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 12 KYA. One should also expect significant differences in the level of technology between these regions around 1500 AD. Kremer (1993, p. 709) and Diamond (1997, p. 313) described some technological differences that have been systematically studied by anthropologists.[12] None of these areas, however, relied on agriculture at the time of the European expansion because there were no animals or plants suitable for domestication. Before the European expansion, all inhabitants of these areas lived as hunter-gatherers.

Some econometric estimates This sub-section verifies that the previous discussion is relevant for thinking about systematic tests of prediction (iv). I now examine the growth of regional populations in samples ending in 1500 AD using the following specification:

$$\ln[N_{i,t}] = \pi_0 + \pi_1 \ln[N_{i,0}] + \pi_2 \mathrm{Time} + \pi_3 \{\ln[N_{i,0}] \times \mathrm{Time}\} + \pi_x X_{i,t} + \delta_i + \varepsilon_{i,t}, \quad (9)$$

where $\ln[N_{i,0}]$ is the log of population in area i at time $t = 0$, during the first period in the sample. (As a robustness check, later on, I replace this variable with arable land.) The term $\ln[N_{i,0}] \times \mathrm{Time}$ is the cross-product of the initial population and time. As before, δ_i is a region-specific unobserved component capturing invariant characteristics in the various regions, and $X_{i,t}$ are additional control variables. In expression (9), π_1 captures how initial differences in population size yield differences in final population size; π_2 captures the time trend in population, and π_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 prediction (iv), π_3 should be positive.

Table 5 presents the results using data from McEvedy and Jones (1985) and Biraben (1979), under two specifications: pooled OLS and fixed effects. 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 $\ln[N_{i,0}] \times \mathrm{Time}$ with no other covariates. In column (1), π_3 is positive, significant, and virtually identical across data sets. These estimates suggest that larger initial population sizes imply a faster population growth, as prediction (iv) suggests. Columns (2) and (3) include a time trend and the initial population size of the country as controls. Time trends have little impact on the point estimates. Initial population size, however, completely overturns the

[12]Henrich (2004) 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 (2006) provides a critical assessment of Henrich's (2004) 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. (2013), Kline and Boyd (2010), and Read (2012). 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.

Table 5 Population change and initial population before 1500

	OLS				FE
	(1)	(2)	(3)	(4)	(5)
I. McEvedy and Jones (1985), t_0= 200 BC					
$\ln[N_{i,0}]\times$Time	5.25***	5.12***	– 2.61***	−2.58***	−2.56***
	(0.51)	(0.46)	(0.64)	(0.46)	(0.46)
	[0.56]	[0.60]	[0.14]	[0.17]	[0.09]
Time	–	4.53***	8.22 ***	8.51***	7.97***
	(1.25)	(0.81)	(0.78)	(0.63)	
$\ln[N_{i,0}]$	–	–	0.98***	0.95***	–
			(0.04)	(0.06)	
Continental control	No	No	No	Yes	–
Obs/Countries	252	252	252	252	252/22
II. Biraben (1979), t_0= 400 BC					
$\ln[N_{i,0}]\times$Time	4.54***	5.24***	−2.05***	−2.05***	−2.05***
	(0.32)	(0.33)	(0.50)	(0.50)	(0.42)
	[1.05]	[1.07]	[1.17]	[1.18]	[1.16]
Time	–	−4.56***	9.36***	9.36***	9.36***
		(1.41)	(0.11)	(0.10)	(0.99)
$\ln[N_{i,0}]$	–	–	1.04***	0.91***	–
			(0.04)	(0.05)	
Continental control	No	No	No	Yes	–
Obs/Countries	216	216	216	216	216/12

The dependent variable is log population size. Robust standard errors are in parentheses. In brackets are standard errors clustered at the continental level. The point estimates and s.e. for interaction between initial population and time, $\ln[N_{i,0}]\times$Time, have been multiplied by 10^4 to aid visually with the presentation of the results. The point estimates and s.e. for Time have been multiplied by 10^3 . ***, ** , and *denote significance at the 1, 5, and 10 percent levels based on the robust standard errors.

point estimates of π_3. In column (3), π_3 is no longer positive; it is negative and statistically significant. Column (4) includes continental controls for Africa, America, Asia, Europe, and Australia. The point estimates for π_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. Column (5) presents the fixed effects estimates (random effects estimates are virtually identical to the fixed effect ones so I omit them). In these specifications, π_3 is also negative and statistically significant.[13]

Table 6 reproduces Table 5 for alternative specifications, for the McEvedy and Jones (1985) data. First, I use 1 AD (or year 1) as the starting date rather than 200

[13] I also added dummy controls for the Black Death and the Mongol invasions to specification (5) in Table 5. The point estimates for these events are negative, but they do not alter the estimate of π_3.

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.[14] In this specifications, π_3 is also positive in the absence of controls, and negative (though insignificant) once the basic controls are added. I also consider (but do not report) alternative specifications for the Biraben (1979) data. I consider two additional starting dates, 200 BC and 1 AD. Both cases reproduce the patterns seen in Tables 5 and 6. Finally, it may be useful to discriminate across regions given that respective pre-1500 AD developments were independent. I have estimated specification (5) from Table 5 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. 0.4) and $\pi_3^{\text{Africa}} = -2.7$ (s.e. 1.0). The only positive but insignificant estimate of the interaction term is for the New World, which also contradicts the idea that areas with larger initial populations have faster population growth.

Overview In pre-modern samples, population growth and initial population size are positively associated but only in the absence of control variables that proxy for systematic differences across countries. Indeed, systematic controls fully reverse this association. These reversals, as with previous predictions, suggest an instability in the relationship between population growth and initial population size. This instability is not a consequence of the modern demographic transition, as prediction (iv) has been tested with pre-modern data. The nature of the instability discussed here is related to the possibility of confounding influences in the analysis of the melting of the ice caps. There is, for instance, an interesting contrast in terms of prediction (iv) if one were to apply it to modern data. A positive estimate of π_3 suggests *momentum dynamics* consistent with Boserupian effects. A negative estimate of π_3 suggests *mean-reverting dynamics* consistent with Malthusian effects. In samples that include modern population data, populations do not exhibit mean reversion and therefore they are inconsistent with Malthusian dynamics.[15] The negative estimates presented in Tables 5 and 6, however, are consistent with the tendency of populations to return to some stationary and self-correcting Malthusian equilibrium.

To eliminate confounding influences in tests of prediction (iv), one should compare more similar geographic areas. One can, for example, compare tropical areas in the Old and New Worlds since they share some similarities in "exogenous"

[14]Population in 200 BC may be an inadequate proxy for the population size prior to the melting of the ice caps. In 200 BC, 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.

[15]For example, regressing $\ln[N_{i,t}]$ on $\ln[N_{i,t-1}]$ in the full sample for McEvedy and Jones (1985) 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.

Table 6 Population change and initial population before 1500

	OLS				FE
	(1)	(2)	(3)	(4)	(5)
Data: McEvedy and Jones (1985)					
A. Different initial date, t_0= 1 AD					
$\ln[N_{i,0}]\times$Time	6.08***	6.14***	− 1.59***	−1.57***	−1.59***
	(0.27)	(0.25)	(0.35)	(0.32)	(0.30)
	[0.17]	[0.22]	[0.40]	[0.42]	[0.43]
Time	No	Yes	Yes	Yes	Yes
$\ln[N_{i,0}]$	No	No	Yes	Yes	–
Continental controls	No	No	No	Yes	–
Obs/Countries	378	378	378	378	378/64
B. Using arable land instead of initial population size					
$\ln[Land_i]\times$Time	1.80***	2.36***	−3.13	−3.42	−0.79
	(0.43)	(0.48)	(9.52)	(7.92)	(2.78)
	[1.15]	[1.34]	[5.27]	[0.42]	[5.97]
Time	No	Yes	Yes	Yes	Yes
$\ln[N_{i,0}]$	No	No	Yes	Yes	–
Continental controls	No	No	No	Yes	–
Obs/Countries	416	416	416	416	416/71

The dependent variable is log population size. Robust standard errors are in parentheses. In brackets are standard errors clustered at the continental level. The specifications are the same as in Table 5. ***, **, and *denote significance at the 1, 5, and 10 percent levels.

conditions and thus are more valid to compare. Their similarities, however, also extended to economic conditions in 1500 AD making definite assessments about the influence of initial population sizes difficult. (I perform a more detailed comparison along the lines suggested here in an Appendix *not* for publication.) Future work might also explore a different *natural experiment*. Holland (2000) considered the fate of European cities if Ogadai Khan had not died on the eve of the Mongol siege of Vienna in 1242 AD 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 Ogadai Khan's death prompted Batu Khan to return to Karakoram to elect a new Khan. Depopulation was fortuitously avoided as the Mongols never returned and Europe.) According to Holland (2000, p. 93), if European cities had experienced Bagdad's massive destruction following the Mongol siege, Europe would have replaced learning with religious prejudice leading to 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".

5 An alternative formulation

This section briefly discusses a simple alternative to the previous analytical framework. I first outline some amendments to the baseline theory of Section 2 that allow for transitional patterns. Later in this section, I provide some remarks about the particular assumptions used here.

Limits to knowledge Technological leapfrogging and transitional growth seem critical to account for the present empirical findings. In particular, past technological sophistication and population size reinforce technological change in ideas-based models such as (1): the more accumulated experience with a given mode of production, the higher the likelihood of additional innovations. This predicted continuity in technological conditions is inconsistent with the main findings of this paper. Moreover, the knowledge production function (1) is not equipped to deal with transitional population growth.

Consider a modified version of the knowledge production function (1) consistent with technological leapfrogging and transitional growth. The following alternative formulation of the knowledge production function assumes that, within a particular mode of production, there is a (possibly unbounded) frontier of knowledge A_+. For $A_+ < \infty$, as the stock of knowledge increases beyond a certain point, marginal knowledge productivity will decline and become negative. This formulation will therefore be consistent with a "fishing out" externality associated with a finite number of fish to catch; see Jones (2001). There will also be different modes of production according to the value of the frontier A_+. In particular, as in leapfrogging models; see, e.g., Brezis et al. (1993), technological change will be of two general forms, "normal" and "radical", with radical changes influencing the frontier of knowledge A_+.

Suppose that the knowledge production follows a logistic growth function given by $\dot{A}(t) = \lambda A(t)^{\phi} N(t)^{\gamma}[1-(A(t)/A_+)^{\kappa}]$, where κ is a normalizing parameter specified in the context of population growth. Under a "subsistence level" $\bar{y}$, population growth also follows a logistic growth function given by

$$\dot{N}(t) = \theta N(t)^{\alpha}\left[1 - \left(\frac{N(t)}{N_+}\right)^{\kappa(1-\eta)}\right], \tag{10}$$

where $N_+ \equiv (A_+/\bar{y})^{1/(1-\eta)}T$. If $\kappa = (1-\alpha)/(1-\eta)$, expression (10) is a Bernoulli differential equation with solution

$$N^*(t|\theta, N_0, N_+) = \left[N_0^{1-\alpha}\exp\left\{-\frac{\theta(1-\alpha)}{N_+}\right\} + \theta(1-\alpha)\int_0^t \exp\left\{\frac{\theta(1-\alpha)}{N_+}[s-t]\right\}ds\right]^{1/(1-\alpha)},$$

which equals (4) as a special case when population size is unbounded, i.e., when $N_+ \to \infty$.

To understand the implications of Eq. 10, consider first the time series properties of a global population whose initial value is N_0. First, notice that a bounded value of A_+ implies that population size will be bounded by N_+. The growth rate of population will also be bounded. In fact, population will follow the traditional S-shaped trajectory with an accelerating segment from N_0 to $\hat{N} \equiv N_+(1-\alpha^{-1})$ reaching a peak population growth, whose value is $\theta \hat{N}^\alpha/\alpha$, followed by a decelerating phase from $\hat{N}$ to N_+. The early transitional trajectory is especially interesting because this phase is indistinguishable from the baseline Malthus-Boserup model outlined in Section 2. During the initial phase of the transition, for example, population growth and the size of population will be positively related, as prediction (i) suggests. (Predictions (ii)–(iv) also hold in this phase.) Expression (10) predicts, however, that population growth will, at some point, start to slow down and continue slowing down until the transition is complete. In demographic data, the accelerating phase of global population growth that ended in 1960 is easily observable in Fig. 1 and Table 1. Figure 1 also hints of a slow down in population growth consistent with an end to the demographic transition and the decelerating phase predicted by Eq. 10.

Consider also the cross-sectional implications of a diffusion of "radical" technological changes. Suppose that a new technology that increases the frontier of knowledge is introduced. This technology has a higher value for A_+ so it dominates old technologies by increasing the population and economic growth potential. Suppose, as in Brezis et al. (1993), that the adoption of a radical technology is based on comparative advantage. The early adopters of this new technology will be the backward countries because the new technologies are more advantageous at low levels of population and sophistication. As in leapfrogging models, the introduction and adoption of radical technological changes will produce reversals such as the ones documented here; backward economies will slowly overtake the population size and technological sophistication of advanced regions. Such overtaking is consistent with the reversals in the role of exogenous factors documented in Table 3.

Some remarks In expression (10), Boserupian effects are present during "normal" times but they are limited to the early stages of a transition, unless the frontier is assumed increasing in population. Since A_+ is given in Eq. 10, a dependence between A_+ and N would represent an additional Boserupian channel, not tested here. The few "radical" technological changes in the present sample (and in history, more generally) make such specification difficult to test.

The absence of Boserupian effects in "radical" technological changes means that an Industrial Revolution is not inevitable. This is a contrast to Jones (2001) and expression (1). The distinction between "normal" and "radical" technological change is also consistent with the persistence in technological sophistication between 1000 BC, 0 AD, and 1500 AD, documented by Comin et al. (2010, 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. (2010, Table 8A). Persistence is natural during "normal" times because knowledge within any one particular mode of production is cumulative. Technological leadership, however, is irrelevant during "radical" technological changes. The irrelevance of past technological conditions is notable in Europe's industrialization. Diamond (1997, pp. 409-410), echoing many other social scientists, 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".

Expression (10) has a "limits to growth" flavor but it does not carry an alarmist or fatalist message as there is no presumption that population is near such limit or that N_+ is unmovable. It is not possible to discuss in detail the role of each of the determinants of $N_+ \equiv (A_+/\bar{y})^{1/(1-\eta)}T$, but note that physical barriers are the most commonly invoked limit to population growth. Complains about the pressure of population on arable land, central in Malthusian theory, date back to the Bible, and Quintus Septimus Florence Tertillianus, if not earlier; see Johnson (2000, p. 1). Limits to scientific knowledge, on the other hand, are rarely discussed although scientists have identified several limits; see, e.g., Casti and Karlqvist (1996) and Hut et al. (1998). These limits are logical (not practical) and they represent conceptual (not technological) limits of science, not limits of scientists. As Casti and Karlqvist (1996, p. 12) noted, citing several 'impossibility theorems' across scientific disciplines,

"[T]o anyone infected with the idea that the human mind is unlimited in its capacity to answer questions about natural and human affairs, a tour of 20th-century science must be quite a depressing experience. Many of the deepest and most well-chronicled results of science in this century have been statements about what *cannot* be done and what *cannot* be known".

Finally, population size is limited by subsistence conditions in the form of $\bar{y}$. Subsistence, as a general demographic concept, has no place in the modern era for developed countries. Instead, it is possible to abuse the interpretation of the model and argue that parental investments in health and education require an acceptable standard that represents, in a loose way, a subsistence requirement during the modern era. At the present, space and knowledge do not seem binding limits to population size. Behavioral factors that determine parental investments seem to critically limit modern population growth.

6 Some final remarks

This paper introduced several new population growth predictions from an ideas-based model of long-term technological change; a model that generalizes Kremer's (1993) and Klasen and Nestmann's (2006) Malthus-Boserup syntheses. It also tested these predictions using numerous alternative data sources, empirical specifications, and sample periods.

In general, and especially outside of the modern era, I found limited support for the hypothesis that population growth spurs technological change. I found that the model's implied relationship between population growth and technological change is very sensitive to the sample period and specification. The sign and statistical significance of the relationships between population growth and size, and between population growth and exogenous factors such as biogeography and arable land, are completely reversed between modern and pre-modern samples. The model also predicts a positive association between population growth and initial population size in isolated populations. The melting of the ice caps provided a *natural experiment* for these tests. In pre-modern samples, however, the association between population growth and initial population size is very sensitive to the controls used; the outcomes of these tests, for example, are typically reversed when confounding influences are taken into account.

It is not possible to conclude unequivocally in favor of a Boserupian view of the long-term relationship between population growth and technological change. The findings, in fact, suggest a sharp contrast between pre-modern and modern technological and demographic regimes. Pre-modern population data exhibit mean reversion consistent with the notion of a stable stationary Malthusian equilibrium; see also Ashraf and Galor (2011). A Mathusian rear-view mirror, however, is not very useful for forecasting future population paths. Although continuity is important in the long-term analysis of population and technology, the main lesson of this paper is that the relationship between population growth and technological change has undergone a major change in the modern era.

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 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 (1993, 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. All these considerations and omissions are important. It is quite unlikely, however, that one can overcome the data limitations in the short term.[16]

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 with a slow diffusion across connected world regions. The current tests only rely on "recent" data. Thus, the tests do not necessarily discriminate against very gradual technological change, which perhaps was the norm prior to the Industrial Revolution. 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. The difficulty is that without reliable data it is nearly impossible to examine the presence of Boserupian effects in early human demography or in "radical" technological changes. While this paper does not support extreme pessimism, one can

[16]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 (2001, 2003). 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 (2009) and Ashraf and Galor (2013).

read the present findings as a call for caution in interpreting the existing empirical evidence using extreme optimism. The findings also show the need for further theoretical and empirical investigations of the long-term relationship between population and development.

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