Dynamics and Stagnation in the Malthusian Epoch*

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Abstract

This paper conducts the first cross-country empirical examination of the predictions of the influential Malthusian theory regarding population density and income per capita during the pre-industrial era of human history. The theory suggests that improvements in the technological environment during this epoch generated only temporary gains in income per capita, eventually leading to a larger, but not richer, population. Employing exogenous sources of cross-country variations in land productivity and the level of technological advancement, the analysis demonstrates that, in accordance with the Malthusian theory, technologically superior societies, or those that were characterized by higher land productivity, had higher population densities, but similar standards of living, during the time period 1-1500 CE.

Keywords: Technological Progress, Population Density, Malthusian Stagnation, Land Productivity, Neolithic Revolution

JEL Classification Numbers: N10, N30, N50, O10, O40, O50

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1 Introduction

There exists a widely held view that the evolution of economies over a vast portion of human history was characterized by Malthusian stagnation. Technological progress and population growth were miniscule by modern standards and the average growth rates of income per capita in various regions of the world were possibly even slower due to the offsetting effect of population growth on the expansion of resources per capita.

In the past two centuries, in contrast, the pace of technological progress increased significantly in association with the process of industrialization. Various regions of the world departed from the Malthusian trap and experienced a considerable rise in the growth rate of income per capita. Unlike episodes of technological progress during pre-industrial times that failed to generate sustained economic growth, the increasing role of human capital in the production process ultimately prompted a demographic transition, liberating the gains in productivity from the counterbalancing effects of population growth. The decline in the growth rate of population and the associated enhancement of technological progress and human capital formation paved the way for the emergence of the modern state of sustained economic growth.

The transition of some economies from Malthusian stagnation to a state of sustained economic growth and the associated divergence in income per capita across countries and regions, as depicted in Figure 1, have significantly shaped the contemporary world income distribution.[1] Nevertheless, despite the centrality of the Malthusian theory in characterizing this important transition, the salient characteristics of the Malthusian mechanism have not been thoroughly explored. In particular, the underlying premise that technological progress and resource expansion during the Malthusian epoch had generated a positive adjustment of the population, leaving income per capita relatively unaffected in the long run, although supported by anecdotal and country-specific empirical evidence, have not been systematically tested in a cross-country framework.[2]

This research conducts the first cross-country empirical analysis of the predictions of the influential Malthusian theory regarding population density and income per capita in the pre-industrial era of human history.[3] The analysis examines the fundamental implications of

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[1] The transition from stagnation to growth has been examined by Galor and Weil (1999, 2000), Lucas (2002), Galor and Moav (2002), Hansen and Prescott (2002), Lagerlöf (2003, 2006), Doepke (2004), Galor (2005), Strulik and Weisdorf (2008) and others, while the associated phenomenon of the Great Divergence in income per capita has been analyzed by Galor and Mountford (2006, 2008), O'Rourke and Williamson (2005), O'Rourke et al. (2008), Voigtländer and Voth (2006, 2009), Ashraf and Galor (2007), and Galor (2010) amongst others.

[2] Indeed, as observed by Adam Smith (1776), *"the most decisive mark of the prosperity of any country [was] the increase in the number of its inhabitants."* Examples of recent studies that provide regional or country-specific evidence of the Malthusian mechanism include Crafts and Mills (2009) for England till the end of the 18th century, and Lagerlöf (2009) for Sweden in the 18-19th centuries.

[3] In contrast to the current study that tests the Malthusian prediction regarding the positive effect of the technological environment on population density, but its neutrality for income per capita, the insightful analysis of Kremer (1993) examines the prediction of a Malthusian-Boserupian interaction. Accordingly, if population size has a positive effect on the rate of technological progress, as argued by Boserup (1965), this effect should manifest itself as a proportional effect on the rate of population growth, *taking as given* the positive Malthusian feedback from technology to population size. Based on this premise, Kremer's study

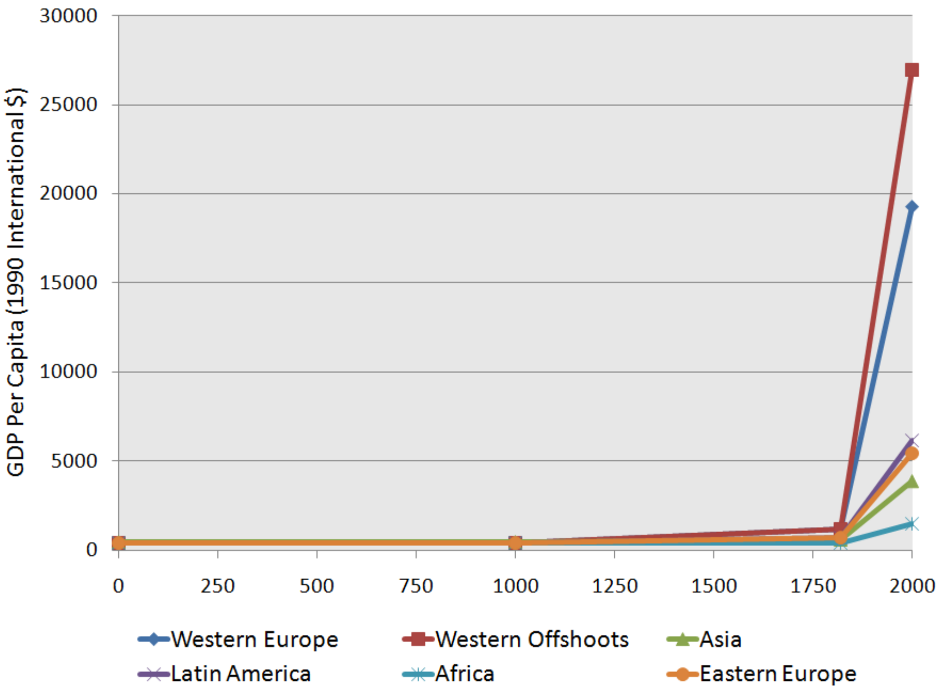

Figure 1: The Evolution of Income Per Capita by World Region, 1-2000 CE

the theory, comprising (i) the hypothesis that population density was ultimately constrained by the availability of *natural* resources, but income per capita was largely independent of it, and (ii) the conjecture that technological progress, by expanding *effective* resources, had enhanced population density with negligible effects on income per capita. Specifically, since resource constraints were slacker for regions with higher land productivity, they would have supported larger populations, conditional on the level of technological advancement. On the other hand, given land productivity, societies that were more advanced technologically would have sustained higher population densities. However, technologically superior societies, or those characterized by higher land productivity, would not have enjoyed better standards of living in the long run.

To test the Malthusian theory empirically, this research exploits exogenous sources of cross-country variation in land productivity and technological levels to explain cross-country variation in either population density or income per capita in the years 1500 CE, 1000 CE and 1 CE. This permits the analysis to examine the *differential* effects of land productivity and technological levels on population density versus income per capita, as hypothesized by the Malthusian theory.

Given the potential effect of population size on technological progress, as argued by Boserup (1965), assessing the impact of the level of technological advancement on population

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defends the role of scale effects in endogenous growth models by empirically demonstrating that the rate of population growth in the world has indeed been proportional to the level of world population throughout human history. Incidentally, Kremer does not test the long-run neutrality of the technological environment for income per capita nor the positive Malthusian feedback from technology to population size.

density requires surmounting the issue of reverse causality. While restricting attention to the pre-Columbian period potentially mitigates this issue, due to an arguably lower prominence of the Boserupian channel in this era, this research additionally develops a novel strategy to examine the hypothesized effects of technological advancement on population density and income per capita. Specifically, the understanding of the transition of societies from hunting and gathering to agriculture, during the Neolithic Revolution, as an event that triggered subsequent technological progress permits the analysis to employ the timing of the Neolithic Revolution as an exogenous source of variation in the level of technological advancement during the time period 1-1500 CE. Moreover, to address the possibility that the relationship between the timing of the Neolithic transition and population density in the Common Era may itself be spurious, the analysis appeals to the role of prehistoric biogeographic factors in determining the timing of the Neolithic Revolution, adopting the numbers of prehistoric domesticable species of wild plants and animals as instrumental variables in establishing the causal effect of the level of technological advancement on population density during the 1-1500 CE time horizon.

Consistent with Malthusian predictions, statistically significant positive effects of land productivity and an earlier onset of the Neolithic Revolution are uncovered for population density in the years 1500 CE, 1000 CE and 1 CE. In contrast, the effects of land productivity and the timing of the Neolithic Revolution on income per capita in the corresponding periods are indeed not significantly different from zero, being about an order of magnitude smaller than their effects on population density. These results are shown to remain robust to controls for other geographical factors, including absolute latitude, access to waterways, distance to the technological frontier, the share of land in tropical versus temperate climatic zones, and small island and landlocked dummies, all of which may have had an impact on aggregate productivity either directly, by affecting the productivity of land, or indirectly by affecting the prevalence of trade and the diffusion of technologies. The results are also qualitatively unaffected when a more direct measure of technological sophistication, rather than the timing of the Neolithic Revolution, is employed as an indicator of the level of aggregate productivity in the years 1000 CE and 1 CE.

Interestingly, the findings also indicate that, in contrast to the relationship between absolute latitude and contemporary income per capita, population density in pre-industrial times was on average higher at latitudinal bands closer to the equator. Thus, while proximity to the equator is known to be detrimental in the industrial stage of development, it appears to have been beneficial during the agricultural stage.

Finally, in order to ensure that the results from the level regressions are not driven by unobserved time-invariant country fixed effects, this research also employs a first-difference estimation strategy. In particular, the robustness analysis exploits cross-country variation in the change in the direct measure of technological sophistication between the years 1 CE and 1000 CE to explain the cross-country variations in the change in population density and the change in income per capita over the same time horizon. Using this strategy, the analysis demonstrates that, while the change in the level of technology between 1 CE and 1000 CE was indeed translated into a change in population density, the level of income per capita was relatively unaffected by technological improvements during this period, as suggested by the Malthusian theory.

2 The Malthusian Model

The Malthusian theory, inspired by Malthus (1798), suggests that the worldwide stagnation in income per capita during the pre-industrial epoch reflected the counterbalancing effect of population growth on the expansion of resources, in an environment characterized by diminishing returns to labor. Specifically, according to Malthus, the expansion of resources led to an increase in population growth, reflecting the natural result of the "passion between the sexes." In contrast, whenever population size grew beyond the capacity sustainable by the available resources, it was reduced by the "preventive check" (i.e., intentional reduction of fertility) and by the "positive check" (i.e., the tool of nature due to malnutrition, disease epidemics, war and famine).[4]

2.1 The Basic Structure of the Model

Consider an overlapping-generations economy in which activity extends over infinite discrete time. In every period, the economy produces a single homogeneous good using land and labor as inputs. The supply of land is exogenous and fixed over time whereas the evolution of labor supply is governed by households' decisions in the preceding period regarding the number of their children.

2.1.1 Production

Production occurs according to a constant-returns-to-scale technology. The output produced at time t, Y_t, is:

$$Y_t = (AX)^\alpha L_t^{1-\alpha}; \qquad \alpha \in (0,1), \tag{1}$$

where L_t and X are, respectively, labor and land employed in production in period t, and A measures the technological level. The technological level may capture the percentage of arable land, soil quality, climate, cultivation and irrigation methods, as well as the knowledge required for engagement in agriculture (i.e., domestication of plants and animals). Thus, AX captures the effective resources used in production.

Output per worker produced at time t, $y_t \equiv Y_t/L_t$, is therefore:

$$y_t = (AX/L_t)^\alpha. \tag{2}$$

2.1.2 Preferences and Budget Constraints

In each period t, a generation consisting of L_t identical individuals joins the workforce. Each individual has a single parent. Members of generation t live for two periods. In the first

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[4] The modern version of the theory has been formalized by Kremer (1993), who models a reduced-form interaction between population size and technology along a Malthusian equilibrium, and Lucas (2002), who presents a Malthusian model in which households optimize over fertility and consumption, labor is subjected to diminishing returns due to the presence of a fixed quantity of land, and the Malthusian level of income per capita is determined endogenously. More recently, Dalgaard and Strulik (2009) model the bio-economic link between productivity, body size, and population size in a Malthusian framework, whereas Aiyar et al. (2008) provide micro-foundations for the dynamic relationship between population size and technology during the pre-industrial Malthusian epoch.

period of life (childhood), $t-1$, they are supported by their parents. In the second period of life (parenthood), t, they inelastically supply their labor, generating an income that is equal to the output per worker, y_t, which they allocate between their own consumption and that of their children.

Individuals generate utility from consumption and the number of their (surviving) children:[5]

$$u^t = (c_t)^{1-\gamma}(n_t)^{\gamma}; \qquad \gamma \in (0,1), \tag{3}$$

where c_t is the consumption of an individual of generation t, and n_t is the number of children of individual t.

Members of generation t allocate their income between their consumption, c_t, and expenditure on children, ρn_t, where ρ is the cost of raising a child.[6] Hence, the budget constraint for a member of generation t (in the second period of life) is:

$$\rho n_t + c_t \leq y_t. \tag{4}$$

2.1.3 Optimization

Members of generation t allocate their income optimally between consumption and child rearing, so as to maximize their intertemporal utility function (3) subject to the budget constraint (4). Hence, individuals devote a fraction $(1-\gamma)$ to consumption and a fraction γ of their income to child rearing:

$$\begin{aligned} c_t &= (1-\gamma)y_t; \\ n_t &= \gamma y_t/\rho. \end{aligned} \tag{5}$$

Thus, in accordance with the Malthusian paradigm, income has a positive effect on the number of surviving children.

2.2 The Evolution of the Economy

2.2.1 Population Dynamics

The evolution of the working population is determined by the initial size of the working population and the number of (surviving) children per adult. Specifically, the size of the working population in period $t+1$, L_{t+1}, is:

$$L_{t+1} = n_t L_t. \tag{6}$$

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[5] For simplicity parents derive utility from the expected number of surviving offspring and the parental cost of child rearing is associated only with surviving children. A more realistic cost structure would not affect the qualitative predictions of the model.

[6] If the cost of children is a time cost then the qualitative results will be maintained as long as individuals are subjected to a subsistence consumption constraint (Galor and Weil, 2000). If both time and goods are required to produce children, the results of the model will not be affected qualitatively. As the economy develops and wages increase, the time cost will rise proportionately with the increase in income, but the cost in terms of goods will decline. Hence, individuals will be able to afford more children.

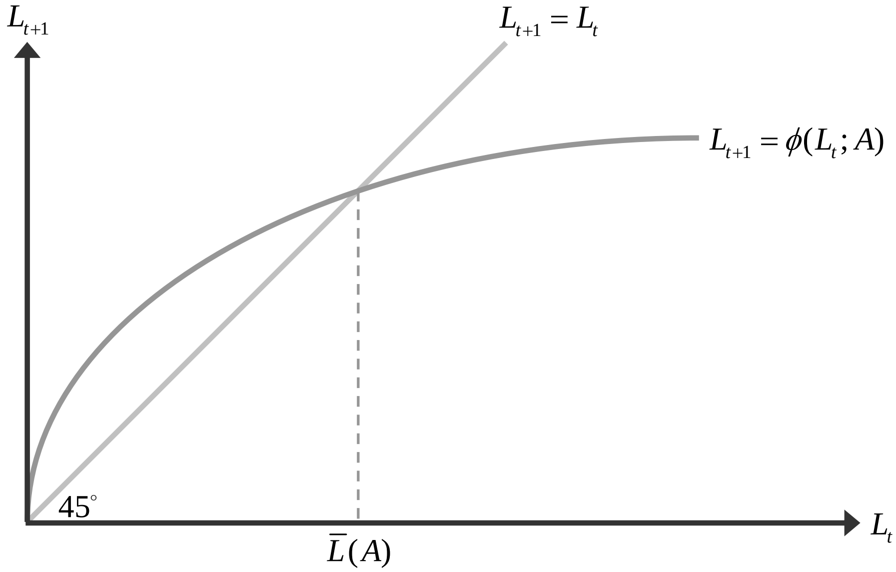

FIGURE 2: The Evolution of Population Size

Substituting (2) and (5) into (6), the time path of the working population is governed by the first-order difference equation:

$$L_{t+1} = (\gamma/\rho)(AX)^{\alpha} L_t^{1-\alpha} \equiv \phi(L_t; A), \tag{7}$$

where, as depicted in Figure 2, $\phi_L(L_t; A) > 0$ and $\phi_{LL}(L_t; A) < 0$ so $\phi(L_t; A)$ is strictly concave in L_t, and $\phi(0; A) = 0$, $\lim_{L_t \to 0} \phi_L(L_t; A) = \infty$ and $\lim_{L_t \to \infty} \phi_L(L_t; A) = 0$.

Hence, for a given level of technology, A, there exists a unique steady-state level of the adult population, $\bar{L}$:

$$\bar{L} = (\gamma/\rho)^{1/\alpha}(AX) \equiv \bar{L}(A), \tag{8}$$

and population density, $\bar{P}_d$:

$$\bar{P}_d \equiv \bar{L}/X = (\gamma/\rho)^{1/\alpha} A \equiv \bar{P}_d(A). \tag{9}$$

Importantly, as is evident from (8) and (9), an improvement in the technological environment, A, increases the steady-state levels of the adult population, $\bar{L}$, and population density, $\bar{P}_d$:

$$\frac{\partial \bar{L}}{\partial A} > 0 \text{ and } \frac{\partial \bar{P}_d}{\partial A} > 0. \tag{10}$$

As depicted in Figure 3, if the economy is in a steady-state equilibrium, an increase in the technological level from A^l to A^h generates a transition process in which population gradually increases from its initial steady-state level, $\bar{L}^l$, to a higher one, $\bar{L}^h$. Similarly, a decline in the population due to an epidemic such as the Black Death (1348-1350 CE) would temporarily reduce population, while temporarily increasing income per capita. The rise in income per capita, however, will generate a gradual increase in population back to the initial steady-state level, $\bar{L}$.

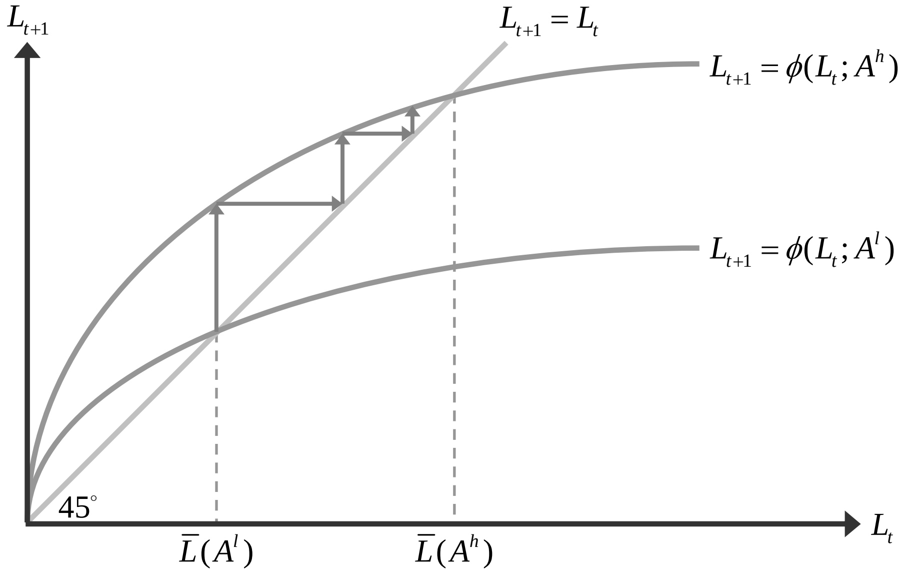

Figure 3: Population Adjustment due to an Increase in Technology

2.2.2 The Time Path of Income Per Worker

The evolution of income per worker is determined by the initial level of income per worker and the number of (surviving) children per adult. Specifically, income per worker in period $t+1$, y_{t+1}, noting (2) and (6), is:

$$y_{t+1} = [(AX)/L_{t+1}]^\alpha = [(AX)/n_t L_t]^\alpha = y_t/n_t^\alpha. \tag{11}$$

Substituting (5) into (11), the time path of income per worker is governed by the first-order difference equation:

$$y_{t+1} = (\rho/\gamma)^\alpha y_t^{1-\alpha} \equiv \psi(y_t), \tag{12}$$

where, as depicted in Figure 4, $\psi'(y_t) > 0$ and $\psi''(y_t) < 0$ so $\psi(y_t)$ is strictly concave, and $\psi(0) = 0$, $\lim_{y_t \to 0} \psi'(y_t) = \infty$ and $\lim_{y_t \to \infty} \psi'(y_t) = 0$.

Hence, regardless of the level of technology, A, there exists a unique steady-state level of income per worker, $\bar{y}$:

$$\bar{y} = (\rho/\gamma). \tag{13}$$

Importantly, as is evident from (2) and (13), while an advancement in the level of technology, A, increases the level of income per worker in the short-run, y_t, it does not affect the steady-state level of income per worker, $\bar{y}$:

$$\frac{\partial y_t}{\partial A} > 0 \text{ and } \frac{\partial \bar{y}}{\partial A} = 0. \tag{14}$$

As depicted in Figure 4, if the economy is in a steady-state equilibrium, an increase in the technological level from A^l to A^h generates a transition process in which income per

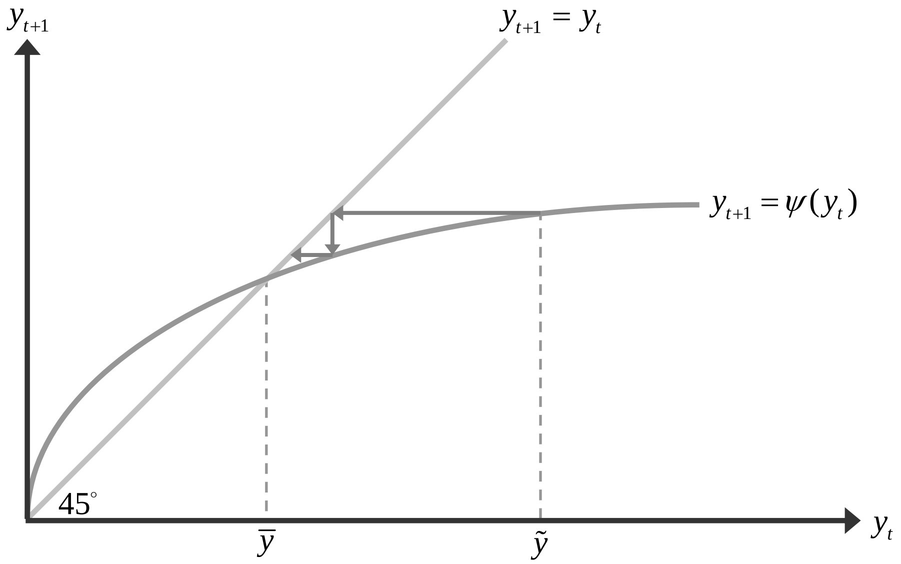

Figure 4: The Evolution of Income Per Worker

worker initially increases to a higher level, $\tilde{y}$, reflecting higher labor productivity in the absence of population adjustment. However, as population increases, income per worker gradually declines to the initial steady-state equilibrium, $\bar{y}$. Similarly, a decline in the population due to an epidemic such as the Black Death (1348-1350 CE) would temporarily reduce population to $\tilde{L}$, while temporarily increasing income per capita to $\tilde{y}$. The rise in income per worker will generate a gradual increase in population back to the steady-state level, $\bar{L}$, and thus a gradual decline in income per worker back to $\bar{y}$.

2.3 Testable Predictions

The Malthusian theory generates the following testable predictions:

1. Within a country, an increase in productivity would lead in the long run to a larger population, without altering the long-run level of income per capita.
2. Across countries, those characterized by superior land productivity would have, all else equal, a higher population density in the long run, but their standard of living would not reflect the degree of their technological advancement.
3. Across countries, those characterized by a superior level of technology would have, all else equal, a higher long-run level of population density, but their standard of living would not reflect the degree of their technological advancement.

3 Empirical Framework

3.1 Hypothesis and Empirical Strategy

The Malthusian theory predicts that regional variation in population density in the long run would ultimately reflect regional variations in technological levels, land productivity and biogeographic factors. These variations in the level of technological advancement, land productivity and biogeographic attributes, however, would not be manifested as significant differences in income per capita across regions. In particular, since resource constraints were slacker for regions naturally blessed by a higher productivity of land, they would have sustained larger populations, given the level of technological advancement. Further, given the natural productivity of land, societies that were more advanced technologically would have sustained higher population densities. However, technologically superior societies, or those that were characterized by higher land productivity, would not necessarily have enjoyed higher standards of living.

Thus, for a given technological environment, greater land productivity, such as higher arable percentage of land, better soil quality, and a favorable climate, would permit society to support a larger, but not richer, population in the long run. Moreover, for a given land productivity, auspicious biogeographic factors, including proximity to waterways, absolute latitude, and a greater availability of domesticable plant and animal species, would enhance population density, by fostering trade and the implementation and diffusion of agricultural technologies, but would not affect the standard of living. In addition, conditional on land productivity and biogeographic factors, a higher level of technological advancement would permit society to sustain a larger population, but would leave income per capita largely unaffected in the long run.

To test the Malthusian theory empirically, this research exploits exogenous sources of cross-country variation in land productivity and technological levels to explain cross-country variation in either population density or income per capita in the years 1500 CE, 1000 CE and 1 CE. This permits the analysis to examine the *differential* effects of land productivity and technological levels on population density versus income per capita, as hypothesized by the Malthusian theory.

In light of the potential effect of population on technological progress, assessing the impact of the level of technological advancement on population density requires surmounting issues of reverse causality. The conceptualization of the Neolithic Revolution as a triggering event for subsequent technological progress, however, permits this research to overcome the problem of endogeneity by using the number of years elapsed since the Neolithic transition as an exogenous source of variation in the level of technological advancement during the time period 1-1500 CE. In particular, favorable biogeographic factors led to an earlier onset of the Neolithic Revolution and facilitated the subsequent diffusion of agricultural techniques. The transition of societies during the Neolithic Revolution from primitive hunting and gathering techniques to the more technologically advanced agricultural mode of production initiated a cumulative process of socioeconomic development. Specifically, it gave some societies a developmental head start, conferred by their superior production technology that enabled the rise of a non-food-producing class whose members were crucial for the advancement of written language and science, and for the formation of cities, technology-based military powers and nation states (Diamond, 1997).[7] The analysis thus employs the time elapsed since the Neolithic Revolution as a baseline metric of the level of aggregate productivity in an agricultural society during the Malthusian era.

In addition, to address the possibility that the relationship between the timing of the Neolithic transition and population density in the Common Era may itself be spurious, being perhaps co-determined by an unobserved channel such as human capital, the analysis appeals to the role of prehistoric biogeographic endowments in determining the timing of the Neolithic Revolution. Specifically, the analysis adopts the numbers of prehistoric domesticable species of plants and animals, that were native to a region *prior* to the onset of sedentary agricultural practices, as instruments for the number of years elapsed since the Neolithic Revolution to demonstrate its causal effect on population density in the common era.[8]

Moreover, a more direct measure of technological sophistication, for the years 1000 CE and 1 CE, is also employed as an alternative metric of the level of aggregate productivity to demonstrate the qualitative robustness of the baseline results.[9] Once again, the link running from prehistoric biogeographic endowments to the level of technological advancement in the common era, via the timing of the Neolithic transition, enables the analysis to exploit the aforementioned biogeographic variables as instruments for the indices of technological sophistication in the years 1000 CE and 1 CE to establish their causal effects on population density in these periods.

Finally, in order to ensure that the results from the level regressions are not driven by unobserved time-invariant country fixed effects, this research also employs a first-difference estimation strategy. In particular, the robustness analysis exploits cross-country variation in the change in the level of technological sophistication between the years 1 CE and 1000 CE to explain the variations in the change in population density and the change in income per capita over the same time horizon.

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[7] See also Weisdorf (2005, 2009). In the context of the Malthusian model presented earlier, the Neolithic Revolution should be viewed as a large positive shock to the level of technology, A, followed by a long discrete series of incremental "aftershocks", where the time elapsed between any two "aftershocks" would be sufficiently large so as to permit the population to attain the new Malthusian steady state. Thus, at any given point in time, a society that experienced the Neolithic Revolution earlier would have a larger history of these "aftershocks" and would therefore reflect a larger steady-state population size (or, equivalently, a higher steady-state population density). The "aftershocks" of the Neolithic Revolution may be historically interpreted as discrete steps comprising the process of socioeconomic development such as urbanization, the emergence of land ownership and property rights institutions, advancements in communication via written language, scientific discoveries, etc.

[8] The insufficient number of observations arising from the greater paucity of historical income data, as compared to data on population density, does not permit a similar IV strategy to be pursued when examining the impact of the timing of the Neolithic Revolution on income per capita.

[9] The absence of sufficient variation in the underlying data obtained from Peregrine (2003) prevents the construction of a corresponding technology measure for the year 1500 CE. While an alternative index for 1500 CE has been constructed by Comin et al. (2008), based on numerous underlying sources, this data is not yet available on the public domain.

3.2 The Data

The most comprehensive worldwide cross-country historical estimates of population and income per capita since the year 1 CE have been assembled by McEvedy and Jones (1978) and Maddison (2003) respectively. Indeed, despite inherent problems of measurement associated with historical data, these sources remain unparalleled in providing comparable estimates across countries in the last 2000 years and have, therefore, widely been regarded as standard sources for such data in the long-run growth literature.[10] For the purposes of the current analysis, the population density of a country for a given year is computed as population in that year, as reported by McEvedy and Jones (1978), divided by total land area, as reported by the World Bank's *World Development Indicators* online database.

In terms of land productivity, the measure employed is the first principal component of the arable percentage of land, as reported by the *World Development Indicators*, and an index reflecting the overall suitability of land for agriculture, based on geospatial soil quality and temperature data, as reported by Ramankutty et al. (2002) and aggregated to the country level by Michalopoulos (2008).[11] The data on the timing of the Neolithic Revolution is based on the measure constructed by Putterman (2008), using a wide variety of both regional and country-specific archaeological studies as well as more general encyclopedic works on the Neolithic transition from hunting and gathering to agriculture, including MacNeish (1992) and Smith (1995). Specifically, the reported measure captures the number of thousand years elapsed, relative to the year 2000 CE, since the majority of the population residing within a country's modern national borders began practicing sedentary agriculture as the primary mode of subsistence.

Last but not least, the index of technological sophistication is constructed based on historical cross-cultural technology data, reported with global coverage in Peregrine's (2003) *Atlas of Cultural Evolution*. In particular, for a given time period and for a given culture in the archaeological record, the *Atlas of Cultural Evolution* draws on various anthropological and historical sources to report the level of technological advancement, on a 3-point scale, in

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[10] Nevertheless, in the context of the current study, the use of Maddison's (2003) income per capita data could have posed a significant hurdle if the data had in part been imputed with a Malthusian viewpoint of the pre-industrial world in mind. While Maddison (2008) suggests that this is not the case, the empirical investigation to follow performs a rigorous analysis to demonstrate that the baseline results remain robust under alternative specifications designed to address this particular concern surrounding Maddison's income per capita estimates. Regarding the historical population data from McEvedy and Jones (1978), while some of their estimates remain controversial, particularly those for sub-Saharan Africa and pre-Columbian Mesoamerica, a recent assessment (see, e.g., www.census.gov/ipc/www/worldhis.html) conducted by the U.S. Census Bureau finds that their aggregate estimates indeed compare favorably with those obtained from other studies. Moreover, the regional estimates of McEvedy and Jones are also very similar to those presented in the more recent study by Livi-Bacci (2001).

[11] The use of contemporary measures of land productivity necessitates an identifying assumption that the spatial distribution of factors governing the productivity of land for agriculture has not changed significantly in the past 2000 years. In this regard, it is important to note that the analysis at hand exploits worldwide variation in such factors, which changes dramatically only in geological time. Hence, while the assumption may not necessarily hold at a sub-regional level in some cases (e.g., in regions south of the Sahara where the desert has been known to be expanding gradually in the past few centuries), it is unlikely that the moments of the *global* spatial distribution of land productivity are significantly different today than they were two millennia ago.

each of four sectors of the economy, including communications, industry (i.e., ceramics and metallurgy), transportation, and agriculture.[12] This data has recently been aggregated to the country level for various historical periods by Comin et al. (2008) in order to demonstrate long-run persistence in cross-country patterns of technology adoption over time. Keeping with historical technology measures previously employed in the literature for cross-country analyses, the index of technological sophistication is constructed following the aggregation methodology of Comin et al.[13]

3.3 The Neolithic Revolution and Technological Advancement

In line with the assertion that the Neolithic Revolution triggered a cumulative process of economic development, conferring a developmental head start to societies that experienced the agricultural transition earlier, Table 1 reveals preliminary results indicating that an earlier onset of the Neolithic Revolution is indeed positively and significantly correlated with the level of technological sophistication in non-agricultural sectors of the economy in the years 1000 CE and 1 CE. For instance, the coefficient estimates for the year 1000 CE, all of which are statistically significant at the 1% level, indicate that a 1% increase in the number of years elapsed since the onset of the Neolithic Revolution is associated with increases in the level of technological advancement in communications, industry, and transportation by 0.37%, 0.07%, and 0.38% respectively.

These findings lend credence to the empirical strategy employed by this research to test the Malthusian theory. Specifically, they provide evidence justifying the use of the exogenous source of cross-country variation in the timing of the Neolithic Revolution as a valid proxy for the variation in the level of technological advancement across countries during the agricultural stage of development. Moreover, they serve as an internal consistency check between the cross-country Neolithic transition timing data and that on historical levels of technological sophistication, both of which are relatively new in terms of their application in the empirical literature on long-run development.

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[12] The level of technology in each sector is indexed as follows. In the communications sector, the index is assigned a value of 0 under the absence of both true writing and mnemonic or non-written records, a value of 1 under the presence of only mnemonic or non-written records, and a value of 2 under the presence of both. In the industrial sector, the index is assigned a value of 0 under the absence of both metalworks and pottery, a value of 1 under the presence of only pottery, and a value of 2 under the presence of both. In the transportation sector, the index is assigned a value of 0 under the absence of both vehicles and pack or draft animals, a value of 1 under the presence of only pack or draft animals, and a value of 2 under the presence of both. Finally, in the agricultural sector, the index is assigned a value of 0 under the absence of sedentary agriculture, a value of 1 when agriculture is practiced but only as a secondary mode of subsistence, and a value of 2 when agriculture is practiced as the primary mode of subsistence. In all cases, the sector-specific indices are normalized to assume values in the $[0, 1]$-interval. The technology index for a given culture is thus the unweighted average across sectors of the sector-specific indices for that culture. The reader is referred to Peregrine (2003) and Comin et al. (2008) for additional details.

[13] Further details on definitions and sources of the primary and control variables employed by the analysis are collected in the appendix, along with the relevant descriptive statistics.

Table 1: The Neolithic Revolution as a proxy for Technological Advancement

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Dependent Variable is Level of:					
	Log Communications Technology in:		Log Industrial Technology in:		Log Transportation Technology in:	
	1000 CE	1 CE	1000 CE	1 CE	1000 CE	1 CE
Log Years since Neolithic Transition	0.368*** (0.028)	0.283*** (0.030)	0.074*** (0.014)	0.068*** (0.015)	0.380*** (0.029)	0.367*** (0.031)
Observations	143	143	143	143	143	143
R-squared	0.48	0.26	0.17	0.12	0.52	0.51

Summary – This table demonstrates that the timing of the Neolithic Revolution is positively and significantly correlated with the level of technology in multiple non-agricultural sectors of an economy in the years 1000 CE and 1 CE, and thereby establishes that the timing of the Neolithic Revolution serves as a valid proxy for the overall level of technological sophistication during the agricultural stage of development.

Notes – (i) the level of technology in communications is indexed according to the absence of both true writing and mnemonic or non-written records, the presence of only mnemonic or non-written records, or the presence of both; (ii) the level of technology in industry is indexed according to the absence of both metalworks and pottery, the presence of only pottery, or the presence of both; (iii) the level of technology in transportation is indexed according to the absence of both vehicles and pack or draft animals, the presence of only pack or draft animals, or the presence of both; (vi) robust standard error estimates are reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

3.4 The Basic Regression Model

Formally, the baseline specifications adopted to test the Malthusian predictions regarding the effects of land productivity and the level of technological advancement on population density and income per capita are:

$$\ln P_{i,t} = \alpha_0 + \alpha_1 \ln T_i + \alpha_2 \ln X_i + \alpha_3^{'}\Gamma_i + \alpha_4^{'} D_i + \delta_{i,t}, \quad (15)$$

$$\ln y_{i,t} = \beta_0 + \beta_1 \ln T_i + \beta_2 \ln X_i + \beta_3^{'}\Gamma_i + \beta_4^{'} D_i + \varepsilon_{i,t}, \quad (16)$$

where $P_{i,t}$ is the population density of country i in a given year t; $y_{i,t}$ is country i's income per capita in year t; T_i is the number of years elapsed since the onset of agriculture in country i; X_i is a measure of land productivity for country i, based on the arable percentage of land area and an index of agricultural suitability; Γ_i is a vector of geographic controls for country i, including absolute latitude and variables gauging access to waterways; D_i is a vector of continental dummies; and, $\delta_{i,t}$ and $\varepsilon_{i,t}$ are country-specific disturbance terms for population density and income per capita, respectively, in year t.

4 Cross-Country Evidence

Consistent with the predictions of the Malthusian theory, the results demonstrate highly statistically significant positive effects of land productivity and the number of years elapsed since the Neolithic Revolution on population density in the years 1500 CE, 1000 CE and 1 CE. The effects of these explanatory channels on income per capita in the corresponding periods, however, are not significantly different from zero, a result that fully complies with Malthusian priors. These results are shown to be robust to controls for other geographic factors, including absolute latitude, access to waterways, distance to the nearest technological frontier, the percentage of land in tropical versus temperate climatic zones, and small island and landlocked dummies, all of which may have had an impact on aggregate productivity either directly, by affecting the productivity of land, or indirectly by affecting trade and the diffusion of technologies.[14] Moreover, as foreshadowed by the initial findings in Table 1, the results are qualitatively unaffected when the index of technological sophistication, rather than the number of years elapsed since the Neolithic Revolution, is employed as a proxy for the level of aggregate productivity.

The detailed discussion of the empirical findings is organized as follows. Section 4.1 presents the results from testing the Malthusian prediction for population density in the year 1500 CE. Analogous findings for population density in the years 1000 CE and 1 CE are revealed in Section 4.2. The results from testing the Malthusian prediction for income per capita in the three historical periods are discussed in Section 4.3. This section also takes a closer look at the income per capita data and demonstrates the qualitative robustness of the baseline results with respect to alternative specifications designed to alleviate potential concerns regarding the possibility that historical estimates of cross-country living standards may in part reflect some prior conformity with a Malthusian view of the world. Section 4.4 reveals the qualitative robustness of the earlier findings when the index of technological sophistication is employed in lieu of the timing of the Neolithic transition as a proxy for the level of technological advancement. Additional results establishing robustness with respect to the technology diffusion hypothesis as well as other geographic factors are collected in Section 4.5. Finally, Section 4.6 concludes the discussion with findings from regressions based on the methodology of first differences, dispelling alternative theories and accounting for unobserved country fixed effects.[15]

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[14] The data on absolute latitude and on small island and landlocked dummies are obtained from the CIA's *World Factbook*. Along with the percentage of land in tropical versus temperate climatic zones, the variables employed to gauge access to waterways are obtained from the CID research datasets online and include the mean within-country distance to the nearest coast or sea-navigable river and the percentage of total land located within 100 km of the nearest coast or sea-navigable river. Finally, data on distance to the nearest technological frontier comes from the dataset of Ashraf and Galor (2009).

[15] The appendix presents additional findings demonstrating robustness. Specifically, Table C.1 establishes that the results for population density and income per capita in 1500 CE are robust under two alternative specifications that relax potential constraints imposed by the baseline regression models, including (i) the treatment of the Americas as a single entity in accounting for continental fixed effects, and (ii) the employment of only the *common variation* in (the logs of) the arable percentage of land and the index of agricultural suitability when accounting for the effect of the land productivity channel by way of the first principal component of these two variables. Moreover, given that historical population estimates are also available from Maddison (2003), albeit for a smaller set of countries than McEvedy and Jones (1978), Table C.2 demonstrates that the baseline results for population density in the three historical periods, obtained using data from McEvedy and Jones, are indeed qualitatively unchanged under Maddison's alternative population estimates. Finally, given the possibility that the disturbance terms in the baseline regression models may be non-spherical in nature, particularly since economic development has been spatially clustered in certain regions of the world, Tables C.3 and C.4 repeat the baseline analyses for population density and income per

4.1 Population Density in 1500 CE

The results from regressions explaining log population density in the year 1500 CE are presented in Table 2. In particular, a number of specifications comprising different subsets of the explanatory variables in equation (15) are estimated to examine the independent and combined effects of the transition timing and land productivity channels, while controlling for other geographic factors and continental fixed effects.

Consistent with Malthusian predictions, Column 1 reveals the positive relationship between log years since transition and log population density in the year 1500 CE, while controlling for continental fixed effects.[16] Specifically, the estimated OLS coefficient implies that a 1% increase in the number of years elapsed since the Neolithic transition increases population density in 1500 CE by 0.83%, an effect that is statistically significant at the 1% level.[17] Moreover, based on the R-squared of the regression, the transition timing channel appears to explain 40% of the variation in log population density in 1500 CE along with the dummies capturing unobserved continental characteristics.

The effect of the land productivity channel, controlling for absolute latitude and continental fixed effects, is reported in Column 2. In line with theoretical predictions, a 1% increase in land productivity raises population density in 1500 CE by 0.58%, an effect that is also significant at the 1% level. Interestingly, in contrast to the relationship between absolute latitude and contemporary income per capita, the estimated elasticity of population density in 1500 CE with respect to absolute latitude suggests that economic development during this period was on average higher at latitudinal bands closer to the equator.[18] Thus, while proximity to the equator was beneficial in the agricultural stage of development, it appears detrimental in the industrial stage. The R-squared of the regression indicates that, along with continental fixed effects and absolute latitude, the land productivity channel explains 60% of the cross-country variation in log population density in 1500 CE.

Column 3 presents the results from examining the combined explanatory power of the previous two regressions. The estimated coefficients on the transition timing and land productivity variables remain highly statistically significant and continue to retain their expected signs, while increasing slightly in magnitude in comparison to their estimates in earlier columns. Furthermore, transition timing and land productivity together explain 66%

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capita in the three historical periods, with the standard errors of the point estimates corrected for spatial autocorrelation following the methodology of Conley (1999).

[16] The results presented throughout are robust to the omission of continental dummies from the regression specifications. Without continental fixed effects, the coefficient of interest in Column 1 is 1.274 [0.169], with the standard error (in brackets) indicating statistical significance at the 1% level.

[17] Evaluating these percentage changes at the sample means of 4895.61 for years since transition and 6.02 for population density in 1500 CE implies that an earlier onset of the Neolithic by about 500 years is associated with an increase in population density in 1500 CE by 0.5 persons per sqkm.

[18] An interesting potential explanation for this finding comes from the field of evolutionary ecology. In particular, biodiversity tends to decline as one moves farther away from the equator – a phenomenon know as *Rapoport's Rule* – due to the stronger forces of natural selection arising from wider annual variation in climate at higher latitudes. Lower resource diversity at higher latitudes would imply lower carrying capacities of these environments due to the greater extinction susceptibility of the resource base under adverse natural shocks such as disease and sudden climatic fluctuations. The lower carrying capacities of these environments would, in turn, imply lower levels of human population density.

Table 2: Explaining Population Density in 1500 CE

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	IV
	Dependent Variable is Log Population Density in 1500 CE					
Log Years since Neolithic Transition	0.827*** (0.299)		1.024*** (0.223)	1.087*** (0.184)	1.389*** (0.224)	2.077*** (0.391)
Log Land Productivity		0.584*** (0.068)	0.638*** (0.057)	0.576*** (0.052)	0.573*** (0.095)	0.571*** (0.082)
Log Absolute Latitude		-0.426*** (0.124)	-0.354*** (0.104)	-0.314*** (0.103)	-0.278** (0.131)	-0.248** (0.117)
Mean Distance to Nearest Coast or River				-0.392*** (0.142)	0.220 (0.346)	0.250 (0.333)
% Land within 100 km of Coast or River				0.899*** (0.282)	1.185*** (0.377)	1.350*** (0.380)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	148	148	148	147	96	96
R-squared	0.40	0.60	0.66	0.73	0.73	0.70
First-stage F-statistic	–	–	–	–	–	14.65
Overid. p-value	–	–	–	–	–	0.440

Summary – This table establishes, consistently with Malthusian predictions, the significant positive effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on population density in the year 1500 CE, while controlling for access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the IV regression employs the numbers of prehistoric domesticable species of plants and animals as instruments for log transition timing; (iii) the statistic for the first-stage F-test of these instruments is significant at the 1% level; (iv) the p-value for the overidentifying restrictions test corresponds to Hansen's J statistic, distributed in this case as chi-square with one degree of freedom; (v) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (vi) regressions (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the IV data-restricted sample; (vii) robust standard error estimates are reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

of the variation in log population density in 1500 CE, along with absolute latitude and continental fixed effects.

The explanatory power of the regression in Column 3 improves by an additional 7% once controls for access to waterways are accounted for in Column 4, which constitutes the baseline regression specification for population density in 1500 CE. In comparison to the estimates reported in Column 3, the effects of the transition timing and land productivity variables remain reassuringly stable in both magnitude and statistical significance when subjected to the additional geographic controls. Moreover, the estimated coefficients on the additional geographic controls indicate significant effects consistent with the assertion that better access to waterways has been historically beneficial for economic development by fostering urbanization, international trade and technology diffusion. To interpret the baseline effects of the variables of interest, a 1% increase in the number of years elapsed since the Neolithic Revolution raises population density in 1500 CE by 1.09%, conditional on land productivity, absolute latitude, waterway access and continental fixed effects. Similarly, a 1% increase in land productivity generates, *ceteris paribus*, a 0.57% increase in population density in 1500 CE.[19] These conditional effects of the transition timing and land productivity channels from the baseline specification are depicted as partial regression lines on the scatter plots in Figures 5(a) and 5(b) respectively.

The analysis now turns to address issues regarding causality, particularly with respect to the transition timing variable. Specifically, while variations in land productivity and other geographic characteristics are inarguably exogenous to the cross-country variation in population density, the onset of the Neolithic Revolution and the outcome variable of interest may in fact be endogenously determined. For instance, the experience of an earlier transition to agriculture may have been caused by a larger proportion of "higher ability" individuals in society, which also fostered population density through other channels of socioeconomic development. Thus, although reverse causality is not a source of concern, given that the vast majority of countries underwent the Neolithic transition prior to the Common Era, the OLS estimates of the effect of the time elapsed since the transition to agriculture may suffer from omitted variable bias, reflecting spurious correlations with the outcome variable being examined.

To establish the causal effect of the timing of the Neolithic transition on population density in the Common Era, the investigation appeals to Diamond's (1997) hypothesis on the role of exogenous geographic and biogeographic endowments in determining the timing of the Neolithic Revolution. Accordingly, the emergence and subsequent diffusion of agricultural practices were primarily driven by geographic conditions such as climate, continental size and orientation, as well as the availability of wild plant and animal species amenable to domestication. However, while geographic factors certainly continued to play a direct role in economic development after the onset of agriculture, it is postulated that the availability of prehistoric domesticable wild plant and animal species did not influence population density in the Common Era other than through the timing of the Neolithic Revolution. The analysis consequently adopts the numbers of prehistoric domesticable species of wild plants and animals as instruments to establish the causal effect of the timing of the Neolithic transition on population density.[20]

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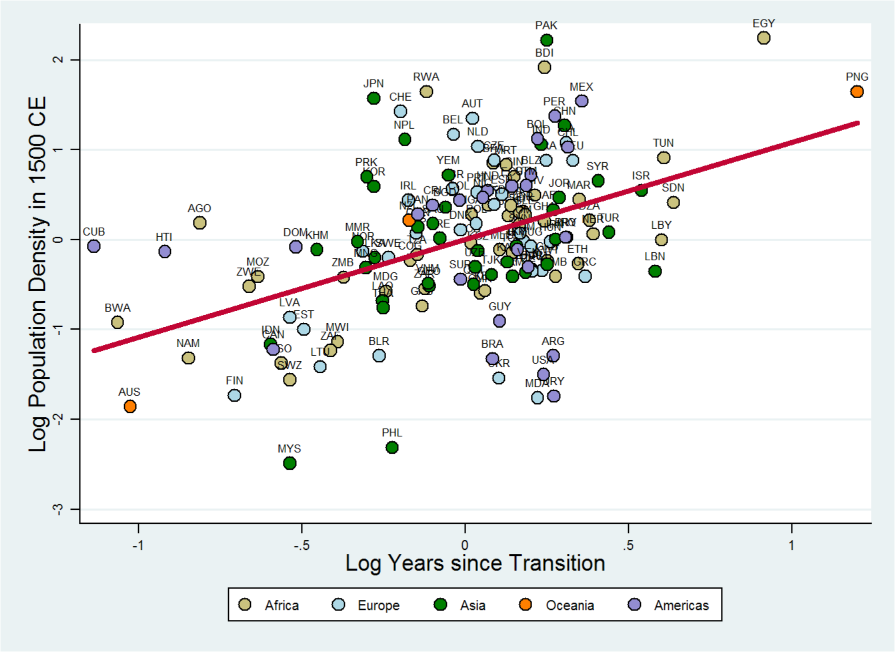
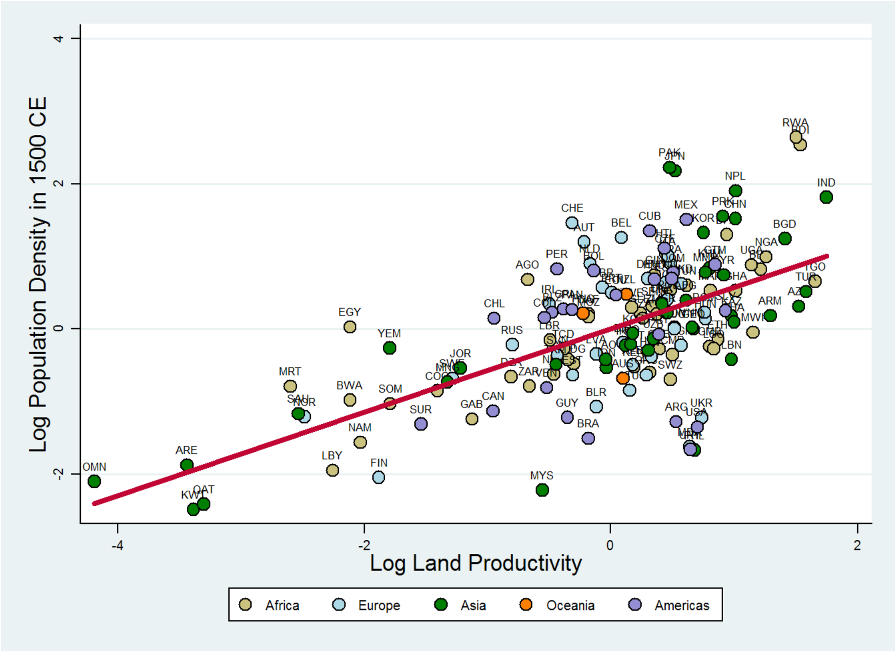
[19] In the absence of continental fixed effects, the coefficient associated with the transition timing channel is 1.373 [0.118] while that associated with the land productivity channel is 0.586 [0.058], with the standard errors (in brackets) indicating statistical significance at the 1% level.

[20] The numbers of prehistoric domesticable species of wild plants and animals are obtained from the dataset of Olsson and Hibbs (2005). It should be noted that an argument could be made for the endogeneity of these biogeographic variables whereby hunter-gatherer populations with "higher ability" individuals settled in regions with a greater availability of domesticable plants and animals. This argument, however, is rather implausible given (i) the vast distance between territories that contained domesticable species, (ii) the highly imperfect flow of information in such a primitive stage of development, and (iii) the evidence that the mobility of hunter-gatherer populations was typically limited to small geographical areas. In addition, even if the selection of "higher ability" hunter-gatherers occurred into regions that eventually proved agriculturally favorable, it is unlikely that the skills that were more productive for hunting and gathering activities were also more conducive to agriculture. Reassuringly, the potential endogeneity of the biogeographic variables is rejected by the overidentifying restrictions test in all IV regressions.



(a) The Partial Effect of Transition Timing on Population Density in 1500 CE



(b) The Partial Effect of Land Productivity on Population Density in 1500 CE

FIGURE 5: Transition Timing, Land Productivity, and Population Density in 1500 CE

<u>SUMMARY</u> – This figure depicts the partial regression line for the effect of transition timing (land productivity) on population density in the year 1500 CE, while controlling for the influence of land productivity (transition timing), absolute latitude, access to waterways, and continental fixed effects. Thus, the x- and y-axes plot the residuals obtained from regressing transition timing (land productivity) and population density, respectively, on the aforementioned set of covariates.

The final two columns in Table 2 report the results associated with a subsample of countries for which data is available on the biogeographic instruments. To allow meaningful comparisons between IV and OLS coefficient estimates, Column 5 repeats the baseline OLS regression analysis on this particular subsample of countries, revealing that the coefficients on the explanatory variables of interest remain largely stable in terms of both magnitude and significance when compared to those estimated using the baseline sample. This is a reassuring indicator that any additional sampling bias introduced by the restricted sample, particularly with respect to the transition timing and land productivity variables, is negligible. Consistent with this assertion, the explanatory powers of the baseline and restricted sample regressions are nearly identical.

Column 6 presents the IV regression results from estimating the baseline specification with log years since transition instrumented by the numbers of prehistoric domesticable species of plants and animals.[21] The estimated causal effect of the timing of the Neolithic transition on population density not only retains statistical significance at the 1% level but is substantially stronger in comparison to the estimate in Column 5. This pattern is consistent with attenuation bias afflicting the OLS coefficient as a result of measurement error in the transition timing variable. Moreover, omitted variable bias that might have been caused by the latent "higher ability" channel discussed earlier appears to be negligible since the IV coefficient on the transition timing variable would have otherwise been weaker in comparison to the OLS estimate.[22] To interpret the causal impact of the Neolithic, a 1% increase in years elapsed since the onset of agriculture causes, *ceteris paribus*, a 2.08% increase in population density in the year 1500 CE.

The coefficient on land productivity, which maintains stability in both magnitude and statistical significance across the OLS and IV regressions, indicates that a 1% increase in land productivity raises population density by 0.57%, conditional on the timing of the Neolithic transition, other geographic factors and continental fixed effects. Finally, the rather strong F-statistic from the first-stage regression provides verification for the significance and explanatory power of the biogeographic instruments employed for the timing of the Neolithic Revolution, while the high p-value associated with the test for overidentifying restrictions asserts that the instruments employed appear to be valid in that they seem not to exert any independent influence on population density in 1500 CE other than through the transition timing channel.

4.2 Population Density in Earlier Historical Periods

The results from replicating the previous analysis for log population density in the years 1000 CE and 1 CE are presented in Tables 3 and 4 respectively. As before, the independent and combined explanatory powers of the transition timing and land productivity channels

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[21] Table C.5 in the appendix summarizes the first-stage regression results from all IV regressions examined by the current analysis.

[22] It should be stressed that the "higher ability" channel is being raised in the discussion as one example of any number of unidentified channels and, as such, the direction of omitted variable bias is obviously *a priori* ambiguous. Hence, the comparatively higher IV coefficient on the transition timing variable should be taken at face value without necessarily prescribing to any one particular interpretation.

Table 3: Explaining Population Density in 1000 CE

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	IV
	Dependent Variable is Log Population Density in 1000 CE					
Log Years since Neolithic Transition	1.227*** (0.293)		1.434*** (0.243)	1.480*** (0.205)	1.803*** (0.251)	2.933*** (0.504)
Log Land Productivity		0.467*** (0.079)	0.550*** (0.063)	0.497*** (0.056)	0.535*** (0.098)	0.549*** (0.092)
Log Absolute Latitude		-0.377** (0.148)	-0.283** (0.117)	-0.229** (0.111)	-0.147 (0.127)	-0.095 (0.116)
Mean Distance to Nearest Coast or River				-0.528*** (0.153)	0.147 (0.338)	0.225 (0.354)
% Land within 100 km of Coast or River				0.716** (0.323)	1.050** (0.421)	1.358*** (0.465)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	143	143	143	142	94	94
R-squared	0.38	0.46	0.59	0.67	0.69	0.62
First-stage F-statistic	–	–	–	–	–	15.10
Overid. p-value	–	–	–	–	–	0.281

Summary – This table establishes, consistently with Malthusian predictions, the significant positive effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on population density in the year 1000 CE, while controlling for access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the IV regression employs the numbers of prehistoric domesticable species of plants and animals as instruments for log transition timing; (iii) the statistic for the first-stage F-test of these instruments is significant at the 1% level; (iv) the p-value for the overidentifying restrictions test corresponds to Hansen's J statistic, distributed in this case as chi-square with one degree of freedom; (v) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (vi) regressions (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the IV data-restricted sample; (vii) robust standard error estimates are reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

are examined while controlling for other geographical factors and unobserved continental characteristics.

In line with the empirical predictions of the Malthusian theory, the findings reveal highly statistically significant positive effects of land productivity and an earlier transition to agriculture on population density in these earlier historical periods as well. Moreover, the positive impact on economic development of geographical factors capturing better access to waterways is also confirmed for these earlier periods.[23]

The stability patterns exhibited by the magnitude and significance of the coefficients on the explanatory variables of interest in Tables 3-4 are strikingly similar to those observed earlier in the 1500 CE analysis. Thus, for instance, while statistical significance remains unaffected across specifications, the independent effects of Neolithic transition timing and

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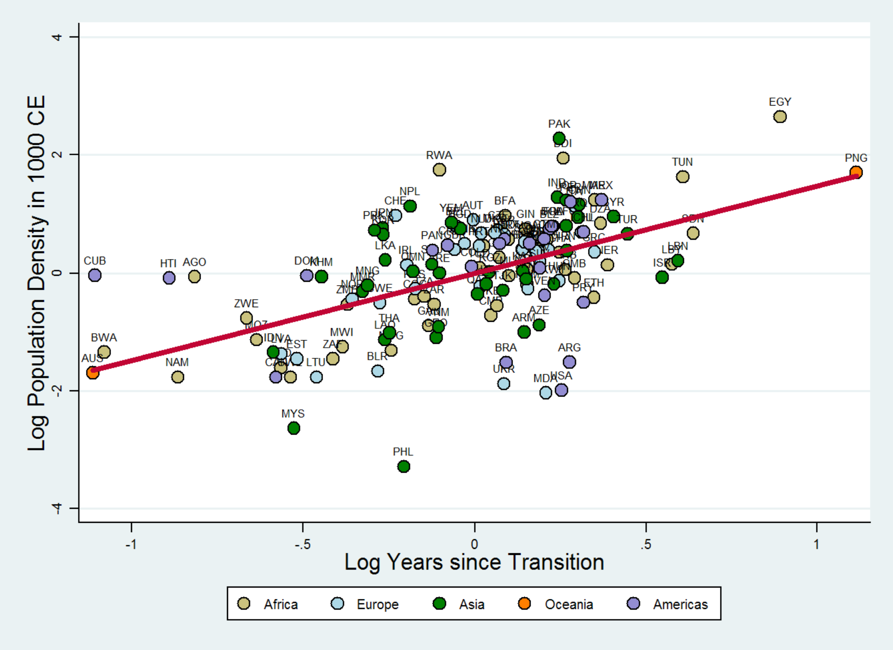
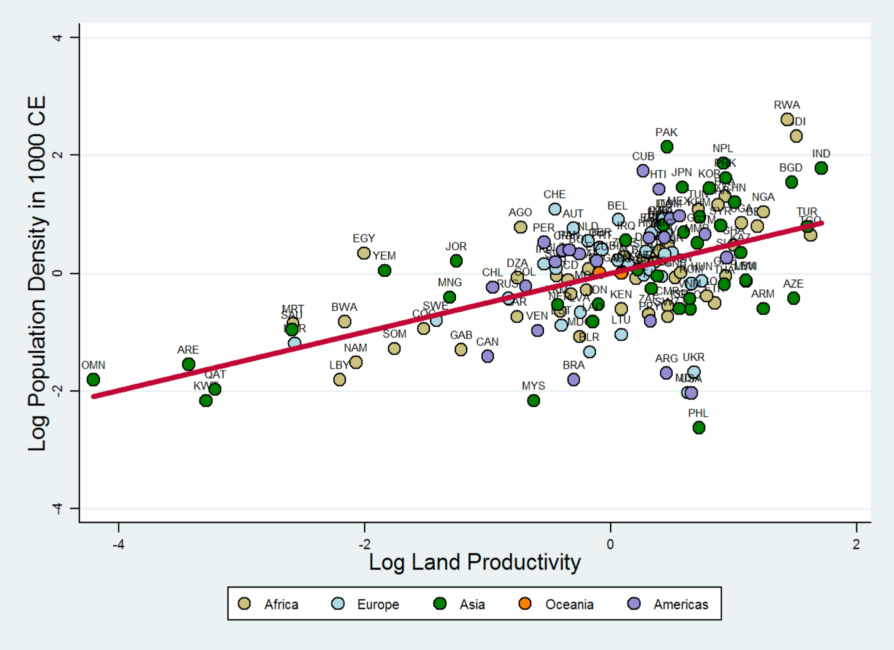
[23] Moreover, the inverse correlation between absolute latitude and population density is maintained in the 1000 CE analysis, but is less clear in the 1 CE analysis.



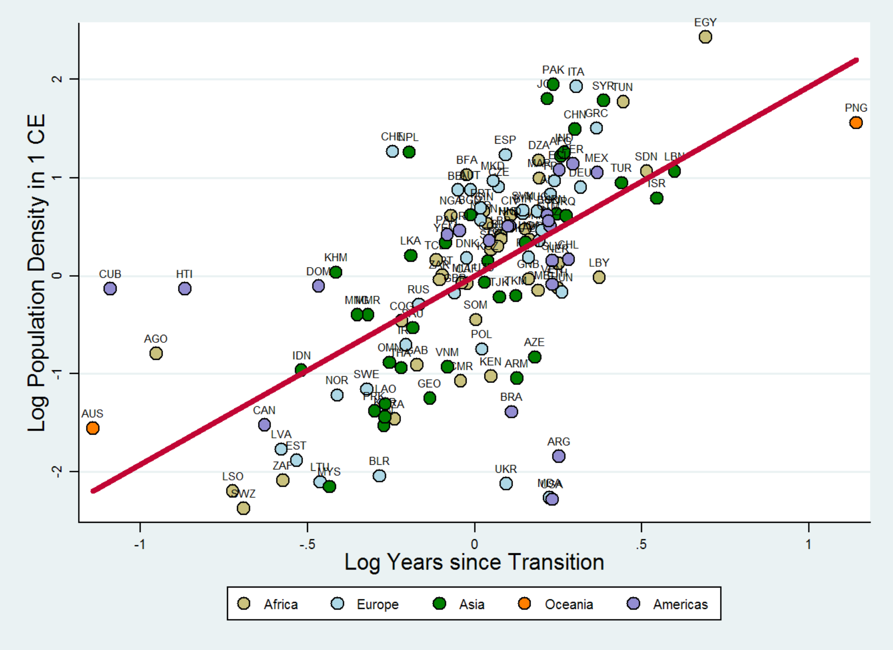
(a) The Partial Effect of Transition Timing on Population Density in 1000 CE



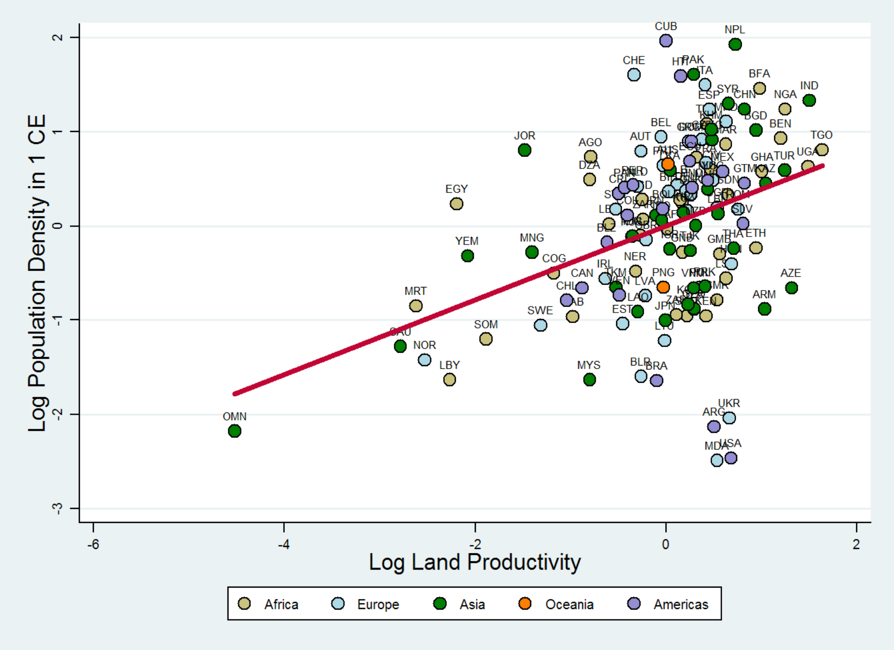
(b) The Partial Effect of Land Productivity on Population Density in 1000 CE

Figure 6: Transition Timing, Land Productivity, and Population Density in 1000 CE

Summary – This figure depicts the partial regression line for the effect of transition timing (land productivity) on population density in the year 1000 CE, while controlling for the influence of land productivity (transition timing), absolute latitude, access to waterways, and continental fixed effects. Thus, the x- and y-axes plot the residuals obtained from regressing transition timing (land productivity) and population density, respectively, on the aforementioned set of covariates.



(a) The Partial Effect of Transition Timing on Population Density in 1 CE



(b) The Partial Effect of Land Productivity on Population Density in 1 CE

Figure 7: Transition Timing, Land Productivity, and Population Density in 1 CE

Summary – This figure depicts the partial regression line for the effect of transition timing (land productivity) on population density in the year 1 CE, while controlling for the influence of land productivity (transition timing), absolute latitude, access to waterways, and continental fixed effects. Thus, the x- and y-axes plot the residuals obtained from regressing transition timing (land productivity) and population density, respectively, on the aforementioned set of covariates.

Table 4: Explaining Population Density in 1 CE

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	IV
	Dependent Variable is Log Population Density in 1 CE					
Log Years since Neolithic Transition	1.560*** (0.326)		1.903*** (0.312)	1.930*** (0.272)	2.561*** (0.369)	3.459*** (0.437)
Log Land Productivity		0.404*** (0.106)	0.556*** (0.081)	0.394*** (0.067)	0.421*** (0.094)	0.479*** (0.089)
Log Absolute Latitude		-0.080 (0.161)	-0.030 (0.120)	0.057 (0.101)	0.116 (0.121)	0.113 (0.113)
Mean Distance to Nearest Coast or River				-0.685*** (0.155)	-0.418 (0.273)	-0.320 (0.306)
% Land within 100 km of Coast or River				0.857** (0.351)	1.108*** (0.412)	1.360*** (0.488)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	128	128	128	128	83	83
R-squared	0.47	0.41	0.59	0.69	0.75	0.72
First-stage F-statistic	–	–	–	–	–	10.85
Overid. p-value	–	–	–	–	–	0.590

Summary – This table establishes, consistently with Malthusian predictions, the significant positive effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on population density in the year 1 CE, while controlling for access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the IV regression employs the numbers of prehistoric domesticable species of plants and animals as instruments for log transition timing; (iii) the statistic for the first-stage F-test of these instruments is significant at the 1% level; (iv) the p-value for the overidentifying restrictions test corresponds to Hansen's J statistic, distributed in this case as chi-square with one degree of freedom; (v) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (vi) regressions (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the IV data-restricted sample; (vii) robust standard error estimates are reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

land productivity from the first two columns in each table increase slightly in magnitude when both channels are examined concurrently in Column 3, and remain stable thereafter when subjected to the additional geographic controls in the baseline regression specification of the fourth column. This is a reassuring indicator that the variance-covariance characteristics of the regression samples employed for the different periods are not fundamentally different from one another, despite differences in sample size due to the greater unavailability of population density data in the earlier historical periods. The qualitative similarity of the results across periods also suggests that the empirical findings are indeed more plausibly associated with the Malthusian theory as opposed to being consistently generated by spurious correlations between population density and the explanatory variables of interest across the different historical periods.

To interpret the baseline effects of interest from Column 4 of the analysis for each historical period, a 1% increase in the number of years elapsed since the onset of the Neolithic

Revolution raises population density in the years 1000 CE and 1 CE by 1.48% and 1.93% respectively, conditional on the productivity of land, absolute latitude, access to waterways and continental fixed effects.[24] Similarly, a 1% increase in land productivity is associated with, *ceteris paribus*, a 0.50% increase in population density in 1000 CE and a 0.39% increase in population density in 1 CE. These conditional effects are depicted as partial regression lines on the scatter plots in Figures 6(a) and 6(b) for the 1000 CE analysis, and in Figures 7(a) and 7(b) for the 1 CE analysis.

For the 1000 CE analysis, the additional sampling bias introduced on OLS estimates by moving to the IV-restricted subsample in Column 5 is similar to that observed earlier in Table 2, whereas the bias appears somewhat larger for the analysis in 1 CE. This is partly attributable to the smaller size of the subsample in the latter analysis. The IV regressions in Column 6, however, once again reflect the pattern that the causal effect of transition timing on population density in each period is stronger than its corresponding reduced-form effect, while the effect of land productivity remains rather stable across the OLS and IV specifications. In addition, the strength and validity of the numbers of domesticable plant and animal species as instruments continue to be confirmed by their joint significance in the first-stage regressions and by the results of the overidentifying restrictions tests. The similarity of these findings with those obtained in the 1500 CE analysis reinforces the validity of these instruments and, thereby, lends further credence to the causal effect of the timing of the Neolithic transition on population density.

Finally, turning attention to the differences in coefficient estimates obtained for the three periods, it is interesting to note that, while the positive effect of land productivity on population density remains rather stable, that of the number of years elapsed since the onset of agriculture declines over time. For instance, comparing the IV coefficient estimates on the transition timing variable across Tables 2-4, the positive causal impact of the Neolithic Revolution on population density diminishes by 0.53 percentage points over the 1-1000 CE time horizon and by 0.85 percentage points over the subsequent 500-year period. This pattern is consistently reflected by all regression specifications examining the effect of the transition timing variable, lending support to the assertion that the process of development initiated by the technological breakthrough of the Neolithic Revolution conferred social gains characterized by diminishing returns over time.[25]

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[24] In both the 1000 CE and 1 CE samples, evaluating these percentage changes at the sample means for years since transition and population density implies that an earlier onset of the Neolithic by about 500 years is associated with an increase in population density by 0.5 persons per sqkm. Despite differences in the estimated elasticities between the two periods, the similarity of the effects at the sample means arises due to counteracting differences in the sample means themselves. Specifically, while population density in 1000 CE has a sample mean of 3.59, that for population density in the 1 CE is only 2.54.

[25] The assertion that the process of development initiated by the Neolithic Revolution was characterized by diminishing returns over time implies that, given a sufficiently large lag following the transition, societies should be expected to converge towards a Malthusian steady-state conditional on the productivity of land and other geographical factors. Hence, the cross-sectional relationship between population density and the number of years elapsed since the Neolithic transition should be expected to exhibit some concavity. This prediction was tested using the following specification:

$$\ln P_{i,t} = \theta_0 + \theta_1 T_i + \theta_2 T_i^2 + \theta_3 \ln X_i + \theta_4^{'} \Gamma_i + \theta_5^{'} D_i + \delta_{i,t}.$$

Table 5: Effects on Income Per Capita versus Population Density

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Dependent Variable is:					
	Log Income Per Capita in:			Log Population Density in:		
	1500 CE	1000 CE	1 CE	1500 CE	1000 CE	1 CE
Log Years since Neolithic Transition	0.159	0.073	0.109	1.337**	0.832**	1.006**
	(0.136)	(0.045)	(0.072)	(0.594)	(0.363)	(0.481)
Log Land Productivity	0.041	-0.021	-0.001	0.584***	0.364***	0.681**
	(0.025)	(0.025)	(0.027)	(0.159)	(0.110)	(0.255)
Log Absolute Latitude	-0.041	0.060	-0.175	0.050	-2.140**	-2.163**
	(0.073)	(0.147)	(0.175)	(0.463)	(0.801)	(0.979)
Mean Distance to Nearest Coast or River	0.215	-0.111	0.043	-0.429	-0.237	0.118
	(0.198)	(0.138)	(0.159)	(1.237)	(0.751)	(0.883)
% Land within 100 km of Coast or River	0.124	-0.150	0.042	1.855**	1.326**	0.228
	(0.145)	(0.121)	(0.127)	(0.820)	(0.615)	(0.919)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31	26	29	31	26	29
R-squared	0.66	0.68	0.33	0.88	0.95	0.89

Summary – This table establishes, consistently with Malthusian predictions, the relatively small effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on income per capita in the years 1500 CE, 1000 CE and 1 CE, but their significantly larger effects on population density in the same time periods, while controlling for access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (iii) regressions (2)-(3) and (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples, restricted by the availability of income per capita data; (iv) robust standard error estimates are reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

4.3 Income Per Capita versus Population Density

Table 5 presents the results from estimating the baseline empirical model, as specified in equation (16), for income per capita in the years 1500 CE, 1000 CE and 1 CE. Since historical income per capita data is available for a relatively smaller set of countries, the analysis at hand also conducts corresponding tests for population density using the income per capita data-restricted samples for the three historical periods. This permits an impartial assessment of whether higher land productivity and an earlier onset of the Neolithic Revolution are

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Consistent with the aforementioned prediction, the OLS regression for 1500 CE yields $\theta_1 = 0.630$ [0.133] and $\theta_2 = -0.033$ [0.011] with the standard errors (in brackets) indicating that both estimates are statistically significant at the 1% level. Moreover, in line with the prediction that a concave relationship should not necessarily be observed in an earlier period, the regression for 1 CE yields $\theta_1 = 0.755$ [0.172] and $\theta_2 = -0.020$ [0.013] with the standard errors indicating that the first-order (linear) effect is statistically significant at the 1% level whereas the second-order (quadratic) effect is insignificant.

manifested mostly in terms of higher population density, as opposed to higher income per capita, as the Malthusian theory would predict.[26]

Columns 1-3 reveal that income per capita in each historical period is effectively neutral to variations in the timing of the Neolithic Revolution, the agricultural productivity of land, and other productivity-enhancing geographical factors, conditional on continental fixed effects.[27] In particular, the effects of transition timing and land productivity on income per capita are not only substantially smaller than those on population density, they are also not statistically different from zero at conventional levels of significance. Moreover, the other geographical factors, which, arguably, had facilitated trade and technology diffusion, do not appear to affect income per capita.

In contrast to the results for income per capita in the three historical periods, the regressions in Columns 4-6 reveal, exploiting the same variation in explanatory variables as in the income per capita regressions, that the effects of Neolithic transition timing and land productivity on population density in the corresponding time periods are not only highly statistically significant, they are also larger by about an order of magnitude. Thus, for the year 1500 CE, a 1% increase in the number of years elapsed since the Neolithic Revolution raises population density by 1.34% but income per capita by only 0.16%, conditional on land productivity, geographical factors and continental fixed effects. Similarly, a 1% increase in land productivity is associated, *ceteris paribus*, with a 0.58% increase in population density in 1500 CE but only a 0.04% increase in income per capita in the same time period. The conditional effects of Neolithic transition timing and land productivity on income per capita versus population density in the year 1500 CE are depicted as partial regression lines on the scatter plots in Figures 8(a) and 8(b) for income per capita, and in Figures 9(a) and 9(b) for population density.

While the results revealing the cross-country neutrality of income per capita, despite differences in aggregate productivity, are fully consistent with Malthusian predictions, there may exist potential concerns regarding the quality of the income per capita data employed by the current analysis. In particular, contrary to Maddison's (2008) implicit assertion, if the historical income per capita estimates were in part imputed under the Malthusian prior regarding similarities in the standard of living across countries, then applying this data to test the Malthusian theory itself would clearly be invalid. However, a closer look at some properties of Maddison's (2003) data suggests that this need not be a concern.

Figure 10 depicts the cross-sectional variability of income per capita according to Maddison's estimates for the year 1500 CE, plotting the cumulative distribution of income per capita against quantiles of the data. The 45-degree line in the figure therefore corresponds to a uniform distribution, wherein in each observation would possess a unique value for income per capita. Indeed, the close proximity of Maddison's observations to the 45-degree

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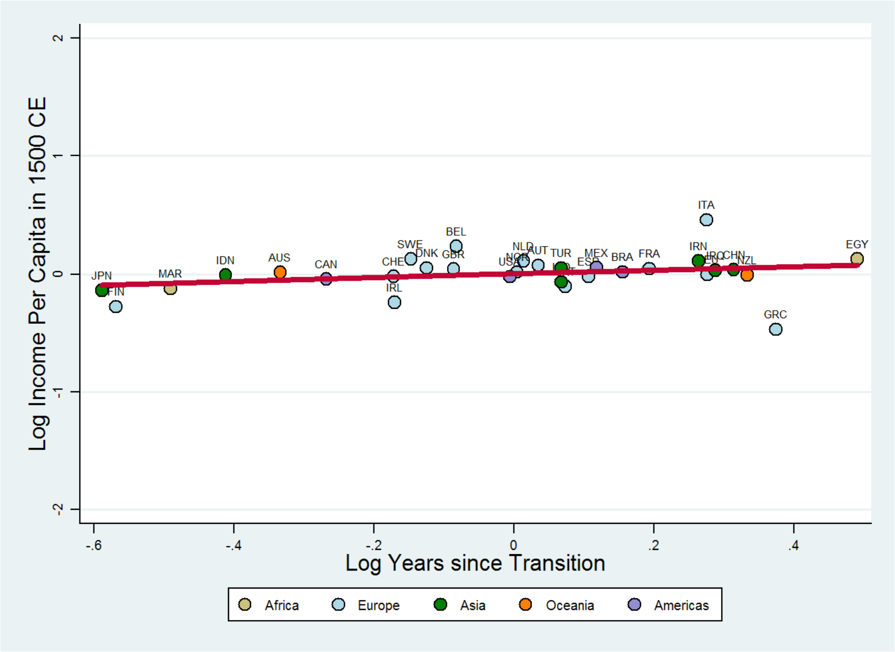
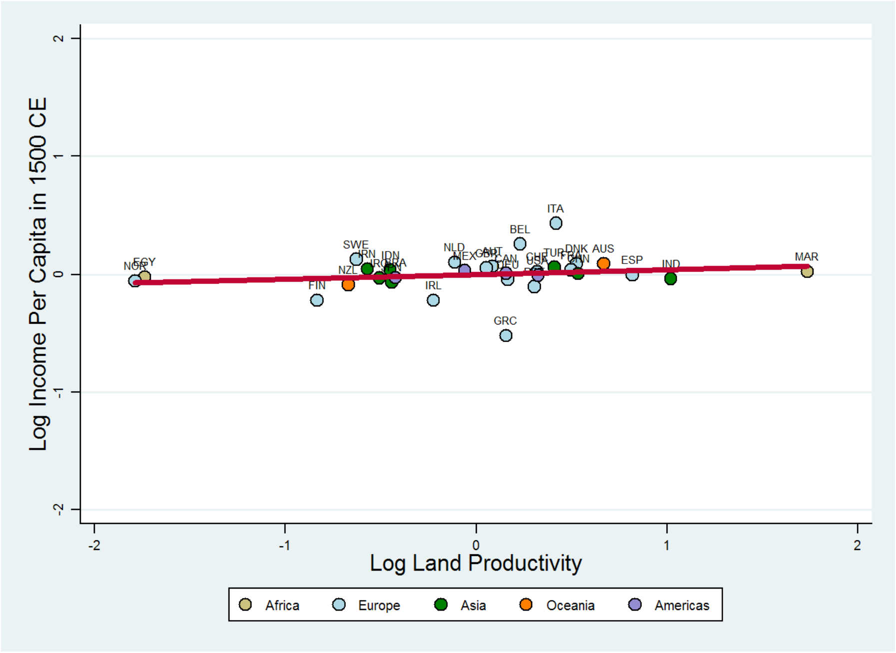
[26] The insufficient number of observations arising from the greater scarcity of historical income data, as compared to data on population density, prevents the analysis from pursuing an IV strategy that uses the numbers of prehistoric domesticable species of wild plants and animals as instruments for the timing of the Neolithic Revolution when examining its impact on income per capita.

[27] The rather high R-squared associated with each of these regressions is entirely due to the explanatory power of the constant term in the specification.



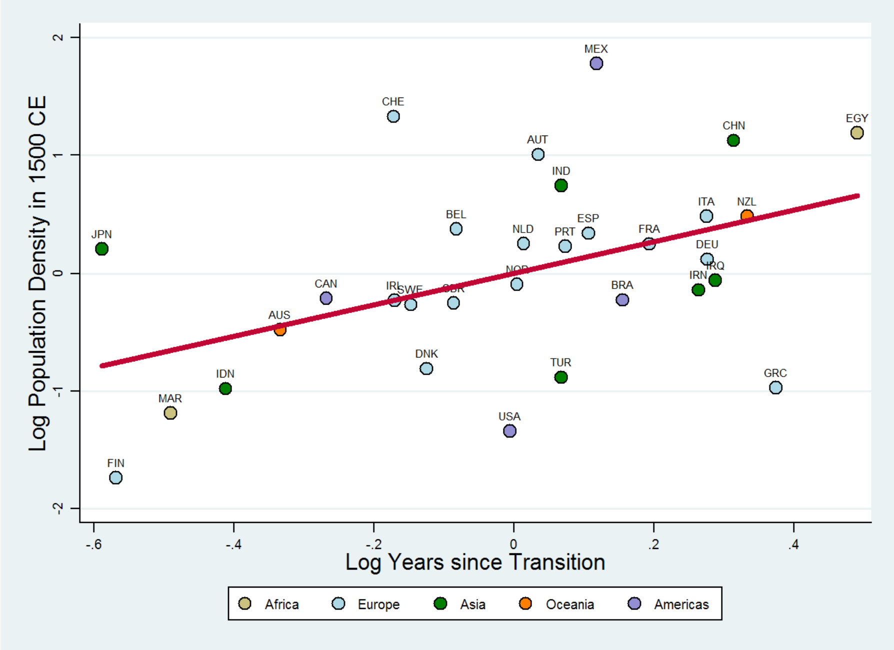
(a) The Partial Effect of Transition Timing on Income Per Capita in 1500 CE



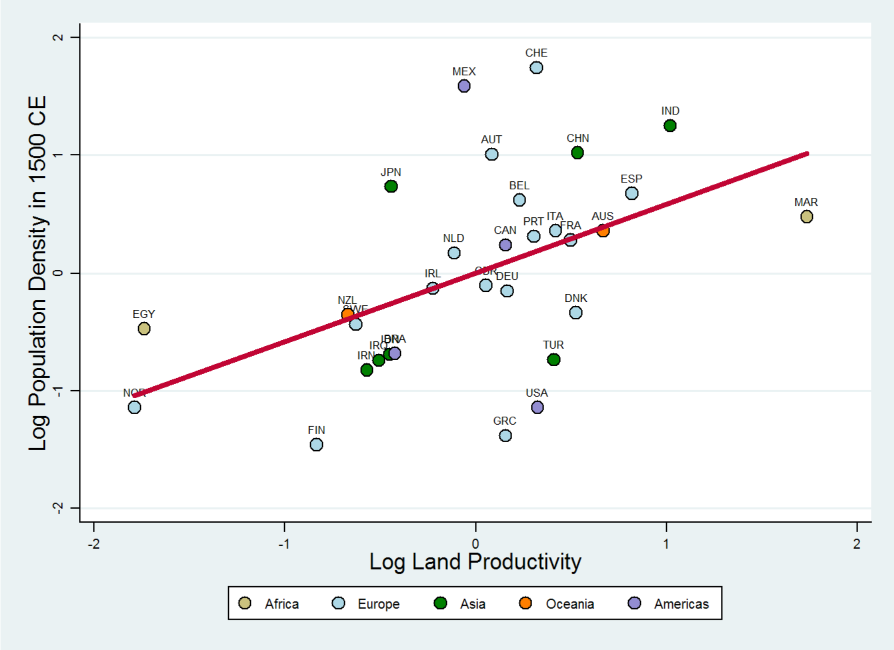
(b) The Partial Effect of Land Productivity on Income Per Capita in 1500 CE

Figure 8: Transition Timing, Land Productivity, and Income Per Capita in 1500 CE

Summary – This figure depicts the partial regression line for the effect of transition timing (land productivity) on income per capita in the year 1500 CE, while controlling for the influence of land productivity (transition timing), absolute latitude, access to waterways, and continental fixed effects. Thus, the x- and y-axes plot the residuals obtained from regressing transition timing (land productivity) and income per capita, respectively, on the aforementioned set of covariates.



(a) The Partial Effect of Transition Timing on Population Density in 1500 CE



(b) The Partial Effect of Land Productivity on Population Density in 1500 CE

Figure 9: Transition Timing, Land Productivity, and Population Density in 1500 CE

Summary – This figure depicts, *using the income per capita data-restricted sample*, the partial regression line for the effect of transition timing (land productivity) on population density in the year 1500 CE, while controlling for the influence of land productivity (transition timing), absolute latitude, access to waterways, and continental fixed effects. Thus, the x- and y-axes plot the residuals obtained from regressing transition timing (land productivity) and population density, respectively, on the aforementioned set of covariates.

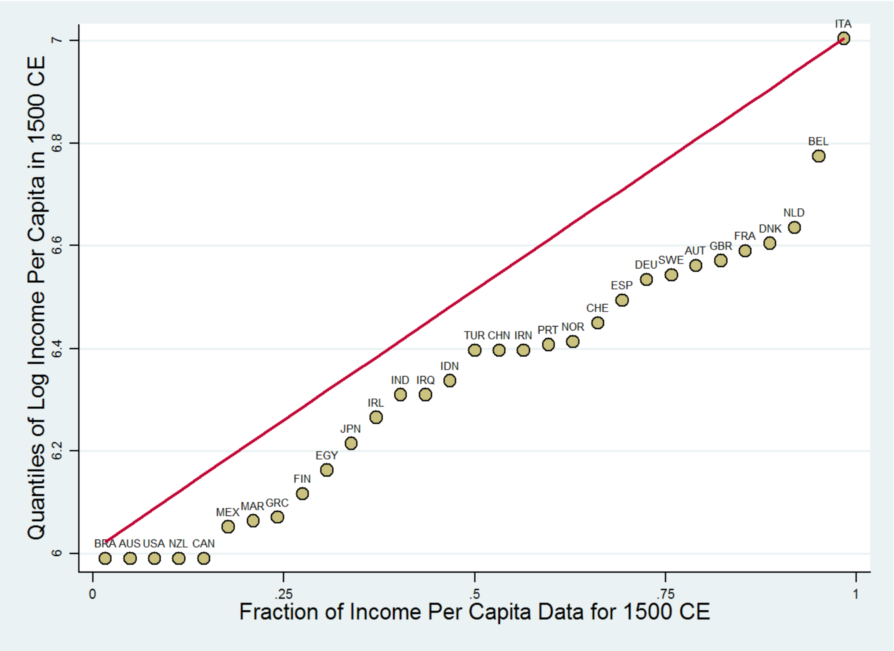


Figure 10: The Cross-Sectional Variability of Income Per Capita in 1500 CE

Summary – This figure depicts the cross-sectional variability of Maddison's (2003) income per capita estimates for the year 1500 CE. The x-axis plots the cumulative fraction of the data corresponding to each observation (in ascending order), and the y-axis plots the quantiles of the uniform distribution of log income per capita in 1500 CE. The closer the observations are to the 45-degree line, the more uniformly distributed is the data and, hence, the larger is the cross-sectional variability.

line indicates a healthy degree of variability across countries, suggesting that the data was not conditioned to conform to a Malthusian view of the world.

Figure 11, which illustrates the intertemporal variability of income per capita over the 1000-1500 CE time horizon, provides further assurance that Maddison's estimates are not tainted by implicit assumptions that make the data unreliable for testing the Malthusian theory. In particular, the departure of the vast majority of observations from the 45-degree line in the figure is at odds with an unconditional Malthusian prior that would otherwise necessitate stagnation in income per capita over time, and hence require a greater proximity of observations to the 45-degree line.

Looking beyond these reassuring characteristics of the data, the current investigation also performs a more rigorous robustness analysis of the baseline results with respect to the aforementioned data quality concerns. In particular, Columns 1-3 in Table 6 reveal the results from estimating the baseline specification for income per capita in the three historical periods, using regressions where each observation is weighted *down* according to the number of observations in the sample reported to possess the same level of income per capita as the observation in question.[28] To the extent that the potential lack of variability in subsets of Maddison's income per data may have biased the baseline results in favor of the Malthusian theory, this methodology alleviates such bias in the regression by reducing the relative importance of clusters of the data where observed variation is lacking.

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[28] The notes to Table 6 provide more formal details on the sample weighting methodologies.

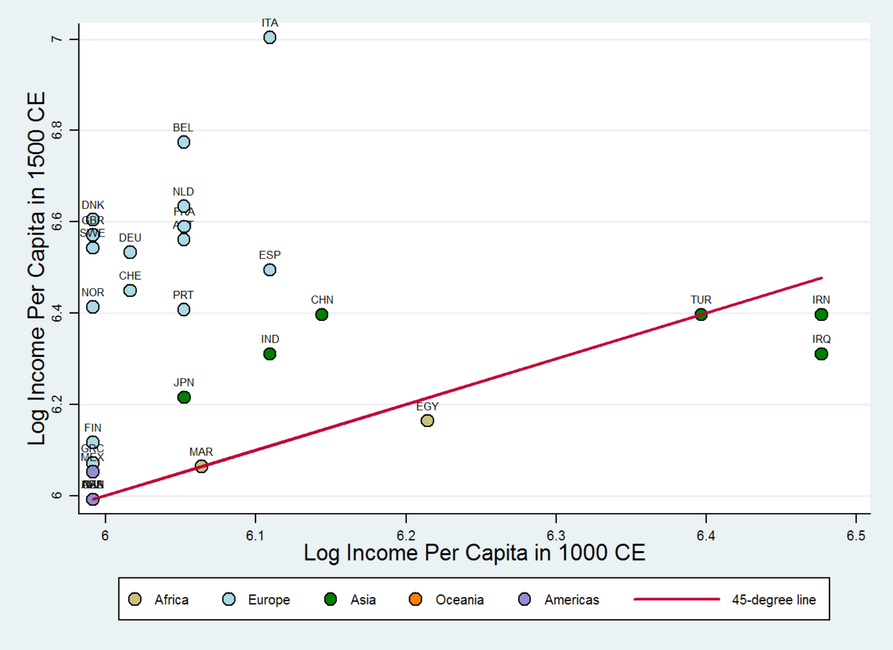


Figure 11: The Intertemporal Variability of Income Per Capita, 1000-1500 CE

Summary – This figure depicts the intertemporal variability of Maddison's (2003) income per capita estimates over the time period 1000-1500 CE. The x- and y-axes plot income per capita in the years 1000 CE and 1500 CE respectively. The farther the observations are from the 45-degree line, the greater is the intertemporal variability.

A comparison of each of the first three columns between Tables 5 and 6 indicates that the baseline results remain both quantitatively and qualitatively robust with respect to the aforementioned weighting procedure. The quantitative robustness of the results are verified by the fact that, despite the statistical significance of some of the effects in the year 1000 CE under the weighted methodology, the transition timing and land productivity channels continue to remain economically non-substantial for income per capita in all three periods, as reflected by coefficients that are still about an order of magnitude smaller than those on population density in the corresponding periods.

Reassuringly, a similar robustness pattern of the baseline results for income per capita is observed with respect to Columns 4-6 of Table 6 where an alternative sample weighting procedure is employed, with individual observations weighted *up* according to their respective population densities. To the extent that the sample variation in income per capita may have been artificially introduced under the premise that technologically advanced societies, as reflected by their higher population densities, also enjoyed *marginally* higher standards of living, this weighting procedure would *a priori* amplify the manifestation of technological differences as differences in income per capita, and thus bias the results against Malthusian predictions. Nevertheless, despite exacerbating any systematic bias in favor of rejecting the theory, the results obtained under this weighting procedure continue to validate the economic insignificance of the land productivity and transition timing channels for income per capita in all three historical periods.

Table 6: Robustness to Income Per Capita Data Quality Concerns

	(1)	(2)	(3)	(4)	(5)	(6)
	Weighted OLS	Weighted OLS	Weighted OLS	Weighted OLS	Weighted OLS	Weighted OLS
	Observations Weighted According to:					
	Income Data Frequency			Total Population Size		
	Dependent Variable is Log Income Per Capita in:					
	1500 CE	1000 CE	1 CE	1500 CE	1000 CE	1 CE
Log Years since Neolithic Transition	0.173 (0.162)	0.122* (0.063)	0.189 (0.121)	0.278 (0.171)	0.143* (0.068)	0.289 (0.175)
Log Land Productivity	0.039 (0.023)	-0.045* (0.022)	0.008 (0.031)	-0.005 (0.026)	-0.062* (0.030)	-0.011 (0.027)
Log Absolute Latitude	-0.042 (0.080)	0.205* (0.108)	-0.442 (0.362)	-0.089 (0.052)	0.298*** (0.031)	0.080 (0.089)
Mean Distance to Nearest Coast or River	0.219 (0.202)	-0.370** (0.148)	0.139 (0.298)	0.332** (0.148)	-0.592*** (0.108)	-0.180 (0.189)
% Land within 100 km of Coast or River	0.153 (0.169)	-0.228 (0.137)	0.159 (0.257)	0.329 (0.227)	-0.477*** (0.122)	0.003 (0.277)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31	26	29	31	26	29
R-squared	0.54	0.79	0.29	0.74	0.83	0.45

Summary – This table demonstrates that the relatively small effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on income per capita in the years 1500 CE, 1000 CE and 1 CE remain robust under two different weighted regression methodologies, designed to dispel concerns regarding the quality of the historical income per capita data series.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the weight of country i in regressions (1)-(3) is *inversely* proportional to the frequency with which i's income per capita occurs in the corresponding samples, i.e., $w_i = n_i^{-1}/\sum_i n_i^{-1}$, where n_i is the number of countries with income per capita identical to i; (iii) the weight of country i in regressions (4)-(6) is *directly* proportional to the population size of i in the corresponding samples, i.e., $w_i = p_i/\sum_i p_i$, where p_i is the size of the population of i; (iv) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (v) regressions (2)-(3) and (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples, restricted by the availability of income per capita data; (vi) robust standard error estimates are reported in parentheses; (vii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

To summarize the main findings of the analysis thus far, the results indicate that more productive societies sustained higher population densities, as opposed to higher standards of living, during the time period 1-1500 CE. These findings are entirely consistent with the Malthusian prediction that in pre-industrial economies, resources temporarily generated by more productive technological environments were ultimately channeled into population growth, with negligible long-run effects of income per capita.

4.4 Technological Sophistication

Table 7 presents the results from estimating the baseline specification for population density and income per capita in the years 1000 CE and 1 CE, employing the index of technological

TABLE 7: Robustness to Direct Measures of Technological Sophistication

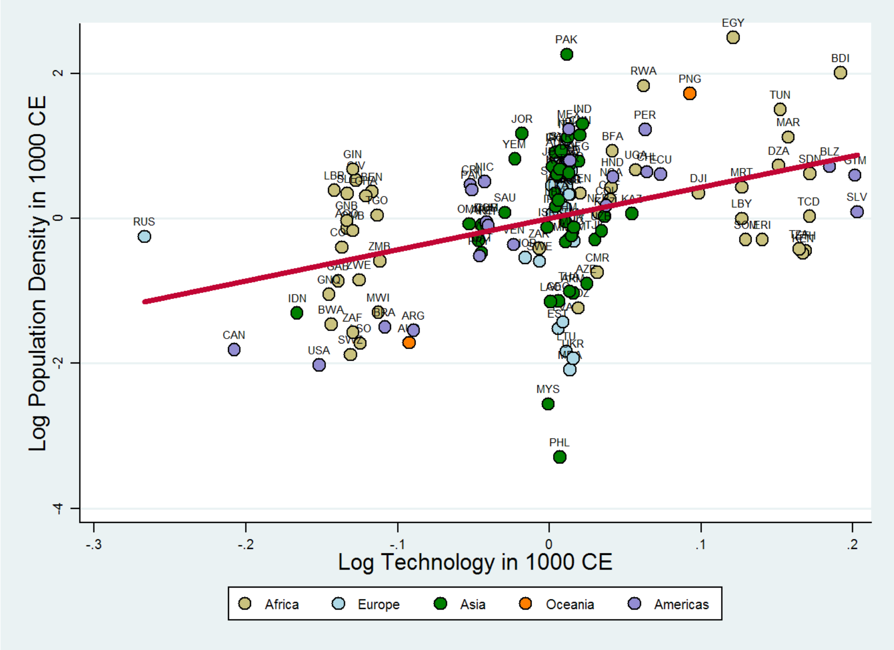
	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Full Sample	Full Sample	Income Sample	Income Sample	Income Sample	Income Sample
	Dependent Variable is:					
	Log Population Density in:		Log Income Per Capita in:		Log Population Density in:	
	1000 CE	1 CE	1000 CE	1 CE	1000 CE	1 CE
Log Technology Index in Relevant Period	4.315***	4.216***	0.064	0.678	12.762***	7.461**
	(0.850)	(0.745)	(0.230)	(0.432)	(0.918)	(3.181)
Log Land Productivity	0.449***	0.379***	-0.016	0.004	0.429**	0.725**
	(0.056)	(0.082)	(0.030)	(0.033)	(0.182)	(0.303)
Log Absolute Latitude	-0.283**	-0.051	0.036	-0.198	-1.919***	-2.350***
	(0.120)	(0.127)	(0.161)	(0.176)	(0.576)	(0.784)
Mean Distance to Nearest Coast or River	-0.638***	-0.782***	-0.092	0.114	0.609	0.886
	(0.188)	(0.198)	(0.144)	(0.164)	(0.469)	(0.904)
% Land within 100 km of Coast or River	0.385	0.237	-0.156	0.092	1.265**	0.788
	(0.313)	(0.329)	(0.139)	(0.136)	(0.555)	(0.934)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140	129	26	29	26	29
R-squared	0.61	0.62	0.64	0.30	0.97	0.88

SUMMARY – This table demonstrates that the relatively small effect of the level of technological advancement on income per capita in the years 1000 CE and 1 CE, but its significantly larger effect on population density in the same time periods, remains qualitatively robust when more direct measures of technological sophistication for the corresponding years are used in lieu of the timing of the Neolithic Revolution.

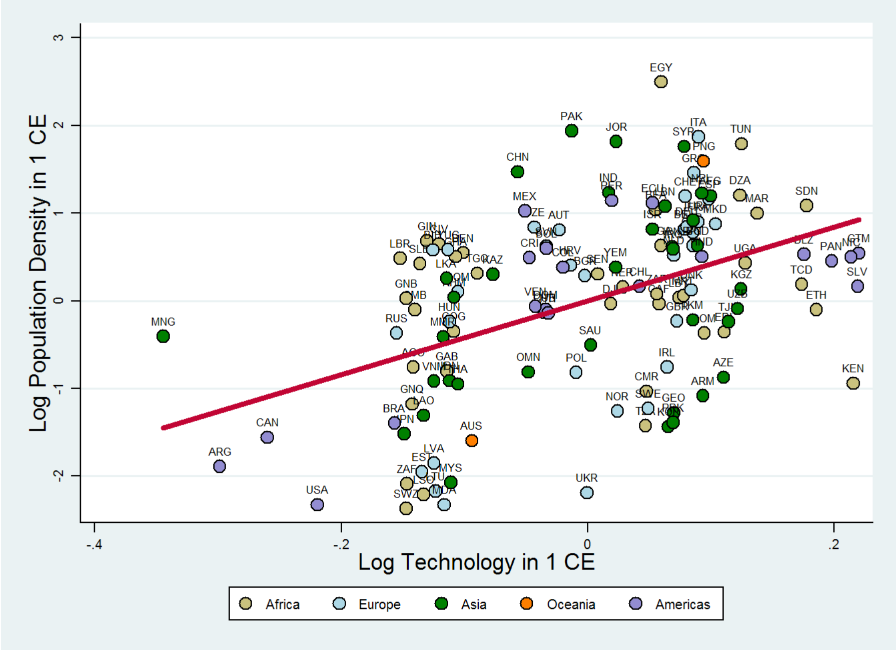
NOTES – (i) the technology index for a given time period reflects the average degree of technological sophistication across communications, transportation, industrial, and agricultural sectors in that period; (ii) the almost perfect collinearity between the degree of technological sophistication in the agricultural sector and the timing of the Neolithic transition does not permit the use of the latter as a covariate in these regressions; (iii) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (iv) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (v) regressions (3)-(6) do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples, restricted by the availability of income per capita data; (vi) robust standard error estimates are reported in parentheses; (vii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

sophistication corresponding to these periods, in lieu of the number of years elapsed since the Neolithic Revolution, as an indicator of the level of aggregate productivity. The purpose of this analysis is to demonstrate the qualitative robustness of earlier findings with regard to the positive effect of technological advancement on population density, but its long-run neutrality for income per capita, during the Malthusian era.

As mentioned previously, the index of technological sophistication in each period is based on cross-cultural, sector-specific technology data from Peregrine (2003), aggregated up to the country level by averaging across sectors and cultures within a country, following the aggregation methodology of Comin et al. (2008). Specifically, the index not only captures the level of technological advancement in communications, transportation, and industry, but



(a) The Partial Effect of Technology on Population Density in 1000 CE



(b) The Partial Effect of Technology on Population Density in 1 CE

Figure 12: Technological Sophistication and Population Density in 1000 CE and 1 CE

Summary – This figure depicts the partial regression lines for the effect of technological sophistication on population density in the years 1000 CE and 1 CE, respectively, while controlling for the influence of land productivity, absolute latitude, access to waterways, and continental fixed effects. Thus, for a given year, the x- and y-axes plot the residuals obtained from regressing the technology index and population density, respectively, for that year on the aforementioned set of covariates.

also incorporates information on the prevalence of sedentary agricultural practices relative to hunting and gathering.[29] Since the timing of the Neolithic transition is *a priori* expected to be highly correlated with the prevalence of agriculture across countries in both 1000 CE and 1 CE, its inclusion as an explanatory variable in the current analysis would constitute the exploitation of redundant information and potentially obfuscate the results of the analysis due to the well-known consequences of multicollinearity. The regressions in Table 7 therefore omit the timing of the Neolithic as an explanatory variable for both population density and income per capita in the two periods examined.[30]

Foreshadowing the qualitative robustness of the findings from previous sections, the logged indices of technology in the years 1000 CE and 1 CE are indeed highly correlated with the logged transition timing variable. For instance, in the full cross-country samples employed by the population density regressions in Section 4.2, the logged Neolithic transition timing variable possesses correlation coefficients of 0.73 and 0.62 with the logged indices of technology in the years 1000 CE and 1 CE respectively. Similarly, in the income per capita data-restricted samples employed in Section 4.3, the corresponding correlation coefficients are 0.82 and 0.74.

Columns 1-2 reveal the full-sample regression results for population density in the years 1000 CE and 1 CE. Consistent with Malthusian predictions, the regressions indicate highly statistically significant positive relationships between technological sophistication and population density in the two time periods. To interpret the coefficients of interest, a 1% increase in the level of technological sophistication in the years 1000 CE and 1 CE corresponds to a rise in population density in the respective time periods by 4.32% and 4.22%, conditional on the productivity of land, geographical factors, and continental fixed effects. The partial regression lines associated with these coefficients are depicted in Figures 12(a) and 12(b) respectively. In addition, Columns 1-2 also indicate that the effects of the land productivity channel on population density remain largely stable in comparison to previous estimates presented in Tables 3-4.

The results from replicating the 1000 CE and 1 CE analyses of Section 4.3, using the period-specific indices of technology as opposed to the timing of the Neolithic, are presented in Columns 3-6. For each time period examined, the regressions for income per capita and population density reveal, exploiting identical variations in explanatory variables, that the positive relationship between the degree of technological sophistication and population density is not only highly statistically significant, but at least an order of magnitude larger than its corresponding relationship with income per capita. Indeed, the correlation between technology and income per capita is not statistically different from zero at conventional levels of significance. A similar pattern also emerges for the effects of land productivity on population density versus income per capita in each period. These findings therefore confirm the Malthusian prior that, in pre-industrial times, variations in the level of technological advancement were ultimately manifested as variations in population density as opposed to variations in the standard of living across regions.

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[29] See Footnote 12 and the appendix for additional details.

[30] Consistent with the symptoms of multicollinearity, the inclusion of the transition timing variable in these regressions results in the coefficients of interest possessing inflated standard errors with relatively minor effects on the coefficient magnitudes themselves.

The remainder of the analysis in this section is concerned with establishing the causal effect of technology on population density in the years 1000 CE and 1 CE. Since the measures of technology employed by the preceding analysis are contemporaneous to population density in the two periods examined, the issue of endogeneity is perhaps more germane in this case than it was when examining the effect of the timing of the Neolithic Revolution on population density under the OLS estimator. In particular, the estimated coefficients associated with the period-specific technology indices in Columns 1-2 of Table 7 may, in part, be capturing reverse causality, due to the potential scale effect of population on technological progress, as well as the latent influence of unobserved country-specific characteristics that are correlated with both technology and population density. To address these issues, the analysis to follow appeals to Diamond's (1997) argument, regarding the Neolithic transition to agriculture as a triggering event for subsequent technological progress, to exploit the exogenous component of cross-country variation in technology during the first millennium CE, as determined by the variation in the prehistoric biogeographic endowments that led to the differential timing of the Neolithic Revolution itself.[31]

The analysis proceeds by first establishing the causal effect of the Neolithic Revolution on subsequent technological progress. Given the high correlation between the prevalence of sedentary agricultural practices in Peregrine's dataset and the timing of the Neolithic transition, the current exercise exploits, for each period examined, an alternative index of technological sophistication that is based only on the levels of technological advancement in communications, transportation, and industry, but otherwise identical in its underlying aggregation methodology to the index employed thus far. This permits a more transparent assessment of the argument that the Neolithic Revolution triggered a cumulative process of development, fueled by the emergence and propagation of a non-food producing class within agricultural societies that enabled sociocultural and technological advancements over and above subsistence activities.

Table 8 presents the results of regressions examining the impact of the timing of the Neolithic Revolution on the level of non-agricultural technological sophistication in the years 1000 CE and 1 CE, while controlling for land productivity, absolute latitude, access to waterways, and continental fixed effects. In line with priors, the regressions in Columns 1 and 4 establish a highly statistically significant positive relationship between the timing of the Neolithic Revolution and the level of non-agricultural technological sophistication in each period, exploiting variation across the full sample of countries. To allow fair comparisons with the results from subsequent IV regressions, Columns 2 and 5 repeat the preceding OLS analyses but on the subsample of countries for which data on the biogeographic instruments for the timing of the Neolithic is available. The results indicate that the OLS coefficients of interest from the preceding full-sample analyses remain robust to this change in the regression sample. Finally, Columns 3 and 6 establish the causal effect of the Neolithic Revolution on the level of non-agricultural technological sophistication in the two time periods, employing the prehistoric availability of domesticable species of plants and animals as instruments

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[31] The potential issue of endogeneity arising from the latent influence of unobserved country fixed effects is also addressed by a first-difference estimation methodology employing data on population density and technological sophistication at two points in time. This strategy is pursued in Section 4.6 below.

Table 8: The Causal Effect of the Neolithic Revolution on Technological Sophistication

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	IV	OLS	OLS	IV
	Full Sample	Restricted Sample	Restricted Sample	Full Sample	Restricted Sample	Restricted Sample
	Dependent Variable is Log Non-Agricultural Technology in:					
	1000 CE			1 CE		
Log Years since Neolithic Transition	0.115***	0.146***	0.279***	0.152***	0.174***	0.339***
	(0.024)	(0.030)	(0.073)	(0.027)	(0.029)	(0.074)
Log Land Productivity	-0.006	-0.012	-0.009	-0.024***	-0.027*	-0.023
	(0.008)	(0.015)	(0.014)	(0.008)	(0.016)	(0.019)
Log Absolute Latitude	0.012	0.000	0.005	0.039**	0.026	0.032
	(0.014)	(0.019)	(0.018)	(0.016)	(0.022)	(0.020)
Mean Distance to Nearest Coast or River	0.008	0.117**	0.129**	0.007	0.050	0.066
	(0.033)	(0.053)	(0.051)	(0.035)	(0.084)	(0.078)
% Land within 100 km of Coast or River	0.024	0.080	0.112*	0.047	0.110	0.149**
	(0.038)	(0.052)	(0.058)	(0.048)	(0.070)	(0.076)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	143	93	93	143	93	93
R-squared	0.76	0.72	0.67	0.59	0.55	0.47
First-stage F-statistic	–	–	13.47	–	–	13.47
Overid. p-value	–	–	0.256	–	–	0.166

Summary – This table presents the causal effect of the timing of the Neolithic Revolution on the level of technology in non-agricultural sectors in the years 1000 CE and 1 CE, while controlling for land productivity, access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) unlike the regular technology index, the index of non-agricultural technology for a given time period reflects the average degree of technological sophistication across only communications, transportation, and industrial sectors in that period; (ii) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (iii) the IV regressions employ the numbers of prehistoric domesticable species of plants and animals as instruments for log transition timing; (iv) the statistic for the first-stage F-test of these instruments is significant at the 1% level; (v) the p-values for the overidentifying restrictions tests correspond to Hansen's J statistic, distributed in both instances as chi-square with one degree of freedom; (vi) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (vii) regressions (2)-(3) and (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the IV data-restricted sample; (viii) robust standard error estimates are reported in parentheses; (ix) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

for the timing of the Neolithic transition. Not surprisingly, as observed with earlier IV regressions, the causal impact of the Neolithic transition is, in each case, larger relative to its impact obtained under the OLS estimator, a pattern that is consistent with measurement error in the transition timing variable and the resultant attenuation bias afflicting OLS coefficient estimates.

In light of the causal link between the timing of the Neolithic transition and the level of technological advancement in the first millennium CE, the analysis may now establish the causal impact of technology on population density in the two time periods examined. This is accomplished by exploiting exogenous variation in the level of technological advancement generated ultimately by differences in prehistoric biogeographic endowments that led to the

Table 9: The Causal Effect of Technological Sophistication on Population Density

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	IV	OLS	OLS	IV
	Full Sample	Restricted Sample	Restricted Sample	Full Sample	Restricted Sample	Restricted Sample
	Dependent Variable is Log Population Density in:					
	1000 CE			1 CE		
Log Technology Index in Relevant Period	4.315*** (0.850)	4.198*** (1.164)	14.530*** (4.437)	4.216*** (0.745)	3.947*** (0.983)	10.798*** (2.857)
Log Land Productivity	0.449*** (0.056)	0.498*** (0.139)	0.572*** (0.148)	0.379*** (0.082)	0.350** (0.172)	0.464** (0.182)
Log Absolute Latitude	-0.283** (0.120)	-0.185 (0.151)	-0.209 (0.209)	-0.051 (0.127)	0.083 (0.170)	-0.052 (0.214)
Mean Distance to Nearest Coast or River	-0.638*** (0.188)	-0.363 (0.426)	-1.155* (0.640)	-0.782*** (0.198)	-0.625 (0.434)	-0.616 (0.834)
% Land within 100 km of Coast or River	0.385 (0.313)	0.442 (0.422)	0.153 (0.606)	0.237 (0.329)	0.146 (0.424)	-0.172 (0.642)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140	92	92	129	83	83
R-squared	0.61	0.55	0.13	0.62	0.58	0.32
First-stage F-statistic	–	–	12.52	–	–	12.00
Overid. p-value	–	–	0.941	–	–	0.160

Summary – This table presents the causal effect of direct measures of technological sophistication in the years 1000 CE and 1 CE, as determined by exogenous factors governing the timing of the Neolithic Revolution, on population density in the same time periods, while controlling for land productivity, access to navigable waterways, absolute latitude, and unobserved continental fixed effects.

Notes – (i) the technology index for a given time period reflects the average degree of technological sophistication across communications, transportation, industrial, and agricultural sectors in that period; (ii) the almost perfect collinearity between the degree of technological sophistication in the agricultural sector and the timing of the Neolithic transition does not permit the use of the latter as a covariate in these regressions; (iii) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (iv) the IV regressions employ the numbers of prehistoric domesticable species of plants and animals as instruments for the log of the technology index in each of the two periods; (v) in both cases, the statistic for the first-stage F-test of these instruments is significant at the 1% level; (vi) the p-values for the overidentifying restrictions tests correspond to Hansen's J statistic, distributed in both instances as chi-square with one degree of freedom; (vii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (viii) regressions (2)-(3) and (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the IV data-restricted sample; (ix) robust standard error estimates are reported in parentheses; (x) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

differential timing of the transition to agriculture across countries. Table 9 reveals the results of this exercise where, as in Table 7, the measure of technology employed is the overall index that incorporates information on the prevalence of sedentary agriculture along with the level of advancement in non-agricultural technologies.

To facilitate comparisons of results obtained under the OLS and IV estimators, the full-sample OLS results from Table 7 for the years 1000 CE and 1 CE are again presented in Columns 1 and 4 of Table 9, while Columns 2 and 5 present the same regressions conducted on the IV-restricted subsample of countries. The causal effects of the level of technological advancement in the years 1000 CE and 1 CE, instrumented by the prehistoric availability of domesticable plant and animal species, on population density in the corresponding periods are revealed in Columns 3 and 6. The estimated IV coefficients indicate a much larger causal impact of technology on population density, with a 1% increase in the level of technological sophistication in 1000 CE and 1 CE raising population density in the respective time periods by 14.53% and 10.80%, conditional on the productivity of land, absolute latitude, access to waterways, and continental fixed effects. Thus, in line with the predictions of the Malthusian theory, the results indicate that, during the agricultural stage of development, temporary gains due to improvements in the technological environment were indeed channeled into population growth, thereby leading technologically more advanced societies to sustain higher population densities.

4.5 Robustness to Technology Diffusion and Geographic Factors

The technology diffusion hypothesis suggests that spatial proximity to societies at the world technology frontier confers a beneficial effect on development by facilitating the diffusion of new technologies from the frontier through trade as well as sociocultural and geopolitical influences. In particular, the diffusion channel implies that, *ceteris paribus*, the greater the geographic distance from the technological "leaders" in a given period, the lower the level of economic development amongst the "followers" in that period. This section establishes the robustness of the results for population density and income per capita in the year 1500 CE with respect to the spatial influence of technological frontiers, as well as other geographic factors such as climate and small island and landlocked dummies, all of which may have had an affect on aggregate productivity either directly, by affecting the productivity of land, or indirectly, by affecting the prevalence of trade and technology diffusion.

To account for the technology diffusion channel, the current analysis employs as a control variable the great-circle distance from the capital city of a country to the closest of eight worldwide regional technological frontiers. These centers of technology diffusion are derived by Ashraf and Galor (2009), who employ historical urbanization estimates provided by Chandler (1987) and Modelski (2003) to identify frontiers based on the size of urban populations. Specifically, for a given time period, their procedure selects from each continent the two largest cities in that period, belonging to distinct sociopolitical entities. Thus, the set of regional technological frontiers identified for the year 1500 CE comprises London and Paris in Europe, Fez and Cairo in Africa, Constantinople and Peking in Asia, and Tenochtitlan and Cuzco in the Americas.

Column 1 of Table 10 reveals the qualitative robustness of the full-sample regression results for population density in the year 1500 CE under controls for distance to the closest regional frontier as well as small island and landlocked dummies. To the extent that the gains from trade and technology diffusion are manifested primarily in terms of population size, as the Malthusian theory would predict, distance to the frontier has a highly statistically significant negative impact on population density. Nevertheless, the regression coefficients associated with the Neolithic transition timing and land productivity channels remain largely stable, albeit somewhat less so for the former, in comparison to their baseline estimates from Column 4 in Table 2. Indeed, the lower magnitude of the coefficient associated with

Table 10: Additional Robustness Checks

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Full Sample	Full Sample	Income Sample	Income Sample	Income Sample	Income Sample
	Dependent Variable is:					
	Log Population Density in 1500 CE		Log Income Per Capita in 1500 CE		Log Population Density in 1500 CE	
Log Years since Neolithic Transition	0.828***	0.877***	0.117	0.103	1.498**	1.478**
	(0.208)	(0.214)	(0.221)	(0.214)	(0.546)	(0.556)
Log Land Productivity	0.559***	0.545***	0.036	0.047	0.596***	0.691***
	(0.048)	(0.063)	(0.032)	(0.037)	(0.123)	(0.122)
Log Absolute Latitude	-0.400***	-0.301**	-0.020	0.028	-0.354	0.668
	(0.108)	(0.129)	(0.110)	(0.247)	(0.392)	(0.783)
Mean Distance to Nearest Coast or River	-0.403***	-0.388***	0.175	0.202	0.394	0.594
	(0.152)	(0.144)	(0.286)	(0.309)	(0.994)	(0.844)
% Land within 100 km of Coast or River	0.870***	0.837***	0.160	0.245	1.766***	2.491***
	(0.272)	(0.280)	(0.153)	(0.208)	(0.511)	(0.754)
Log Distance to Frontier	-0.186***	-0.191***	-0.005	-0.001	-0.130*	-0.108*
	(0.035)	(0.036)	(0.011)	(0.013)	(0.066)	(0.055)
Small Island Dummy	0.067	0.086	-0.118	-0.046	1.962**	2.720***
	(0.582)	(0.626)	(0.216)	(0.198)	(0.709)	(0.699)
Landlocked Dummy	0.131	0.119	0.056	0.024	1.490***	1.269***
	(0.209)	(0.203)	(0.084)	(0.101)	(0.293)	(0.282)
% Land in Temperate Climate Zones		-0.196		-0.192		-1.624*
		(0.513)		(0.180)		(0.917)
% Land in (Sub)Tropical Climate Zones		0.269		-0.025		1.153
		(0.307)		(0.308)		(1.288)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	147	147	31	31	31	31
R-squared	0.76	0.76	0.67	0.67	0.94	0.96

Summary – This table demonstrates that the relatively small effects of land productivity and the level of technological advancement, as proxied by the timing of the Neolithic Revolution, on income per capita in the years 1500 CE, 1000 CE and 1 CE, but their significantly larger effects on population density in the same time periods, remain robust under additional controls for technology diffusion and climatic factors.

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (iii) robust standard error estimates are reported in parentheses; (iv) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

the transition timing channel is attributable to the fact that several frontiers in the year 1500 CE, including Egypt, China, and Mexico, were also centers of diffusion of agricultural practices during the Neolithic Revolution and, as such, distance to the frontier in 1500 CE is partly capturing the effect of the differential timing of the Neolithic itself.

The regression in Column 2 extends the robustness analysis of Column 1 by adding controls for the percentage of land in temperate and tropical zones. The findings demonstrate that the effects of the Neolithic transition timing, land productivity, and spatial technology diffusion channels on population density are indeed not spuriously driven by these additional climatological factors.

Columns 3-6 reveal the robustness of the results for income per capita as well as population density in the income per capita data-restricted sample, under controls for the technology diffusion channel and additional geographic factors. In comparison to the relevant baseline regressions presented in Columns 1 and 4 of Table 5, the coefficients associated with the transition timing and land productivity channels remain both qualitatively and quantitatively stable, with the effects of these channels on population density being about an order of magnitude larger than their effects on income per capita, regardless of the set of additional controls included in the specification.

With regard to the influence of technology diffusion, the qualitative pattern of the effects on population density versus income per capita is similar to those associated with the transition timing and land productivity channels. The finding that the detrimental effect of distance to the frontier on income per capita is not only statistically insignificant but also at least an order of magnitude smaller than that on population density confirms Malthusian priors that the gains from trade and technology diffusion were primarily channeled into population growth rather than to improvements in living standards during pre-industrial times.[32] While this finding may also be consistent with a non-Malthusian migration-driven theory of population movements against a spatial productivity gradient, the results uncovered by the first-difference estimation strategy pursued in the next section provide evidence in favor of the proposed Malthusian interpretation.

4.6 Robustness to Alternative Theories and Country Fixed Effects

This section examines the robustness of the empirical findings to alternative theories and time-invariant country fixed effects. Specifically, the level regression results may be explained by the following non-Malthusian theory. In a world where labor is perfectly mobile, regions with higher aggregate productivity would experience labor inflows until regional wage rates were equalized, implying that, in levels, technology should be positively associated with population density but should not be correlated with income per capita across regions. Such a theory would also imply, however, that increases in the level of technology in any given region should generate increases in the standard of living in all regions. This runs contrary to the Malthusian prediction that increases in the level of technology in a given region should ultimately translate into increases in population density in that region, leaving income per capita constant at the subsistence level in all regions. Thus, examining the effect of changes on changes, as opposed to levels on levels, constitutes a more discriminatory test of the Malthusian model.

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[32] Galor and Mountford (2008) reveal similar findings amongst non-OECD countries in the period spanning 1985-90, indicating that this phenomenon is more broadly associated with economies in the agricultural stage of development, even in the contemporary period.

Moreover, the results of the level regressions in Table 7, indicating the significant positive effect of the level of technology on population density but its neutrality for income per capita, could potentially reflect spurious correlations between technology and one or more unobserved time-invariant country fixed effects. By investigating the effect of changes on changes, however, one may "difference out" time-invariant country fixed effects, thereby ensuring that the coefficients of interest in the regression will not be afflicted by any such omitted variable bias.

The current investigation examines the effect of the change in the level of technology between the years 1 CE and 1000 CE on the change in population density, versus its effect on the change in income per capita, over the same time horizon.[33] In particular, the analysis compares the results from estimating the following empirical models:

$$\begin{aligned} \Delta \ln P_{i,t} &= \mu_0 + \mu_1 \Delta \ln A_{i,t} + \phi_{i,t}, && (17) \\ \Delta \ln y_{i,t} &= \nu_0 + \nu_1 \Delta \ln A_{i,t} + \psi_{i,t}, && (18) \end{aligned}$$

where $\Delta \ln P_{i,t} \equiv \ln P_{i,t+\tau} - \ln P_{i,t}$ (i.e., the difference in log population density in country i between 1000 CE and 1 CE); $\Delta \ln y_{i,t} \equiv \ln y_{i,t+\tau} - \ln y_{i,t}$ (i.e., the difference in log income per capita of country i between 1000 CE and 1 CE); $\Delta \ln A_{i,t} \equiv \ln A_{i,t+\tau} - \ln A_{i,t}$ (i.e., the difference in log technology of country i between 1000 CE and 1 CE); and, $\phi_{i,t}$ and $\psi_{i,t}$ are country-specific disturbance terms for the changes in log population density and log income per capita. In addition, the intercept terms, μ_0 and ν_0, capture the average trend growth rates of population density and income per capita respectively. These models are simply the first-difference counterparts of (15) and (16) when $\ln A_{i,t}$ is used in lieu of $\ln T_i$ in those specifications.

As discussed earlier, the alternative migration-driven theory predicts that an increase in technology in a given region will not differentially increase income per capita in that region due to the cross-regional equalization of wage rates, but will increase income per capita in all regions. In light of the specifications defined above, this theory would therefore imply that $\nu_1 = 0$ and $\nu_0 > 0$. According to the Malthusian theory, on the other hand, not only will the long-run level of income per capita remain unaffected in the region undergoing technological advancement, it will indeed remain unaffected in all regions as well. The Malthusian theory thus implies that both $\nu_1 = 0$ and $\nu_0 = 0$.

Table 11 presents the results from estimating equations (17) and (18). As predicted by the Malthusian theory, the change in the level of technology between the years 1 CE and 1000 CE has a positive and highly statistically significant effect on the change in population density, but a relatively marginal and statistically insignificant effect on the change in income per capita, over the same time horizon. Indeed, the slope coefficients indicate that the effect on the change in population density between 1 CE and 1000 CE is about an order of magnitude larger than the effect on the change in income per capita. Moreover, the intercept coefficients reveal that, while there may have been some trend growth in population during the time period 1-1000 CE, the standard of living in 1000 CE was not significantly different from that in 1 CE, a finding that accords well with the Malthusian viewpoint. Overall, the

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[33] Due to the unavailability of an index of technological sophistication for the year 1500 CE, it is infeasible to conduct a similar analysis using differences between the years 1000 CE and 1500 CE.

Table 11: Robustness to First Differences

	(1)	(2)
	OLS	OLS
	Dependent Variable is: Differences between 1000 CE and 1 CE in	
	Log Population Density	Log Income Per Capita
Diff. in Log Technology Index between 1 CE and 1000 CE	6.458***	0.522
	(1.771)	(0.573)
Constant	0.216*	-0.045
	(0.110)	(0.036)
Observations	26	26
R-squared	0.36	0.03

Summary – This table establishes that the change in the level of technological sophistication that occurred between the years 1 CE and 1000 CE was reflected primarily as a change in population density as opposed to a change in income per capita over the same time horizon, and also reveals that there was no trend growth in income per capita during this period, thereby dispelling an alternative migration-driven theory that is consistent with the level regression results and demonstrating robustness to country fixed effects.

Notes – (i) the technology index for a given time period reflects the average degree of technological sophistication across communications, transportation, industrial, and agricultural sectors in that period; (ii) the absence of controls from both regressions is justified by the removal of country fixed effects through the application of the first difference methodology; (iii) robust standard error estimates are reported in parentheses; (iv) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

results from the first-difference estimation strategy lend further credence to the Malthusian interpretation of the level regression results presented earlier.

5 Concluding Remarks

This research conducts the first cross-country empirical examination of the predictions of the influential Malthusian theory regarding population density and income per capita in the pre-industrial era of human history. The theory suggests that, improvements in the technological environment or in the availability of land generated only temporary gains in income per capita, eventually leading to a larger, but not richer, population. Thus, during the pre-industrial Malthusian epoch, technologically superior economies ultimately sustained higher population densities but their standard of living did not reflect the degree of their technological advancement.

The current analysis examines the fundamental Malthusian implications, including the hypothesis that population density was ultimately constrained by the availability of *natural* resources, but income per capita was largely independent of it, and the conjecture that technological progress, by expanding *effective* resources, enhanced population density but left income per capita relatively unaffected in the long run. Specifically, since resource constraints were slacker for regions with higher land productivity, they would have supported larger populations, given their technological advancement. On the other hand, conditional on the productivity of land, societies that were more advanced technologically would have sustained higher population densities. However, technologically superior societies, or those that were naturally blessed with a higher productivity of land, would not have enjoyed better living standards.

The Malthusian theory predicts that regional variation in population density in the long run would ultimately reflect regional variations in technological levels, land productivity and biogeographic factors. These variations in the level of technological advancement, land productivity and biogeographic attributes, however, would not be manifested as significant differences in income per capita across regions. Thus, for a given level of technology, greater land productivity, such as higher arable percentage of land, better soil quality, and favorable climatic conditions, would permit society to support a larger, but not richer, population in the long run. Further, for a given land productivity, auspicious biogeographic factors, such as proximity to waterways, absolute latitude, and a greater availability of domesticable plant and animal species, would enhance population density, by augmenting the gains from trade and the implementation and diffusion of agricultural technologies, but would not affect the standard of living. Moreover, conditional on land productivity and biogeographic factors, a higher level of technology would permit society to sustain a larger population, leaving income per capita largely unaffected in the long run.

To test the Malthusian theory empirically, this research exploits exogenous sources of cross-country variation in land productivity and technological levels to explain cross-country variation in either population density or income per capita in the years 1500 CE, 1000 CE and 1 CE. This permits the analysis to examine the *differential* effects of land productivity and technological levels on population density versus income per capita, as hypothesized by the Malthusian theory.

The conceptualization of the Neolithic transition to agriculture as a triggering event for subsequent technological advancement permits the empirical analysis to surmount the problem of endogeneity arising from the potential Boserupian effect of population size on technological progress. Specifically, the analysis employs the number of years elapsed since the Neolithic Revolution as an exogenous source of variation in the level of technological advancement during the time period 1-1500 CE. Moreover, to address the possibility that the relationship between the timing of the Neolithic transition and population density may itself be spurious, the analysis appeals to the role of prehistoric biogeographic factors in determining the timing of the Neolithic Revolution, adopting the numbers of prehistoric domesticable species of wild plants and animals as instrumental variables in establishing the causal effect of the level of technological advancement on population density during the 1-1500 CE time horizon.

Consistent with Malthusian predictions, statistically significant positive effects of land productivity and an earlier onset of the Neolithic Revolution are uncovered for population density in the years 1500 CE, 1000 CE and 1 CE. In contrast, the effects of land productivity and the timing of the Neolithic Revolution on income per capita in the corresponding periods are indeed not significantly different from zero, being about an order of magnitude smaller than their effects on population density. These results are shown to remain robust to controls for other geographical factors, including absolute latitude, access to waterways, distance to the technological frontier, the share of land in tropical versus temperate climatic zones, and small island and landlocked dummies, all of which may have had an impact on aggregate productivity either directly, by affecting the productivity of land, or indirectly by affecting trade and the diffusion of technologies. In addition, the results are qualitatively unaffected when a more direct measure of historical technological sophistication, rather than the timing of the Neolithic Revolution, is employed as an indicator of the level of aggregate productivity in pre-industrial times.

The analysis also dispels a non-Malthusian theory that may appear consistent with the level regression results. Specifically, in a world with perfect labor mobility, regions with higher aggregate productivity would have experienced labor inflows until regional wage rates were equalized, implying that, in levels, technology should be positively associated with population density but should not be correlated with income per capita. However, labor inflows in response to technological improvements in a given region, would result in higher income per capita in all regions, implying that changes in the level of technology should be positively associated with changes in the standard of living. On the contrary, using a first difference estimation strategy, the analysis demonstrates that, while changes in the level of technology between 1 CE and 1000 CE were indeed translated into changes in population density, the level of income per capita across regions was, in fact, unaffected by technological improvements during this period, as suggested by the Malthusian theory.

Appendix A Variable Definitions and Sources

Population Density in 1 CE, 1000 CE, and 1500 CE: Population density in a given year is calculated as population in that year, as reported by McEvedy and Jones (1978), divided by land area today, as reported by the World Bank's *World Development Indicators*. The cross-sectional unit of observation in McEvedy and Jones' dataset is a region delineated by its international borders in 1975. Historical population estimates are provided for regions corresponding to either individual countries or, in some cases, to sets comprised of 2-3 neighboring countries (e.g., India, Pakistan and Bangladesh). In the latter case, a set-specific population density figure is calculated based on total land area and the figure is then assigned to each of the component countries in the set. The same methodology is also employed to obtain population density for countries that exist today but were part of a larger political unit (e.g., the former Yugoslavia) in 1975. The population data reported by the authors is based on a wide variety of country and region-specific historical sources, the enumeration of which would be impractical for this appendix. The interested reader is therefore referred to McEvedy and Jones (1978) for more details on the original data sources cited therein.

Income Per Capita in 1 CE, 1000 CE, and 1500 CE: The level of income per capita, as reported by Maddison (2003), for a given year. Additional details are available on the author's website. The interested reader is also referred to www.ggdc.net/maddison/other%5Fbooks/HS-8%5F2003.pdf for a discussion of the data by the author.

Years since Neolithic Transition: The number of thousand years elapsed, till the year 2000, since the majority of the population residing within a country's modern national borders began practicing sedentary agriculture as the primary mode of subsistence. This data, reported by Putterman (2008), is compiled using a wide variety of both regional and country-specific archaeological studies as well as more general encyclopedic works on the transition from hunting and gathering to agriculture during the Neolithic. The reader is referred to www.econ.brown.edu/fac/Louis%5FPutterman/agricultural%20data%20page.htm for a detailed description of the primary and secondary data sources employed by the author in the construction of this variable.

Plants and Animals (used as instrumental variables): The number of domesticable species of plants and animals, respectively, that were prehistorically native to the continent or landmass to which a country belongs. These variables are obtained from the dataset of Olsson and Hibbs (2005).

Land Productivity: This measure is composed of (1) the arable percentage of land, as reported by the *World Development Indicators*, and (2) an index of the suitability of land for agriculture, based on geospatial soil pH and temperature data, as reported by Ramankutty et al. (2002) and aggregated to the country level by Michalopoulos (2008). In particular, log land productivity is the first principal component of the logs of these variables, capturing 83% of their combined variation.

Absolute Latitude: The absolute value of the latitude of a country's centroid, as reported by the CIA's *World Factbook* online resource.

Mean Distance to Nearest Coast or River: The distance, in thousands of kilometers, from a GIS grid cell to the nearest ice-free coastline or sea-navigable river, averaged across the grid cells located within a country. This variable is obtained from the CID's Research Datasets on *General Measures of Geography* that are available online at http://www.cid.harvard.edu/ciddata/geographydata.htm.

% Land within 100 km of Coast or River: The percentage of a country's total land area that is located within 100 kilometers of an ice-free coastline or sea-navigable river, as reported by the CID's Research Datasets on *General Measures of Geography.*

Technology Index in 1 CE and 1000 CE: The index of technology for a given year is constructed using worldwide historical cross-cultural data on sector-specific levels of technology, reported on a 3-point scale by the *Atlas of Cultural Evolution* (Peregrine, 2003). Following the aggregation methodology adopted by Comin et al. (2008), the index employs technology data on four sectors, including communications, industry (i.e., ceramics and metallurgy), transportation, and agriculture.

The level of technology in each sector is indexed as follows. In the communications sector, the index is assigned a value of 0 under the absence of both true writing and mnemonic or non-written records, a value of 1 under the presence of only mnemonic or non-written records, and a value of 2 under the presence of both. In the industrial sector, the index is assigned a value of 0 under the absence of both metalworks and pottery, a value of 1 under the presence of only pottery, and a value of 2 under the presence of both. In the transportation sector, the index is assigned a value of 0 under the absence of both vehicles and pack or draft animals, a value of 1 under the presence of only pack or draft animals, and a value of 2 under the presence of both. Finally, in the agricultural sector, the index is assigned a value of 0 under the absence of sedentary agriculture, a value of 1 when agriculture is practiced but only as a secondary mode of subsistence, and a value of 2 when agriculture is practiced as the primary mode of subsistence. In all cases, the sector-specific indices are normalized to assume values in the $[0, 1]$-interval. The technology index for a given culture is thus the unweighted average across sectors of the sector-specific indices for that culture.

Given that the cross-sectional unit of observation in Peregrine's dataset is an archaeological tradition or culture, specific to a given region on the global map, and since spatial delineations in Peregrine's dataset do not necessarily correspond to contemporary international borders, the culture-specific technology index in a given year is aggregated to the country level by averaging across those cultures from Peregrine's map that appear within the modern borders of a given country. For more details on the underlying data and the aggregation methodology employed to construct this index, the reader is referred to Peregrine (2003) and Comin et al. (2008).

Non-agricultural Technology Index in 1 CE and 1000 CE: The index of non-agricultural technology for a given year is based on the same underlying data and aggregation methodology discussed above for the overall technology index. However, unlike the overall index, the non-agricultural counterpart incorporates data on the sector-specific technology indices for only the communications, industrial (i.e., ceramics and metallurgy), and transportation sectors.

Distance to Frontier in 1500 CE: The distance, in thousands of kilometers, from a country's modern capital city to the closest regional technological frontier in the year 1500 CE, as reported by Ashraf and Galor (2009). Specifically, the authors employ historical urbanization estimates from Chandler (1987) and Modelski (2003) to identify frontiers based on the size of urban populations, selecting the two largest cities from each continent that belong to different sociopolitical entities. Thus, in the year 1500 CE, the set of regional frontiers comprises London (UK), Paris (France), Cairo (Egypt), Fez (Morocco), Constantinople (Turkey), Peking (China), Tenochtitlan (Mexico), and Cuzco (Peru). For additional details, the reader is referred to Ashraf and Galor (2009).

% Land in Temperate Climate Zones: The percentage of a country's total land area in Köppen-Geiger temperate zones (including zones classified as Cf, Cs, Df, and Dw), as reported by the CID's Research Datasets on *General Measures of Geography.*

% Land in Tropical and Subtropical Climate Zones: The percentage of a country's total land area in Köppen-Geiger tropical and subtropical zones (including zones classified as Af, Am, Aw, and Cw), as reported by the CID's Research Datasets on *General Measures of Geography.*

Small Island and Landlocked Dummies: 0/1-indicators for whether or not a country is a small island nation, and whether or not it possesses a coastline. These variables are constructed by the authors based on information reported by the CIA's *World Factbook*.

Appendix B Descriptive Statistics

Table B.1: Descriptive Statistics – Means and Standard Deviations

	Obs.	Mean	S.D.	Min.	Max.
Log Population Density in 1500 CE	184	0.883	1.424	-3.817	4.135
Log Population Density in 1000 CE	177	0.449	1.366	-4.510	3.442
Log Population Density in 1 CE	155	-0.163	1.455	-4.510	3.170
Log Income Per Capita in 1500 CE	31	6.343	0.260	5.991	7.003
Log Income Per Capita in 1000 CE	28	6.084	0.141	5.991	6.477
Log Income Per Capita in 1 CE	30	6.129	0.163	5.991	6.696
Log Years since Neolithic Transition	164	8.313	0.642	5.892	9.259
Log Technology Index in 1000 CE	149	0.573	0.160	0.118	0.693
Log Technology Index in 1 CE	149	0.529	0.163	0.061	0.693
Log Land Productivity	158	0.000	1.293	-4.815	1.657
Log Absolute Latitude	205	2.913	0.967	-0.693	4.277
Mean Distance to Nearest Coast or River	160	0.342	0.471	0.008	2.386
% Land within 100 km of Coast or River	160	0.463	0.375	0.000	1.000
Log Distance to Frontier	207	7.499	1.435	0.000	9.288
% Land in Temperate Climate Zones	160	0.297	0.420	0.000	1.000
% Land in (Sub)Tropical Climate Zones	160	0.364	0.433	0.000	1.000

TABLE B.2: Descriptive Statistics – Pairwise Correlations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Log Population Density in 1500 CE	1.000 (184)														
Log Population Density in 1000 CE	0.965 (177)	1.000 (177)													
Log Population Density in 1 CE	0.881 (155)	0.940 (155)	1.000 (155)												
Log Income Per Capita in 1500 CE	0.726 (31)	0.641 (29)	0.670 (29)	1.000 (31)											
Log Income Per Capita in 1000 CE	0.128 (28)	0.238 (26)	0.253 (26)	0.106 (28)	1.000 (28)										
Log Income Per Capita in 1 CE	0.225 (30)	0.323 (29)	0.453 (29)	0.337 (27)	0.485 (27)	1.000 (30)									
Log Years since Neolithic Transition	0.498 (158)	0.571 (152)	0.638 (135)	0.561 (31)	0.463 (28)	0.415 (30)	1.000 (164)								
Log Technology Index in 1000 CE	0.584 (148)	0.562 (143)	0.565 (131)	0.646 (31)	0.303 (28)	0.329 (30)	0.715 (146)	1.000 (149)							
Log Technology Index in 1 CE	0.495 (148)	0.524 (144)	0.554 (132)	0.635 (30)	0.283 (27)	0.380 (30)	0.597 (146)	0.827 (148)	1.000 (149)						
Log Land Productivity	0.509 (152)	0.433 (147)	0.397 (131)	0.408 (31)	-0.115 (28)	-0.051 (30)	-0.002 (151)	-0.011 (146)	-0.126 (146)	1.000 (158)					
Log Absolute Latitude	0.139 (184)	0.147 (177)	0.347 (155)	0.320 (31)	-0.363 (28)	-0.302 (30)	0.304 (163)	0.325 (149)	0.279 (149)	0.120 (158)	1.000 (205)				
Mean Distance to Nearest Coast or River	-0.302 (157)	-0.326 (152)	-0.358 (136)	-0.387 (31)	0.173 (28)	-0.123 (30)	-0.020 (154)	0.003 (148)	-0.042 (148)	-0.167 (153)	-0.014 (160)	1.000 (160)			
% Land within 100 km of Coast or River	0.367 (157)	0.343 (152)	0.365 (136)	0.452 (31)	-0.417 (28)	0.002 (30)	0.091 (154)	0.086 (148)	0.095 (148)	0.215 (153)	0.212 (160)	-0.670 (160)	1.000 (160)		
Log Distance to Frontier	-0.351 (184)	-0.363 (177)	-0.429 (155)	-0.168 (31)	-0.025 (28)	-0.055 (30)	-0.396 (164)	-0.271 (149)	-0.258 (149)	-0.121 (158)	-0.369 (205)	0.156 (160)	-0.195 (160)	1.000 (207)	
% Land in Temperate Climate Zones	0.355 (157)	0.347 (152)	0.372 (136)	0.420 (31)	-0.544 (28)	-0.188 (30)	0.273 (154)	0.258 (148)	0.168 (148)	0.326 (153)	0.605 (160)	-0.263 (160)	0.422 (160)	-0.327 (160)	1.000 (160)
% Land in (Sub)Tropical Climate Zones	-0.071 (157)	-0.094 (152)	-0.225 (136)	-0.226 (31)	-0.007 (28)	-0.093 (30)	-0.436 (154)	-0.476 (148)	-0.461 (148)	0.160 (153)	-0.710 (160)	-0.136 (160)	0.024 (160)	0.334 (160)	-0.577 (160)

NOTES – Number of observations in parentheses.

Appendix C Supplementary Results

This appendix presents additional findings demonstrating robustness, as well as the first-stage regression results of instrumented transition timing and technological advancement. Specifically, Table C.1 establishes that the results for population density and income per capita in 1500 CE are robust under two alternative specifications that relax potential constraints imposed by the baseline regression models, including (i) the treatment of the Americas as a single entity in accounting for continental fixed effects, and (ii) the employment of only the *common variation* in (the logs of) the arable percentage of land and the index of agricultural suitability when accounting for the effect of the land productivity channel by way of the first principal component of these two variables. Moreover, given that historical population estimates are also available from Maddison (2003), albeit for a smaller set of countries than McEvedy and Jones (1978), Table C.2 demonstrates that the baseline results for population density in the three historical periods, obtained using data from McEvedy and Jones, are indeed qualitatively unchanged under Maddison's alternative population estimates. In addition, given the possibility that the disturbance terms in the baseline regression models may be non-spherical in nature, particularly since economic development has been spatially clustered in certain regions of the world, Tables C.3 and C.4 repeat the baseline analyses for population density and income per capita in the three historical periods, with the standard errors of the point estimates corrected for spatial autocorrelation following the methodology of Conley (1999). Finally, Table C.5 summarizes the first-stage regression results of all IV regressions that employ the numbers of prehistoric domesticable plant and animal species as instruments for the timing of the Neolithic transition or for the level of technological advancement in the first millennium CE.

TABLE C.1: Robustness to Alternative Specifications

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Standard OLS	Standard OLS	Standard OLS	Weighted OLS	Standard OLS	Standard OLS	Standard OLS	Weighted OLS
	Full Sample	Income Sample	Income Sample	Income Sample	Full Sample	Income Sample	Income Sample	Income Sample
	Alternative Specification Includes:							
	Both North and South America Dummies				Both Components of Land Productivity			
	Dependent Variable is:							
	Log Population Density in 1500 CE		Log Income Per Capita in 1500 CE		Log Population Density in 1500 CE		Log Income Per Capita in 1500 CE	
Log Years since Neolithic Transition	1.169***	1.390**	0.160	0.174	1.079***	1.536**	0.145	0.151
	(0.183)	(0.649)	(0.143)	(0.166)	(0.183)	(0.596)	(0.163)	(0.208)
Log Land Productivity	0.562***	0.562***	0.040	0.039				
	(0.052)	(0.157)	(0.025)	(0.023)				
Log Absolute Latitude	-0.341***	-0.091	-0.045	-0.043	-0.325***	0.124	-0.046	-0.046
	(0.104)	(0.554)	(0.086)	(0.084)	(0.108)	(0.423)	(0.067)	(0.071)
Mean Distance to Nearest Coast or River	-0.477***	-0.501	0.213	0.219	-0.390***	-0.248	0.203	0.187
	(0.142)	(1.300)	(0.198)	(0.206)	(0.142)	(1.102)	(0.226)	(0.267)
% Land within 100 km of Coast or River	0.703**	1.803*	0.122	0.153	0.900***	1.693**	0.135	0.153
	(0.302)	(0.865)	(0.147)	(0.173)	(0.284)	(0.723)	(0.135)	(0.178)
Log Arable % of Land					0.343***	-0.315	0.064	0.079
					(0.095)	(0.504)	(0.085)	(0.117)
Log Suitability Index for Agriculture					0.270***	0.736*	-0.008	-0.017
					(0.086)	(0.356)	(0.067)	(0.084)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	147	31	31	31	147	31	31	31
R-squared	0.74	0.89	0.66	0.54	0.73	0.90	0.66	0.54

NOTES – (i) log land productivity in regressions (1)-(4) is the first principal component of the log of the arable percentage of land and the log of the agricultural suitability index that are used in regressions (5)-(8); (ii) the weight of country i in regressions (4) and (8) is *inversely* proportional to the frequency with which i's income per capita occurs in the corresponding samples, i.e., $w_i = n_i^{-1} / \sum_i n_i^{-1}$, where n_i is the number of countries with income per capita identical to i; (iii) a single continent dummy is used to represent the Americas in regressions (5)-(8); (iv) robust standard error estimates are reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table C.2: Robustness to Population Data from Maddison's Historical Statistics

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Full Sample	Income Sample	Full Sample	Income Sample	Full Sample	Income Sample
	Dependent Variable is Log Population Density based on Maddison's Estimates for:					
	1500 CE		1000 CE		1 CE	
Log Years since Neolithic Transition	1.190*** (0.287)	0.984* (0.498)	1.845*** (0.360)	0.809*** (0.273)	1.865*** (0.576)	0.824*** (0.277)
Log Land Productivity	0.481*** (0.115)	0.625*** (0.184)	0.489*** (0.137)	0.348*** (0.104)	0.474*** (0.163)	0.582** (0.219)
Log Absolute Latitude	-0.102 (0.293)	0.109 (0.401)	0.012 (0.297)	-1.838** (0.635)	0.092 (0.265)	-2.207*** (0.638)
Mean Distance to Nearest Coast or River	-0.983* (0.551)	-0.844 (1.066)	-0.941* (0.535)	-0.616 (0.606)	-1.128 (0.707)	-0.501 (0.601)
% Land within 100 km of Coast or River	1.546** (0.583)	1.492** (0.688)	0.954 (0.725)	1.446** (0.630)	1.182 (0.773)	1.119 (0.733)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	48	31	47	26	43	29
R-squared	0.85	0.88	0.84	0.95	0.81	0.92

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (iii) regressions (4)-(6) do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples; (iv) robust standard error estimates are reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

TABLE C.3: Robustness to Corrections for Spatial Autocorrelation

	(1)	(2)	(3)	(4)	(5)	(6)
	Corrected OLS	Spatial GMM	Corrected OLS	Spatial GMM	Corrected OLS	Spatial GMM
	Full Sample	Restricted Sample	Full Sample	Restricted Sample	Full Sample	Restricted Sample
	Dependent Variable is Log Population Density in:					
	1500 CE		1000 CE		1 CE	
Log Years since Neolithic Transition	1.087***	2.038***	1.480***	2.713***	1.930***	3.322***
	[0.184]	[0.387]	[0.213]	[0.498]	[0.316]	[0.404]
Log Land Productivity	0.576***	0.583***	0.497***	0.575***	0.394***	0.448***
	[0.053]	[0.092]	[0.066]	[0.095]	[0.076]	[0.093]
Log Absolute Latitude	-0.314***	-0.257*	-0.229*	-0.117	0.057	0.124
	[0.108]	[0.141]	[0.123]	[0.138]	[0.101]	[0.115]
Mean Distance to Nearest Coast or River	-0.392**	0.318	-0.528**	0.373	-0.685***	-0.423
	[0.195]	[0.351]	[0.207]	[0.370]	[0.168]	[0.294]
% Land within 100 km of Coast or River	0.899***	1.395***	0.716**	1.550***	0.857**	1.143**
	[0.319]	[0.417]	[0.351]	[0.409]	[0.371]	[0.461]
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	147	96	142	94	128	83
R-squared	0.73	0.70	0.67	0.62	0.69	0.72

NOTES – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the spatial GMM regressions employ the numbers of prehistoric domesticable species of plants and animals as instruments for log transition timing; (iii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (iv) the spatial GMM regressions do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples; (v) standard errors corrected for spatial autocorrelation are reported in square brackets; (vi) the spatial distribution of countries in $\Re^2$ is specified using aerial distances between geodesic centroids; (vii) the spatial autocorrelation in error terms is modelled as declining linearly along a 5,000 km radius from each observation; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

TABLE C.4: Additional Robustness to Corrections for Spatial Autocorrelation

	(1)	(2)	(3)	(4)	(5)	(6)
	Corrected OLS	Corrected OLS	Corrected OLS	Corrected OLS	Corrected OLS	Corrected OLS
	Dependent Variable is:					
	Log Income Per Capita in:			Log Population Density in:		
	1500 CE	1000 CE	1 CE	1500 CE	1000 CE	1 CE
Log Years since Neolithic Transition	0.159** [0.064]	0.073* [0.038]	0.109 [0.069]	1.337*** [0.437]	0.832*** [0.263]	1.006*** [0.376]
Log Land Productivity	0.041** [0.016]	-0.021 [0.023]	-0.001 [0.020]	0.584*** [0.125]	0.364*** [0.098]	0.681*** [0.147]
Log Absolute Latitude	-0.041 [0.043]	0.060 [0.108]	-0.175 [0.123]	0.050 [0.343]	-2.140*** [0.704]	-2.163*** [0.838]
Mean Distance to Nearest Coast or River	0.215** [0.100]	-0.111 [0.125]	0.043 [0.116]	-0.429 [0.893]	-0.237 [0.656]	0.118 [0.859]
% Land within 100 km of Coast or River	0.124* [0.075]	-0.150 [0.110]	0.042 [0.082]	1.855*** [0.620]	1.326** [0.524]	0.228 [0.605]
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31	26	29	31	26	29
R-squared	0.66	0.68	0.33	0.88	0.95	0.89

NOTES – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (iii) regressions (2)-(3) and (5)-(6) do not employ the Oceania dummy due to a single observation for this continent in the corresponding regression samples; (iv) standard errors corrected for spatial autocorrelation are reported in square brackets; (v) the spatial distribution of countries in $\Re^2$ is specified using aerial distances between geodesic centroids; (vi) the spatial autocorrelation in error terms is modelled as declining linearly along a 5,000 km radius from each observation; (vii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table C.5: First-Stage Regressions

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	Second-Stage Dependent Variable is:					
	Log of Population Density in 1500 CE	Log of Population Density in 1000 CE	Log of Population Density in 1 CE	Log of Technology Index in 1/1000 CE	Log of Population Density in 1000 CE	Log of Population Density in 1 CE
	Endogenous Variable is:					
	Log Years since Neolithic Transition				Log Technology Index in: 1000 CE	Log Technology Index in: 1 CE
Excluded Instruments:						
Domesticable Plants	0.012**	0.013**	0.012**	0.012**	0.001	0.007***
	(0.005)	(0.005)	(0.006)	(0.005)	(0.001)	(0.002)
Domesticable Animals	0.067**	0.064**	0.048*	0.063**	0.020***	-0.002
	(0.029)	(0.028)	(0.029)	(0.028)	(0.006)	(0.008)
Second-Stage Controls:						
Log Land Productivity	0.040	0.025	-0.011	0.023	0.002	-0.003
	(0.049)	(0.049)	(0.037)	(0.049)	(0.014)	(0.017)
Log Absolute Latitude	-0.127***	-0.130***	-0.083*	-0.120***	-0.015	-0.005
	(0.042)	(0.043)	(0.044)	(0.044)	(0.014)	(0.019)
Mean Distance to Nearest Coast or River	0.127	0.103	0.094	0.079	0.112**	0.055
	(0.141)	(0.140)	(0.156)	(0.143)	(0.044)	(0.093)
% Land within 100 km of Coast or River	-0.165	-0.190	-0.227*	-0.171	0.044	0.061
	(0.137)	(0.136)	(0.136)	(0.137)	(0.036)	(0.063)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	96	94	83	93	92	83
R-squared	0.68	0.70	0.71	0.67	0.71	0.51
Partial R-squared	0.27	0.28	0.25	0.26	0.17	0.16
F-statistic	14.65	15.10	10.85	13.47	12.52	12.00

Notes – (i) log land productivity is the first principal component of the log of the arable percentage of land and the log of an agricultural suitability index; (ii) the partial R-squared reported is for the excluded instruments only; (iii) the F-statistic is from the test of excluded instruments and is always significant at the 1% level; (iv) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (v) the dummy for Oceania is not employed due to the presence of a single observation for this continent in the corresponding regression samples; (vi) robust standard error estimates are reported in parentheses; (vii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

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