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ABSTRACT

Dynamics and Stagnation in the Malthusian Epoch: Theory and Evidence*

This paper empirically tests the predictions of the Malthusian theory with respect to both population dynamics and income per capita stagnation in the pre-Industrial Revolution era. The theory suggests that improvements in technology during this period generated only temporary gains in income per capita, eventually leading to a larger but not richer population. Using exogenous cross-country variations in land productivity and the timing of the Neolithic Revolution, the analysis demonstrates that, in accordance with the Malthusian theory, societies that were characterized by higher land productivity and an earlier onset of agriculture had higher population densities, but similar standards of living, during the time period 1-1500 CE.

JEL Classification: N10, N30, N50, O10, O40 and O50
Keywords: land, Malthusian stagnation, population dynamics and technological progress

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1 Introduction

The evolution of economies during the major portion of human history was marked 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 initially experienced a considerable rise in the growth rates of income per capita and population. Unlike episodes of technological progress in the pre-Industrial Revolution era that failed to generate sustained economic growth, the increasing role of human capital in the production process in the second phase of industrialization 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 escape from the Malthusian epoch to the state of sustained economic growth and the related divergence in income per capita across countries and regions, as depicted in Figure 1, have significantly shaped the contemporary world economy.[1] The transition from Malthusian stagnation to modern growth has been the subject of intensive research in the growth literature in recent years, as it has become apparent that a comprehensive understanding of the hurdles faced by less developed economies in reaching a state of sustained economic growth would be futile unless the factors that prompted the transition of the currently developed economies into a state of sustained economic growth could be identified and their implications modified to account for differences in the growth structure of less developed economies in an interdependent world.[2]

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[1] The ratio of GDP per capita between the richest region and the poorest region in the world was only 1.1:1 in the year 1000 CE, 2:1 in the year 1500 CE, and 3:1 in the year 1820 CE. In the course of the Great Divergence, however, the ratio of GDP per capita between the richest region and the poorest region widened considerably to an 18:1 ratio by 2001 (Maddison, 2003).

[2] The transition from Malthusian stagnation to sustained economic growth was explored by Galor and Weil (1999, 2000), Lucas (2002), Galor and Moav (2002), Hansen and Prescott (2002), Jones (2001), Lagerlöf (2003, 2006), Doepke (2004), Fernández-Villaverde (2005), as well as others, and the association of the Great Divergence with this transition was analyzed by Galor and Mountford (2006, 2008), O'Rourke and Williamson (2005), Voigtländer and Voth (2006), and Ashraf and Galor (2007) amongst others.

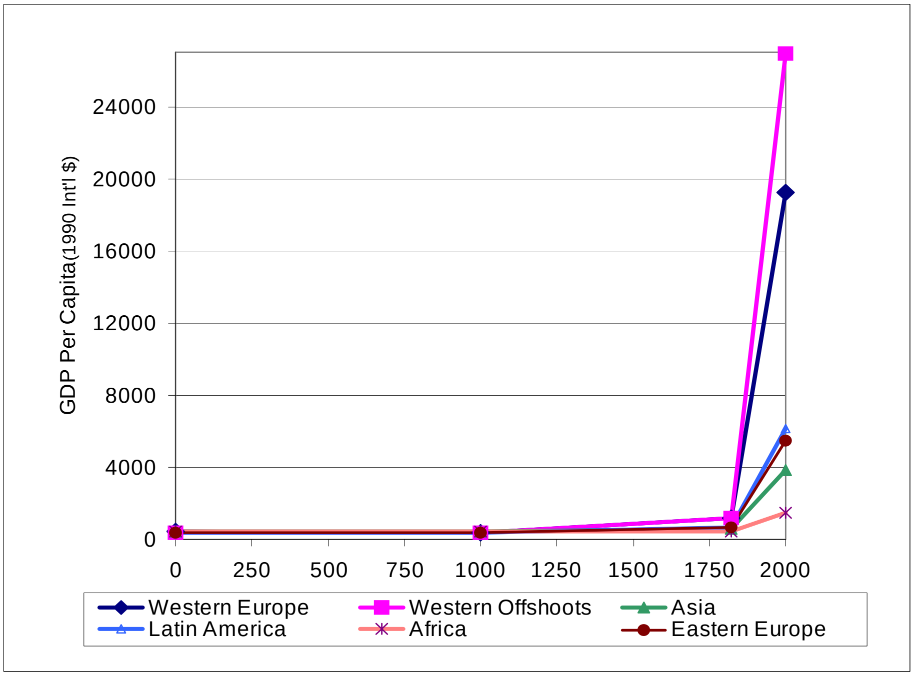

Figure 1: The Evolution of Regional Income Per Capita, 1-2000 CE

The forces that generated the remarkable escape from the Malthusian epoch and their significance in understanding the contemporary growth process of developed and less developed economies has raised fundamentally important questions: What accounts for the epoch of stagnation that characterized most of human history? What is the origin of the sudden spurt in growth rates of output per capita and population? Why had episodes of technological progress in the pre-industrialization era failed to generate sustained economic growth? What was the source of the dramatic reversal in the positive relationship between income per capita and population that existed throughout most of human history? What triggered the demographic transition? Would the transition to a state of sustained economic growth have been feasible without the demographic transition? What are the underlying behavioral and technological structures that can simultaneously account for these distinct phases of development and what are their implications for the contemporary growth process of developed and underdeveloped countries?

The differential timing of the escape from the Malthusian epoch that gave rise to the divergence in income per capita across regions of the world in the past two centuries has generated some additional intriguing research debates: What accounts for the sudden take-off from stagnation to sustained growth in some countries and the persistent stagnation in others? Why has the positive link between income per capita and population growth reversed its course in some economies but not in others? Why have the differences in income per capita across countries increased so markedly in the last two centuries? Has the transition to a state of sustained economic growth in advanced economies adversely affected the process of development in less-developed economies?

Unified growth theory (Galor, 2005) suggests that the transition from stagnation to growth is an inevitable by-product of the process of development. The inherent Malthusian interaction between technology and the size (Galor and Weil, 2000) and the composition (Galor and Moav, 2002; Galor and Michalopoulos, 2006) of the population, accelerated the pace of technological progress, and eventually brought about an industrial demand for human capital. Human capital formation and thus further technological progress triggered a demographic transition, enabling economies to convert a larger share of the fruits of factor accumulation and technological progress into growth of income per capita. Moreover, the theory suggests that differences in the timing of the take-off from stagnation to growth across countries contributed significantly to the Great Divergence and to the emergence of convergence clubs. According to the theory, variations in the economic performance across countries and regions (e.g., the earlier industrialization in England than in China) reflect initial differences in geographical factors and historical accidents and their manifestation in variations in institutional, demographic, and cultural characteristics, as well as trade patterns, colonial status, and public policy.

The underlying viewpoint about the operation of the world during the Malthusian epoch is based, however, on the basic premise that technological progress and resource expansion generated a positive adjustment of the population, leaving resources per capita unchanged. Although there exists supporting anecdotal evidence, these salient characteristics of the Malthusian mechanism have not been tested empirically. A notable exception is the time series analysis of Crafts and Mills (2008), which confirms that real wages in England were stationary till the end of the 18th century and that wages had a positive effect on fertility (although no effect on mortality) till the mid-17th century.

This paper empirically tests the predictions of the Malthusian theory regarding both population dynamics and stagnation in income per capita in the pre-Industrial Revolution era of human history.[3] The theory suggests that, in early stages of development, resource

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[3] In contrast to the current study that directly tests the Malthusian prediction regarding the positive effect of the technological environment on population density, the empirical study of Kremer (1993) examines the reduced-form 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 defends the role of scale effects

expansions beyond the maintenance of subsistence consumption were channeled primarily into population growth, leaving income per capita close to subsistence and, thus, relatively constant across regions. In particular, regions that were naturally blessed by higher land productivity would have supported larger populations, given the level of their technological advancement. Moreover, given the natural productivity of land, societies possessing more advanced technologies, as reflected by their cumulative experience with the agricultural production paradigm since the onset of the Neolithic Revolution, would have sustained higher population densities. Using exogenous variations in the natural productivity of land and the timing of the Neolithic Revolution, the analysis demonstrates that, in accordance with the Malthusian theory, societies that were characterized by higher land productivity and experienced an earlier onset of agriculture had higher population densities, but similar levels of income per capita, in the time period 1-1500 CE.

2 Historical Evidence

According to the Malthusian theory, during the Malthusian epoch that had characterized most of human history, humans were subjected to a persistent struggle for existence. The rate of technological progress was insignificant by modern standards and resources generated by technological progress and land expansion were channeled primarily towards an increase in population size, with negligible long-run effects on income per capita. The positive effect of the standard of living on population growth along with diminishing labor productivity kept income per capita in the proximity of a subsistence level.[4] Periods marked by the absence of changes in the level of technology or in the availability of land, were characterized by a stable population size as well as a constant income per capita, whereas periods characterized by 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. Technologically superior economies ultimately had denser populations but their standard of living did not reflect the degree of their technological advancement.[5]

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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. However, explicit tests of the positive Malthusian feedback from technology to population size, or the long-run neutrality of the technological environment for income per capita, are absent from Kremer's analysis.

[4] The subsistence level of consumption may have been well above the minimal physiological requirements that were necessary to sustain an active human being.

[5] 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."*

2.1 Income Per Capita

During the Malthusian epoch, the average growth rate of output per capita was negligible and the standard of living did not differ greatly across countries. The average level of income per capita during the first millennium fluctuated around \$450 per year while the average growth rate of output per capita in the world was nearly zero. This state of Malthusian stagnation persisted until the end of the 18th century. In the 1000-1820 CE time period, the average level of income per capita in the world economy was below \$670 per year and the average growth rate of the world income per capita was rather miniscule, creeping at a rate of about 0.05% per year (Maddison, 2001).[6]

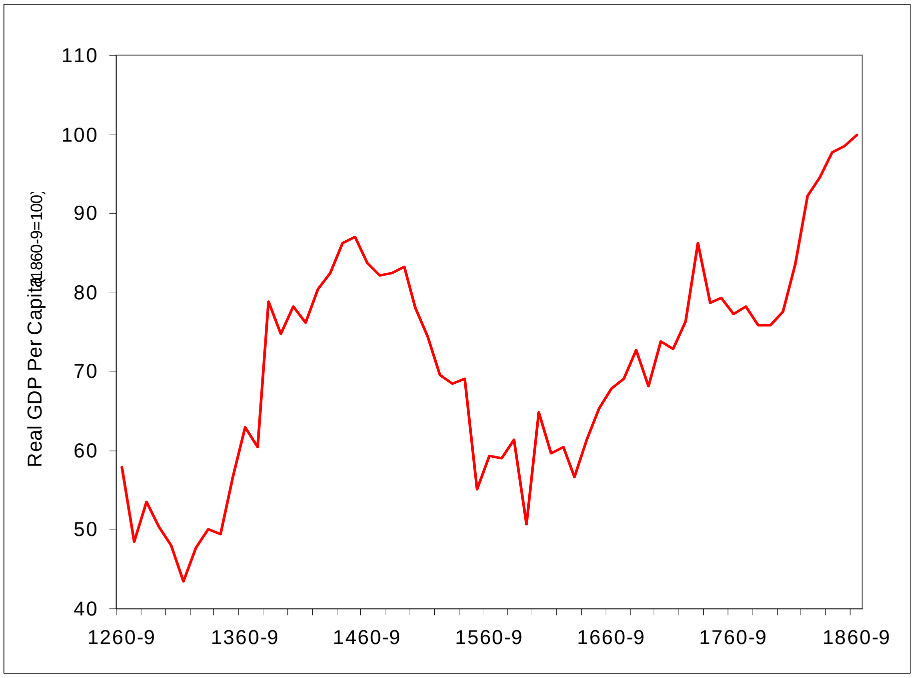

Figure 2: Fluctuations in Real GDP Per Capita in England, 1260-1870 CE

This pattern of stagnation was observed across all regions of the world. As depicted in Figure 1, the average level of income per capita in Western and Eastern Europe, the Western Offshoots, Asia, Africa, and Latin America was in the range of \$400-450 per year in the first millennium and the average growth rate of income per capita in each of these regions was nearly zero. This state of stagnation persisted until the end of the 18th century across all regions, with the level of income per capita in 1820 CE ranging from \$418 per year in Africa, \$581 in Asia, \$692 in Latin America, and \$683 in Eastern Europe, to \$1202 in the Western Offshoots (i.e., the United States, Canada, Australia and New Zealand) and

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[6] Maddison's estimates of income per capita are evaluated in terms of 1990 international dollars.

$1204 in Western Europe. Furthermore, the average growth rate of income per capita over this period ranged from 0% in the impoverished region of Africa to a sluggish rate of 0.14% in the prosperous region of Western Europe.

Despite remarkable stability in the evolution of world income per capita during the Malthusian epoch from a millennial perspective, GDP per capita and real wages fluctuated significantly within regions, deviating from their sluggish long-run trend over decades and sometimes several centuries. In particular, as depicted in Figure 2, real GDP per capita in England fluctuated drastically over the majority of the past millennium. Declining during the 13th century, it increased sharply during the 14th and 15th centuries in response to the catastrophic population drop in the aftermath of the Black Death. This two-century rise in real income per capita stimulated population growth, which subsequently brought about a decline of income per capita in the 16th century, back to its level from the first half of the 14th century. Real income per capita increased once again in the 17th century and remained stable during the 18th century, prior to the take-off in the 19th century (Clark, 2005).

2.2 Income and Population

2.2.1 Population Growth and the Level of Income

Population growth during this era exhibited the Malthusian pattern as well. As depicted in Figure 3, the slow pace of resource expansion in the first millennium was reflected in a modest increase in the population of the world from 231 million people in 1 CE to 268 million in 1000 CE, a miniscule average growth rate of 0.02% per year.[7] The more rapid (but still very slow) expansion of resources in the period 1000-1500 CE permitted the world population to increase by 63%, from 268 million in 1000 CE to 438 million in 1500 CE, a slow 0.1% average growth rate per year. Resource expansion over the period 1500-1820 CE had a more significant impact on the world population, which grew 138% from 438 million in 1500 CE to 1041 million in 1820 CE, an average pace of 0.27% per year (Maddison, 2001).[8] This apparent positive effect of income per capita on the size of the population was maintained during the last two centuries as well, as the population of the world attained the remarkable level of nearly 6 billion people.

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[7] Since output per capita grew at an average rate of 0% per year over the period 1-1000 CE, the pace of resource expansion was approximately equal to the pace of population growth, namely, 0.02% per year.

[8] Since output per capita in the world grew at an average rate of 0.05% per year in the time period 1000-1500 CE as well as in the period 1500-1820 CE, the pace of resource expansion was approximately equal to the sum of the pace of population growth and the growth of output per capita. Namely, 0.15% per year in the period, 1000-1500 CE and 0.32% per year in the period 1500-1820 CE.

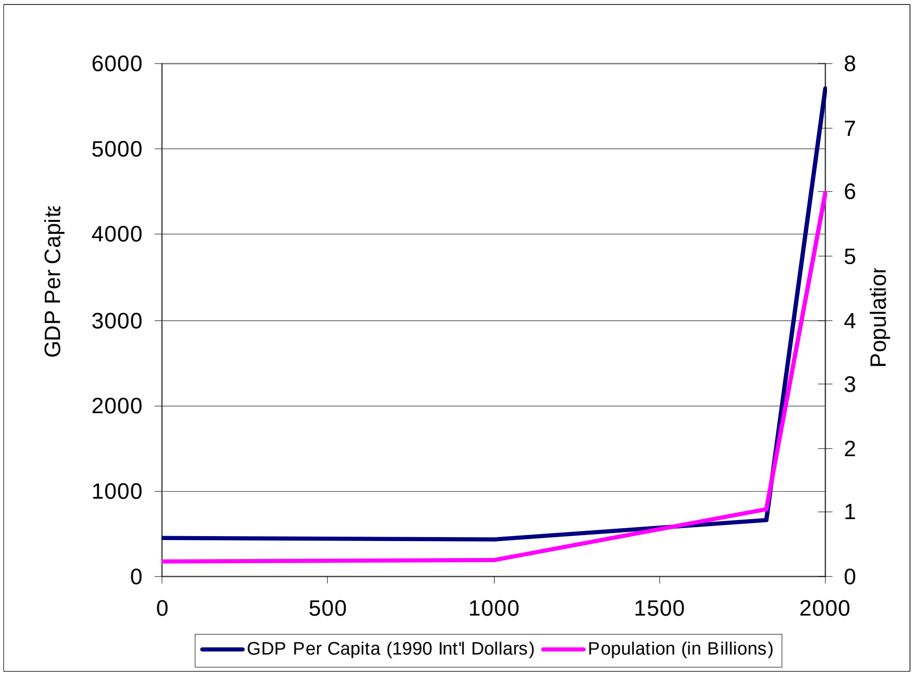

Figure 3: The Evolution of World Population and Income Per Capita, 1-2000 CE

Moreover, the gradual increase in income per capita during the Malthusian epoch was associated with a monotonic increase in the average rate of growth of world population, as depicted in Figure 4. This pattern existed both within and across countries.[9]

2.2.2 Fluctuations in Income and Population

Fluctuations in population size and real wages over this epoch also reflected the Malthusian pattern. Episodes of technological progress, land expansion, favorable climatic conditions, or major epidemics (resulting in a decline of the adult population), brought about a temporary increase in real wages and income per capita. As depicted in Figure 5, the catastrophic decline in the population of England during the Black Death (1348-1349 CE), from about 6 million to about 3.5 million people, significantly increased the land-labor ratio, tripling real wages over the subsequent 150 years.[10] Ultimately, however, the majority of this increase in real resources per capita was channeled towards higher fertility rates, increasing the size

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[9] Lee (1997) reports a positive income elasticity of fertility and a negative income elasticity of mortality from studies examining a wide range of pre-industrial countries. Similarly, Wrigley and Schofield (1981) uncover a strong positive correlation between real wages and marriage rates in England over the period 1551-1801 CE.

[10] Reliable population data is not available for the period 1405-1525 CE. Figure 5 is depicted under the assumption maintained by Clark (2005) that the population was rather stable over this period.

of the population and bringing the real wage rate in the 1560s back to the proximity of its pre-plague level (Clark, 2005).

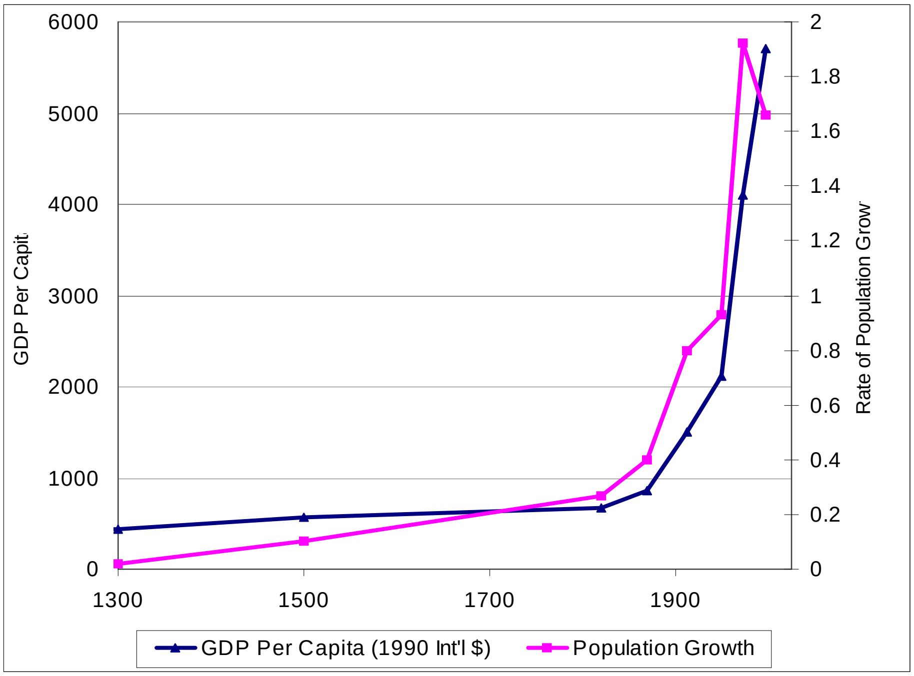

Figure 4: World Population Growth and Income Per Capita

2.3 Population Density

Variations in population density across countries during the Malthusian epoch reflected primarily cross-country differences in technologies and land productivity. Due to the positive adjustment of the population to an increase in income per capita, differences in technologies or in land productivity across countries resulted in variations in population density rather than in the standard of living.[11] For instance, China's technological advancement in the period 1500-1820 CE permitted its share of world population to increase from 23.5% to 36.6%, while its income per capita at the beginning and end of this time interval remained constant at roughly $600 per year.[12]

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[11] Consistent with the Malthusian paradigm, China's sophisticated agricultural technologies allowed high per-acre yields but failed to increase the standard of living above subsistence. Likewise, the introduction of potatoes in Ireland in the middle of the 17th century generated a large increase in population over two centuries without significant improvements in the standard of living. Furthermore, the destruction of potatoes by fungus in the middle of the 19th century generated a massive decline in population due to the Great Famine and mass migration (Mokyr, 1985).

[12] The Chinese population more than tripled over this period, increasing from 103 million in 1500 CE to 381 million in 1820 CE.

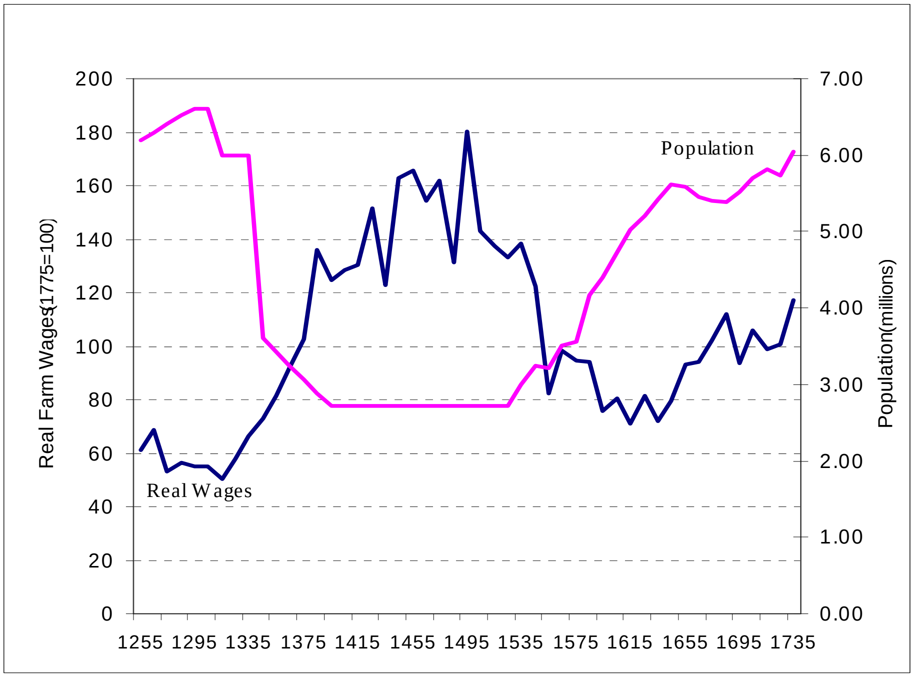

Figure 5: Population and Real Wages in England, 1250-1750 CE

The Malthusian pattern historically persisted until the onset of the demographic transition, namely, as long as the positive relationship between income per capita and population growth was maintained. In the period 1600-1870 CE, the United Kingdom's technological advancement relative to the rest of the world more than doubled its share of world population from 1.1% to 2.5%. Similarly, during the 1820-1870 CE time period, the land abundant, technologically advanced economy of the United States experienced a 220% increase in its share of world population from 1% to 3.2%.[13]

3 The Malthusian Model

The Malthusian theory, inspired by Malthus (1798), suggests that the worldwide stagnation in income per capita over this epoch reflected the counterbalancing effect of population growth on the expansion of resources, in an environment characterized by diminishing returns to labor. The expansion of resources, according to Malthus, led to an increase in population

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[13] The population of the United Kingdom nearly quadrupled over the period 1700-1870 CE, increasing from 8.6 million in 1700 CE to 31.4 million in 1870 CE. Similarly, the population of the United states increased 40-fold, from 1.0 million in 1700 CE to 40.2 million in 1870 CE, due to significant labor migration as well as high fertility rates.

growth, reflecting the natural result of the “passion between the sexes”. In contrast, when population size grew beyond the capacity sustainable by available resources, it was reduced by the “preventive check” (i.e., intentional reduction of fertility) as well as by the “positive check” (i.e., the tool of nature due to malnutrition, disease, war and famine).[14]

According to the theory, periods marked by the absence of changes in the level of technology or in the availability of land, were characterized by a stable population size as well as a constant income per capita. In contrast, episodes of technological progress, land expansion, and favorable climatic conditions, brought about temporary gains in income per capita, triggering an increase in the size of the population, which led eventually to a decline in income per capita to its long-run level. Due to the positive adjustment of population to an increase in income per capita, differences in technologies or in land productivity across countries resulted in cross-country variations in population density rather than in the standard of living.

3.1 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.

3.1.1 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 is, 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

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[14] The theory was formalized by Kremer (1993), who models a reduced-form interaction between population 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 (2007) have modelled the bio-economic link between economic productivity, body size, and population size in a Malthusian world, while Aiyar et al. (2008) provide micro-foundations for the dynamic relationship between population and technology during the pre-Industrial Malthusian epoch.

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:

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

3.1.2 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 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:[15]

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

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.[16] Hence, the budget constraint for a member of generation t (in the second period of life) is:

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

3.1.3 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

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[15] 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.

[16] 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 process described 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.

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.

3.2 The Evolution of the Economy

3.2.1 Population Dynamics

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

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

where n_t is the number of children per adult in generation t.

Lemma 1 *The time path of working population, as depicted in Figure 6, is governed by the first-order difference equation*

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

Therefore:

- *the rate of population growth between periods t and $t+1$, g^L_{t+1}, is*

$$g^L_{t+1} \equiv (L_{t+1} - L_t)/L_t = (\gamma/\rho)(AX)^\alpha L_t^{-\alpha} - 1 \equiv g^L(L_t; A);$$

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

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

- *for a given level of technology, A, there exists a unique steady-state level of population density, $\bar{P}_d$,*

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

Proof. Substituting (2) and (5) into (6) yields $L_{t+1} = (\gamma/\rho)(AX)^\alpha L_t^{1-\alpha}$. Hence, $\phi_L(L_t; A) > 0$ and $\phi_{LL:}(L_t; A) < 0$ so, as depicted in Figure 6, $\phi(L_t; A)$ is strictly concave in L_t with

$\phi(0;A) = 0$, $\lim_{L_t \to 0} \phi_L(L_t;A) = \infty$ and $\lim_{L_t \to \infty} \phi_L(L_t;A) = 0$. Thus, for a given A, there exists a unique steady-state level of population and population density. The expressions for the levels of $\bar{L}$, $\bar{P}_d$, and g^L_{t+1} follow immediately from their definitions. $\square$

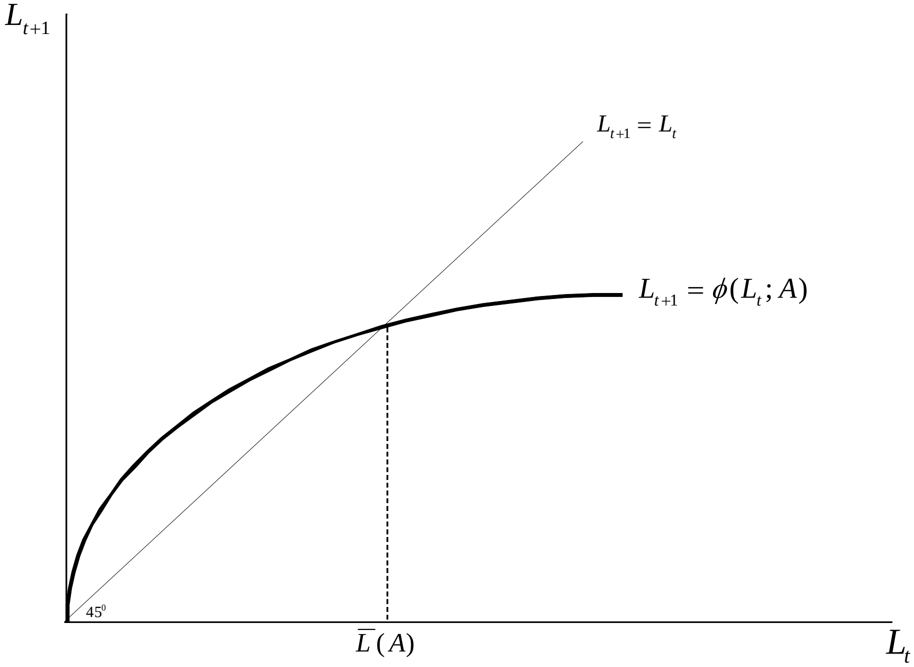

Figure 6: The Evolution of Population

Proposition 1 *1. Technological advancement:*

- *increases the steady-state levels of population, $\bar{L}$, and population density, $\bar{P}_d$, i.e.,*

$$\frac{\partial \bar{L}}{\partial A} > 0 \text{ and } \frac{\partial \bar{P}_d}{\partial A} > 0;$$

- *increases the rate of population growth between period t and $t+1$, g^L_{t+1}, i.e.,*

$$\frac{\partial g^L_{t+1}}{\partial A} > 0.$$

2. Given the level of technology, the rate of population growth is lower the higher is the level of the population, i.e.,

$$\frac{\partial g^L_{t+1}}{\partial L_t} < 0.$$

Proof. Follows from differentiating the relevant expressions in Lemma 1. $\square$

As depicted in Figure 7, 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 $\bar{L}^h$.

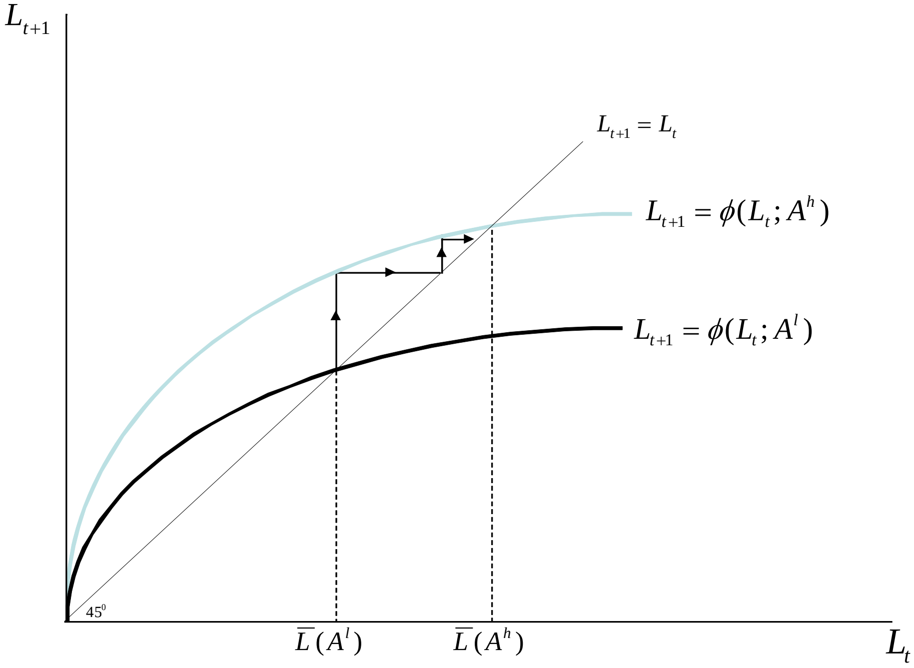

Figure 7: The Adjustment of Population due to an Advancement in the Level of Technology

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 will generate a gradual increase in population back to the steady-state level $\bar{L}$.

3.2.2 The Time Path of Income Per Worker

The evolution of income per worker is governed by the initial level of income per worker, the level of technology and the size of the population. Specifically, income per capita in period $t+1$, y_{t+1}, noting (2) and (6), is

$$y_{t+1} = [(AX)/L_{t+1}]^{\alpha} = [(AX)/n_t L_t]^{\alpha} = y_t/n_t^{\alpha}. \tag{7}$$

Lemma 2 *The time path of income per worker, as depicted in Figure 8, is governed by the* *first-order difference equation*

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

- *The growth rate of income per capita between periods* t *and* $t+1$, g^y_{t+1}, *is therefore*

$$g^y_{t+1} \equiv (y_{t+1} - y_t)/y_t = (\rho/\gamma)^{\alpha} y_t^{-\alpha} - 1 = (\rho/\gamma)^{\alpha}(AX/L_t)^{-\alpha^2} - 1 \equiv g^y(L_t; A).$$

- *Regardless of level of technology,* A, *there exists a unique steady-state level of income per capita,* $\bar{y}$,

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

Proof. Substituting (5) into (7) yields $y_{t+1} = (\rho/\gamma)^{\alpha} y_t^{1-\alpha}$. Hence, $\psi'(y_t) > 0$ and $\psi''(y_t) < 0$ so, as depicted in Figure 8, $\psi(y_t)$ is strictly concave in y with $\psi(0) = 0$, $\lim_{y_t \to 0} \psi'(y_t) = \infty$ and $\lim_{y_t \to \infty} \psi'(y_t) = 0$. Thus, regardless of the level of A, there exists a unique steady-state level of income per worker, $\bar{y}$. The expressions for the levels of $\bar{y}$ and g^y_{t+1} follow immediately from their definitions. $\square$

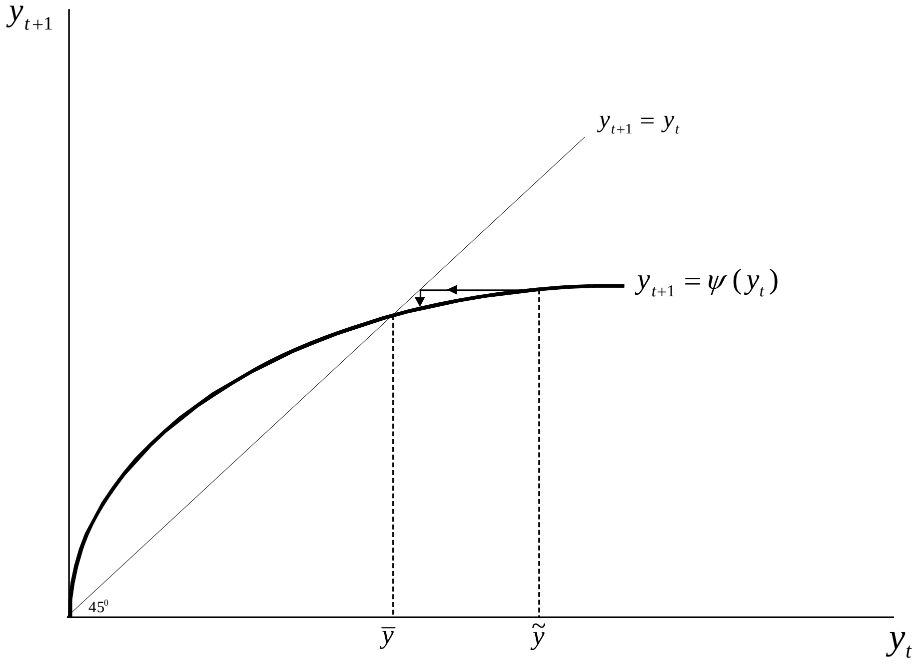

Figure 8: The Evolution of Income Per Capita

Proposition 2 *Technological advancement:*

- *increases the level of income per capita in time* t, y_t, *and reduces the growth rate of* *income per worker between period* t *and* $t+1$, g^y_{t+1}, *i.e.,*

$$\frac{\partial y_t}{\partial A} > 0 \text{ and } \frac{\partial g^y_{t+1}}{\partial A} < 0.$$

- *does not affect the steady-state levels of income per worker, i.e.,*

$$\frac{\partial \bar{y}}{\partial A} = 0.$$

Proof. Follows from differentiating the relevant expressions in Lemma 2. □

As depicted in Figure 8, if the economy is in a steady-state equilibrium, $\bar{y}$, an advancement in the technological level from A^l to A^h generates a transition process in which initially income per worker 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 therefore a gradual decline in income per worker back to $\bar{y}$.

3.3 Testable Predictions

The Malthusian theory generates the following testable predictions:

1. A higher productivity of land leads in the long run to a larger population, without altering the long-run level of income per capita.
2. Countries characterized by superior land productivity would have, *ceteris paribus*, a higher population density in the long run, but their standard of living would not reflect the degree of their technological advancement.
3. Countries that experienced a universal technological advancement (e.g., the Neolithic Revolution) earlier would have, *ceteris paribus*, a higher long-run level of population density, but not necessarily higher income per capita.
4. Conditional on the overall productivity of land, countries with smaller populations would, in a given time period, exhibit faster rates of population growth.

The empirical analysis to follow will test the predictions of the Malthusian theory on multiple fronts, including (i) the effects of measures of land productivity (e.g., the arable percentage of land area, the suitability of land for agriculture, etc.) and an earlier onset of the Neolithic Revolution on population density in the pre-industrial era; (ii) the neutrality of land productivity and agricultural transition timing for income per capita in pre-industrial times; and (iii) the relationship between population density in a given historical period and the subsequent long-run rate of population growth.

4 Cross-Country Evidence

The Malthusian theory suggests that, during the agricultural stage of development, social surpluses beyond the maintenance of subsistence consumption were channelled primarily into population growth, with living standards remaining close to subsistence in the long run and, hence, relatively similar across regions. As such, at any point in time, the population density of a given region, as opposed to its income per capita, would have largely reflected its carrying capacity, determined by the effective resource constraints that were binding at that point in time. The theory can therefore be tested in several dimensions, including (i) the assertion that population density during the Malthusian epoch was largely constrained by the availability of *natural* resources, but income per capita was independent of it, and (ii) the role of technological progress in expanding *effective* resources and, thus, population density, while leaving income per capita unchanged in the long run.

In particular, since resource constraints were slacker for regions naturally blessed by a higher agricultural productivity of land, they would have sustained larger populations, given the level of technological advancement. Moreover, conditional on land productivity, societies that were more advanced technologically, as reflected by their cumulative experience with the agricultural technological paradigm since the Neolithic Revolution, would have sustained higher population densities. However, societies that experienced the Neolithic Revolution earlier, or those that were characterized by higher land productivity, would not have enjoyed higher standards of living.

The Malthusian theory predicts that regional variation in population density in the long run would ultimately reflect variations in land productivity and biogeographic attributes. Thus, for a given technological environment, greater land productivity, such as a higher arable percentage of land, better soil quality, and a favorable climate, would enable society to sustain a larger population. 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 via trade and the implementation and diffusion of agricultural technologies. The variations in land productivity and biogeographic factors, however, would not be manifested as significant differences in income per capita across regions.

Beyond the Malthusian predictions for population density and income per capita, the theory also suggests that, at a given point in time, societies should have been gravitating towards their respective Malthusian steady states, determined by their land productivities and their levels of technological advancement at that point in time. In particular, conditional on the natural productivity of land and the level of technological advancement, a society with a higher population density at a given point in time would have exhibited a relatively slower rate of subsequent population growth.

Favorable biogeographic factors led to an earlier onset of the Neolithic Revolution and facilitated the subsequent diffusion of agricultural techniques. The transition of societies in the Neolithic from primitive hunting and gathering techniques to the more technologically advanced agricultural mode of production initiated a cumulative process of socioeconomic development. It gave some societies a developmental headstart, 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).[17] The current analysis therefore employs the number of years elapsed since the Neolithic Revolution as a baseline metric of the level of aggregate productivity in an agricultural society during the Malthusian era. Nevertheless, a more direct measure of technological sophistication is also employed as an alternative metric of the level of aggregate productivity to demonstrate the qualitative robustness of the baseline results.

To examine the predictions of the Malthusian theory empirically, the analysis at hand exploits cross-country variation in land productivity and in the number of years elapsed since the onset of the Neolithic Revolution to explain cross-country variation in either population density or income per capita in the years 1500 CE, 1000 CE and 1 CE. As mentioned above, the investigation also exploits cross-country variation in an index of technological

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[17] See Weisdorf (2005) as well. 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 series of aftershocks, thereby preventing populations from approaching their Malthusian steady-state within a few generations. These aftershocks 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. As will become evident, the empirical findings suggest that conditional convergence in the evolution of population takes place, suggesting therefore that the social gains from this subsequent process of development were eventually characterized by diminishing returns over time.

sophistication, in the years 1000 CE and 1 CE, as an alternative to the Neolithic transition timing measure of aggregate productivity.[18] Finally, the analysis exploits variations in the aforementioned independent variables as well as in initial population densities to explain cross-country variation in the average rate of population growth over the 1-1000 CE and the 1000-1500 CE time horizons.

Consistent with the predictions of the theory, the regression results demonstrate highly statistically significant positive effects of land productivity and an earlier onset of the Neolithic Revolution on population density in each historical period. The effects of these explanatory variables on income per capita, however, are not significantly different from zero, a result that fully complies with theoretical predictions. Furthermore, in line with the conditional convergence hypothesis implied by the Malthusian theory, the findings also reveal statistically significant negative effects of initial population density on the average rate of population growth in the two time horizons.[19] These results are shown to be robust to controls for other geographical factors such as access to waterways, which historically played a major role in augmenting productivity by facilitating trade and the diffusion of technologies, and to different cuts of the relevant regression samples that eliminate the influence of potential outliers.[20] Moreover, the results are qualitatively unaffected when the index of technological sophistication, rather than the timing of the Neolithic Revolution, is employed as a proxy for the level of aggregate productivity.

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

$$\begin{aligned} \ln P_{i,t} &= \alpha_0 + \alpha_1 \ln T_i + \alpha_2 \ln X_i + \alpha_3^{'} \Gamma_i + \alpha_4^{'} D_i + \delta_{i,t}, \qquad (8) \\ \ln y_{i,t} &= \beta_0 + \beta_1 \ln T_i + \beta_2 \ln X_i + \beta_3^{'} \Gamma_i + \beta_4^{'} D_i + \varepsilon_{i,t}, \qquad (9) \end{aligned}$$

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[18] Historical population and income per capita estimates are obtained from McEvedy and Jones (1978) and Maddison (2003), respectively. The measure of land productivity employed is the first principal component of the arable percentage of land, from the World Development Indicators, and an index of the overall suitability of land for agriculture, based on soil quality and temperature, from Michalopoulos (2008). Data on the timing of the Neolithic Revolution is from Putterman (2006). The index of technological sophistication is constructed using data from Peregrine's (2003) Atlas of Cultural Evolution, following the methodology employed by Comin et al. (2007). See the appendix for additional details and statistics.

[19] This is analogous to the findings of Barro (1991) regarding conditional convergence in income per capita across countries in the contemporary world.

[20] 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. See the appendix for additional details and statistics.

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 the 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 geographical 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.

The baseline specification adopted to examine the conditional convergence hypothesis for population growth rates, on the other hand, is:

$$g_{i,t}^{L} = \gamma_0 + \gamma_1 \ln P_{i,t} + \gamma_2 \ln T_i + \gamma_3 \ln X_i + \gamma_4^{'} \Gamma_i + \gamma_5^{'} D_i + \lambda_{i,t}, \tag{10}$$

where $g_{i,t}^{L}$ is the average rate of growth of the population in country i between years t and $t+\tau$, measured as the log difference in population between t and $t+\tau$; $P_{i,t}$ is the population density of country i in year t; and $\lambda_{i,t}$ is a country-specific disturbance term for the rate of population growth between years t and $t+\tau$.

The detailed discussion of the empirical findings is organized as follows. Section 4.1 presents the regression results from testing the Malthusian prediction for population density in 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. Section 4.4 presents the qualitative robustness of the earlier findings when a more direct measure of technology is employed in lieu of the Neolithic transition timing variable. Some additional robustness results, dispelling alternative theories and unobserved country fixed effects, are revealed in Section 4.5. Finally, Section 4.6 concludes with findings from testing the conditional convergence hypothesis implied by the Malthusian theory.

4.1 Population Density in 1500 CE

The results from regressions explaining log population density in the year 1500 CE are presented in Table 1. In particular, a number of specifications comprising different subsets of the explanatory variables in equation (8) are estimated to examine the independent and combined effects of the transition timing and land productivity channels, while controlling for other geographical factors and continental fixed effects.

Consistent with the predictions of the Malthusian theory, Column 1 reveals the positive relationship between log years since transition and log population density in the year

1500 CE, controlling for continental fixed effects. Specifically, the estimated OLS coefficient implies that a 1% increase in the number of years elapsed since the transition to agriculture increases population density in 1500 CE by 0.83%, an effect that is statistically significant at the 1% level. Moreover, based on the R-squared coefficient 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.

Table 1: 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	-	-	-	-	-	0.44

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 reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

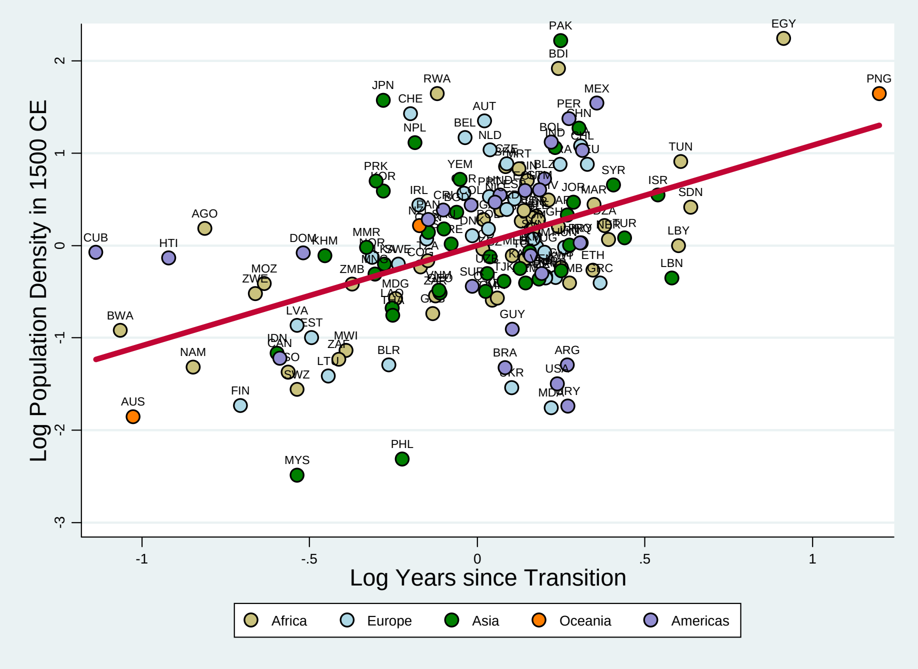

Figure 9a: Transition Timing and Population Density in 1500 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

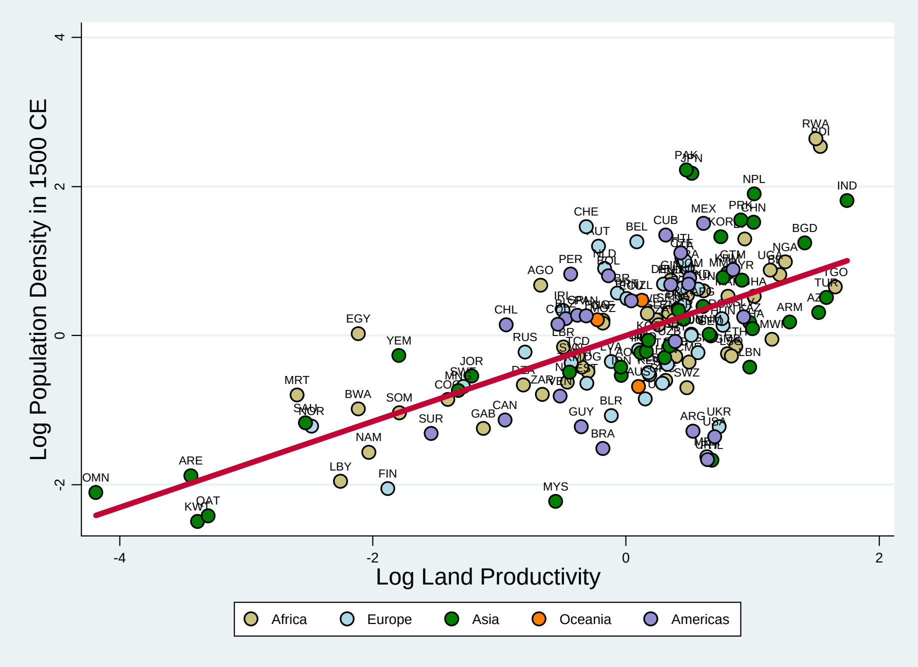

Figure 9b: Land Productivity and Population Density in 1500 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

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 the Malthusian stage was on average higher at latitudinal bands closer to the equator. 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% 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 is associated, *ceteris paribus*, with a 0.57% increase in population density in 1500 CE. These conditional effects are depicted on the scatter plots in Figures 9a-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 geographical 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 experienced the Neolithic Revolution by the common era, OLS estimates of the effect of the time elapsed since the transition to agriculture may indeed suffer from omitted variable bias, reflecting spurious correlations with the outcome variable being examined.

To demonstrate 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 by biogeographic factors such 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 prehistorical biogeographic endowments 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 prehistorical domesticable species of wild plants and animals as instruments to establish the causal effect of transition timing on population density.[21]

The final two columns in Table 1 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

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[21] The numbers of prehistorical 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. As will become evident, the potential endogeneity of the biogeographic variables is rejected by the overidentifying restrictions test in all IV regressions examined.

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 identical.

Column 6 presents the IV regression results from estimating the baseline specification with log years since transition instrumented by the numbers of prehistorical domesticable species of plants and animals.[22] The estimated causal effect of transition timing 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 than the OLS estimate.[23] To interpret the causal impact of the Neolithic transition, 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 the agricultural productivity of land raises population density by 0.57%, conditional on transition timing, other geographical factors and continental fixed effects. Finally, it is reassuring to observe the rather large F-statistic in the first-stage regression, verifying the significance and explanatory power of the biogeographic instruments for the timing of the Neolithic Revolution. In addition, the high p-value associated with the test for overidentifying restrictions asserts that the instruments employed are indeed valid in that they do not 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 2 and 3 respectively. As before, the independent

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[22] See Table A5 in the appendix for the first-stage regression results.

[23] 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.

and combined explanatory powers of the transition timing and land productivity channels are examined while controlling for other geographical factors and unobserved continental characteristics.

Table 2: 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***		1.434***	1.480***	1.803***	2.933***
	(0.293)		(0.243)	(0.205)	(0.251)	(0.504)
Log Land Productivity		0.467***	0.550***	0.497***	0.535***	0.549***
		(0.079)	(0.063)	(0.056)	(0.098)	(0.092)
Log Absolute Latitude		-0.377**	-0.283**	-0.229**	-0.147	-0.095
		(0.148)	(0.117)	(0.111)	(0.127)	(0.116)
Mean Distance to Nearest Coast or River				-0.528***	0.147	0.225
				(0.153)	(0.338)	(0.354)
% Land within 100 km of Coast or River				0.716**	1.050**	1.358***
				(0.323)	(0.421)	(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	-	-	-	-	-	0.28

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 reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

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, as is the inverse relationship between absolute latitude and population density, particularly for the 1000 CE analysis.

Table 3: 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***		1.903***	1.930***	2.561***	3.459***
	(0.326)		(0.312)	(0.272)	(0.369)	(0.437)
Log Land Productivity		0.404***	0.556***	0.394***	0.421***	0.479***
		(0.106)	(0.081)	(0.067)	(0.094)	(0.089)
Log Absolute Latitude		-0.080	-0.030	0.057	0.116	0.113
		(0.161)	(0.120)	(0.101)	(0.121)	(0.113)
Mean Distance to Nearest Coast or River				-0.685***	-0.418	-0.320
				(0.155)	(0.273)	(0.306)
% Land within 100 km of Coast or River				0.857**	1.108***	1.360***
				(0.351)	(0.412)	(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	-	-	-	-	-	0.59

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 reported in parentheses; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

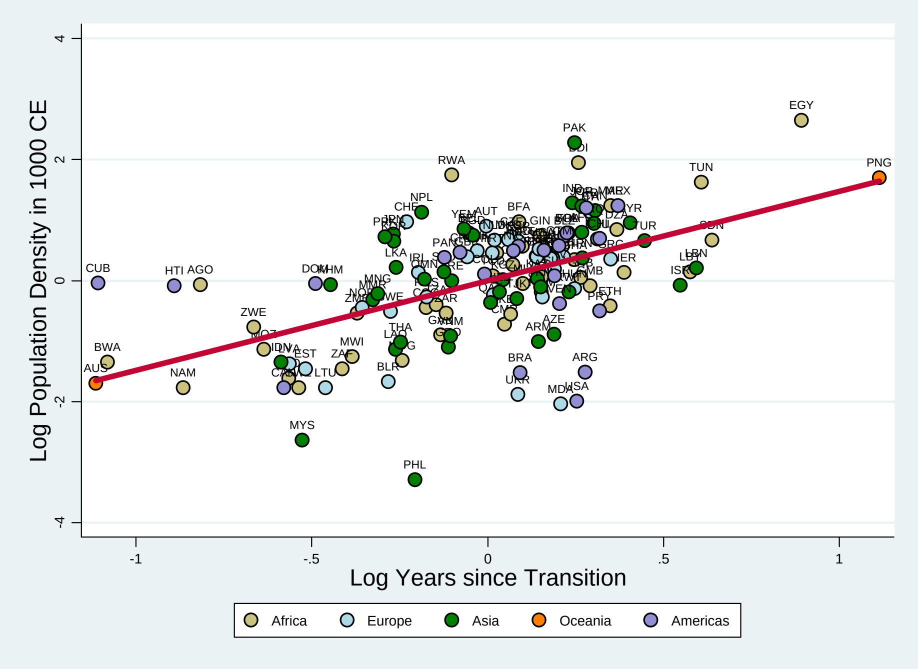

Figure 10a: Transition Timing and Population Density in 1000 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

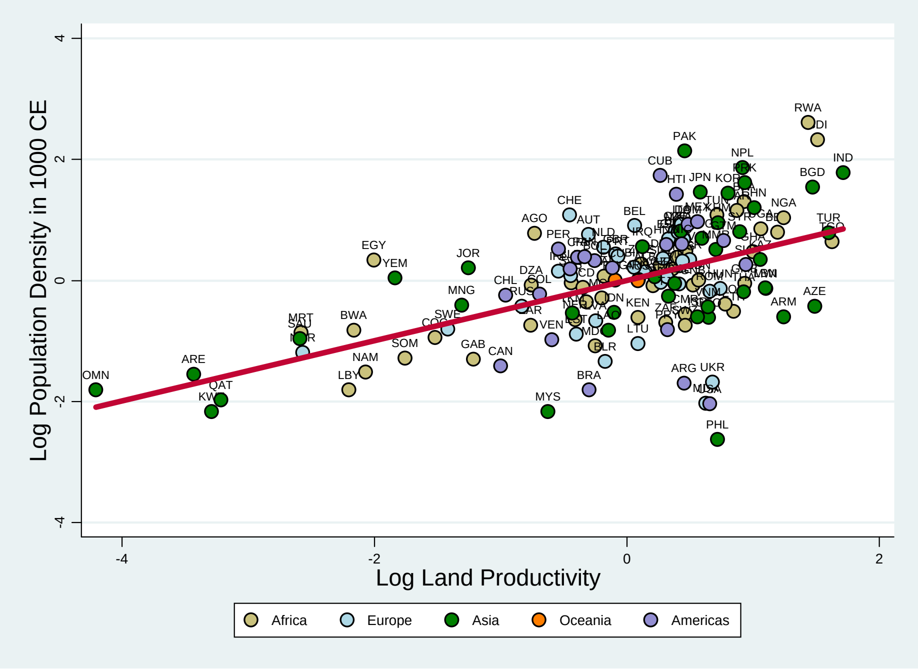

Figure 10b: Land Productivity and Population Density in 1000 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

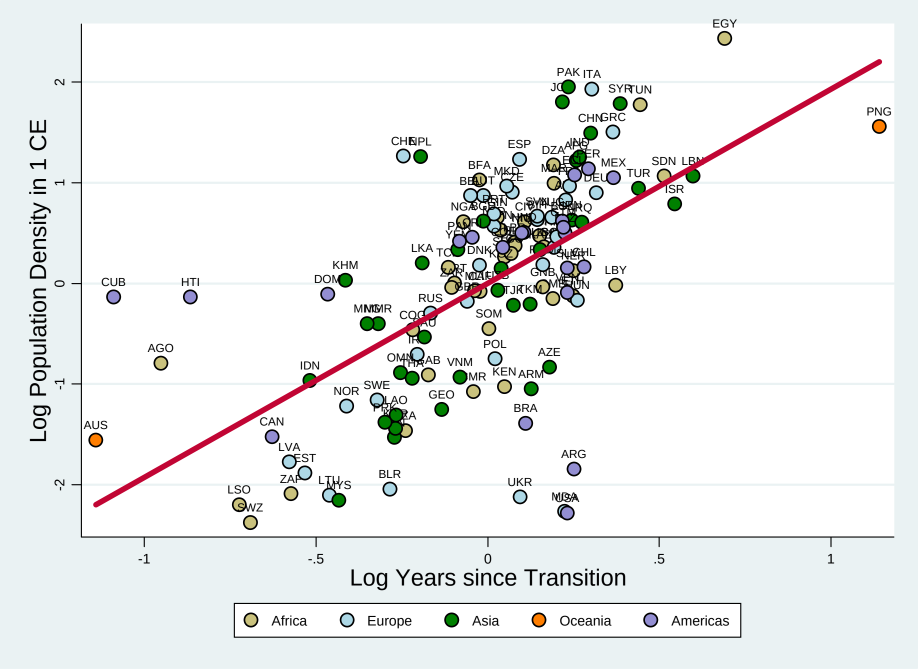

Figure 11a: Transition Timing and Population Density in 1 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

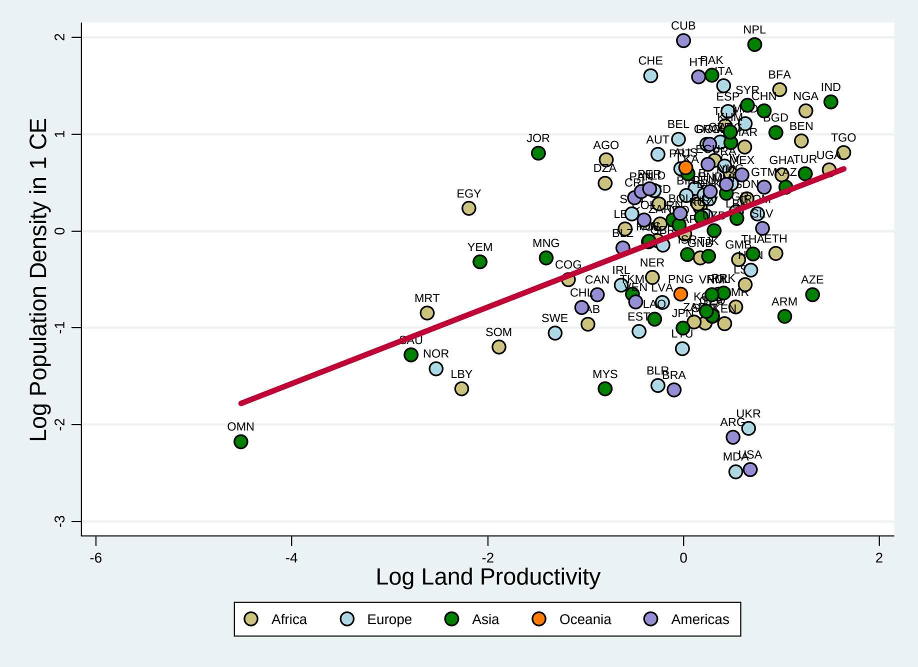

Figure 11b: Land Productivity and Population Density in 1 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

The stability patterns exhibited by the magnitude and significance of the coefficients on the explanatory variables of interest in Tables 2-3 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 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 in each historical period, a 1% increase in the number of years elapsed since 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. 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 on the scatter plots in Figures 10a-b for the 1000 CE analysis and in Figures 11a-b for the 1 CE analysis.

For the 1000 CE analysis, the additional sampling bias on OLS estimates introduced by moving to the IV-restricted subsample in Column 5 is similar to that observed in Table 1, whereas the bias appears somewhat larger for the analysis in 1 CE. This is attributable to the smaller size of the subsample in the latter analysis. The subsequent 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.[24] For instance, comparing the IV coefficient estimates on the transition timing variable across Tables 1-3, 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]

4.3 Income Per Capita versus Population Density

Table 4 presents the results from estimating the baseline empirical model, as specified in equation (9), for income per capita in the years 1500 CE, 1000 CE and 1 CE. Since historical income data is available for a relatively smaller set of countries, the analysis 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 manifested mostly in terms of higher population density, as the Malthusian theory would predict.

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[24] Another interesting pattern concerns the increasing strength and significance of the inverse relationship between population density and absolute latitude over time. This finding may in part reflect the assertion that technological diffusion during the Malthusian epoch, constrained largely amongst societies residing under similar geographical conditions, was complementary with the overall level of agricultural development. The importance of absolute latitude therefore increases at more advanced stages of development.

[25] The assertion that the process of economic 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 only on the productivity of land. 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:

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

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.

Table 4: Effects on Income Per Capita versus Population Density

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
	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 (0.136)	0.073 (0.045)	0.109 (0.072)	1.337** (0.594)	0.832** (0.363)	1.006** (0.483)
Log Land Productivity	0.041 (0.025)	-0.021 (0.025)	-0.001 (0.027)	0.584*** (0.159)	0.364*** (0.110)	0.681** (0.255)
Log Absolute Latitude	-0.041 (0.073)	0.060 (0.147)	-0.175 (0.175)	0.050 (0.463)	-2.140** (0.801)	-2.163** (0.979)
Mean Distance to Nearest Coast or River	0.215 (0.198)	-0.111 (0.138)	0.043 (0.159)	-0.429 (1.237)	-0.237 (0.751)	0.118 (0.883)
% Land within 100 km of Coast or River	0.124 (0.145)	-0.150 (0.121)	0.042 (0.127)	1.855** (0.820)	1.326** (0.615)	0.228 (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

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 reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

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. In particular, the effects on income per capita of Neolithic transition timing and land productivity are not only rather small in magnitude, 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 have much explanatory power for income per capita.

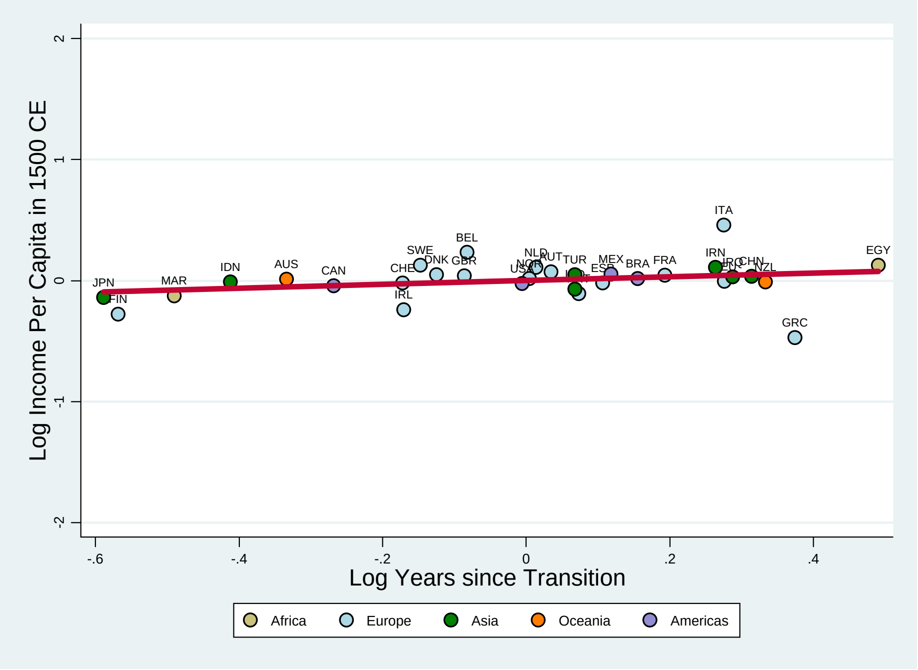

Figure 12a: Transition Timing and Income Per Capita in 1500 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

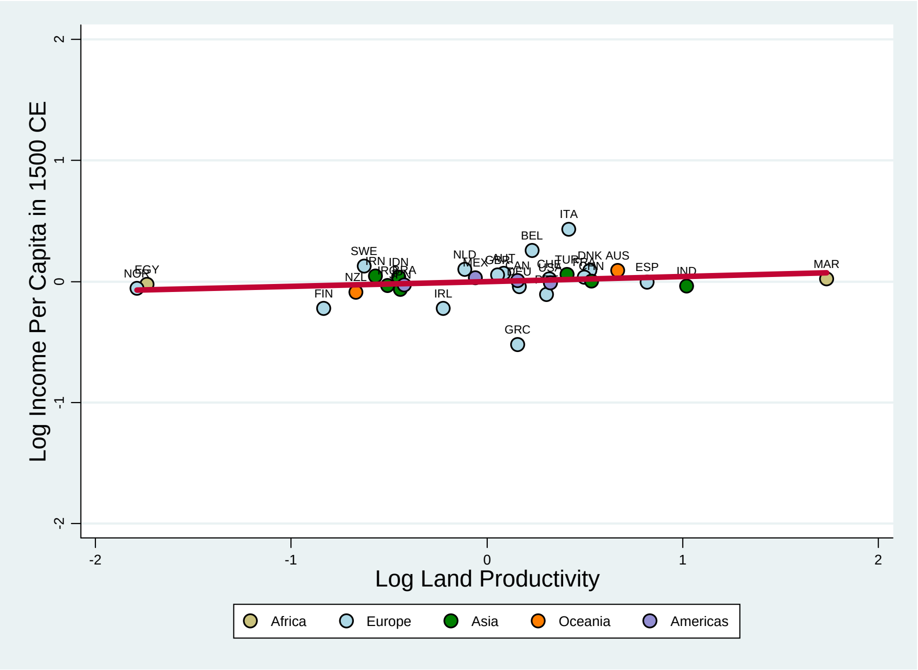

Figure 12b: Land Productivity and Income Per Capita in 1500 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

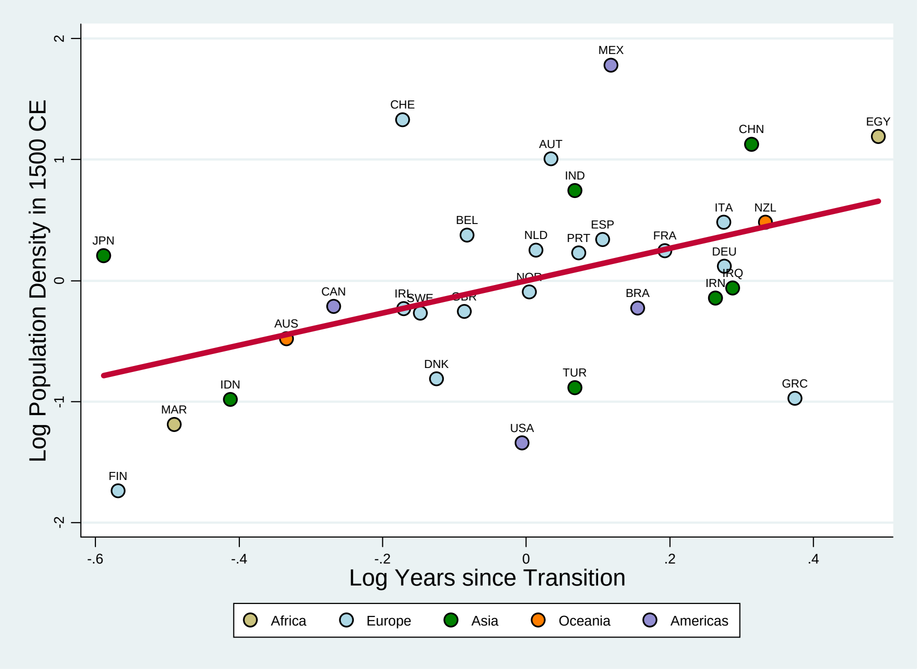

Figure 13a: Transition Timing and Population Density in 1500 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

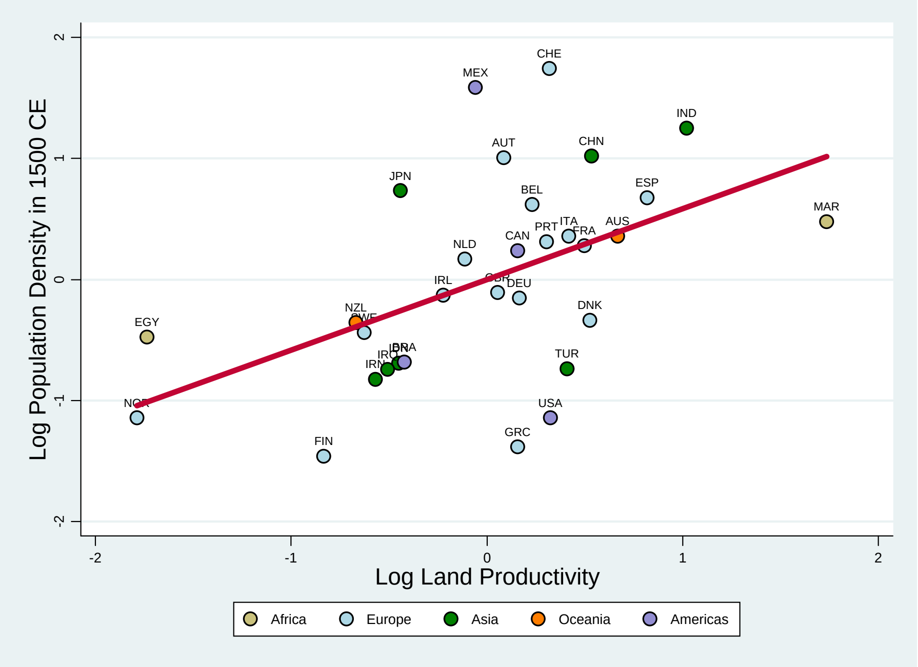

Figure 13b: Land Productivity and Population Density in 1500 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

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. These conditional effects on income per capita and population density are depicted on the scatter plots in Figures 12a-b and 13a-b respectively.

In general, the results presented in Table 4 indicate that, during the Malthusian epoch, more productive societies sustained higher population densities, as opposed to higher standards of living. This finding is 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 5 presents the results from estimating the baseline specification for population density and income per capita in the years 1000 CE and 1 CE, employing a more direct measure of technological sophistication in 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.

The index of technological sophistication, for each period examined, is constructed using historical cross-cultural technology data, reported with global coverage in Peregrine's (2003) Atlas of Cultural Evolution. Specifically, for a given time period and for a given culture in the archaeological record, Peregrine draws on various anthropological sources to report, on a 3-point scale, the level of technological advancement in each of four sectors including communications, ceramics and metallurgy, transportation, and agriculture. This data has recently been aggregated to the country-level for different historical periods by Comin et al. (2007) in order to demonstrate long-run persistence in cross-country patterns of technology adoption over time. Keeping with historical technology measures previously used in the literature for cross-country analyses, the index of technological sophistication employed by the current analysis was constructed following the aggregation methodology applied by Comin et al.

Table 5: Robustness to Direct Measures of Technological Sophistication

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS Full Sample	OLS Full Sample	OLS Income Sample	OLS Income Sample	OLS Income Sample	OLS Income Sample
	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 1000 CE	4.315*** (0.850)		0.064 (0.230)		12.762*** (0.918)	
Log Technology Index in 1 CE		4.216*** (0.745)		0.678 (0.432)		7.461** (3.181)
Log Land Productivity	0.449*** (0.056)	0.379*** (0.082)	-0.016 (0.030)	0.004 (0.033)	0.429** (0.182)	0.725** (0.303)
Log Absolute Latitude	-0.283** (0.120)	-0.051 (0.127)	0.036 (0.161)	-0.198 (0.176)	-1.919*** (0.576)	-2.350*** (0.784)
Mean Distance to Nearest Coast or River	-0.638*** (0.188)	-0.782*** (0.198)	-0.092 (0.144)	0.114 (0.164)	0.609 (0.469)	0.886 (0.904)
% Land within 100 km of Coast or River	0.385 (0.313)	0.237 (0.329)	-0.156 (0.139)	0.092 (0.136)	1.265** (0.555)	0.788 (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

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 (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; (iv) robust standard error estimates reported in parentheses; (v) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

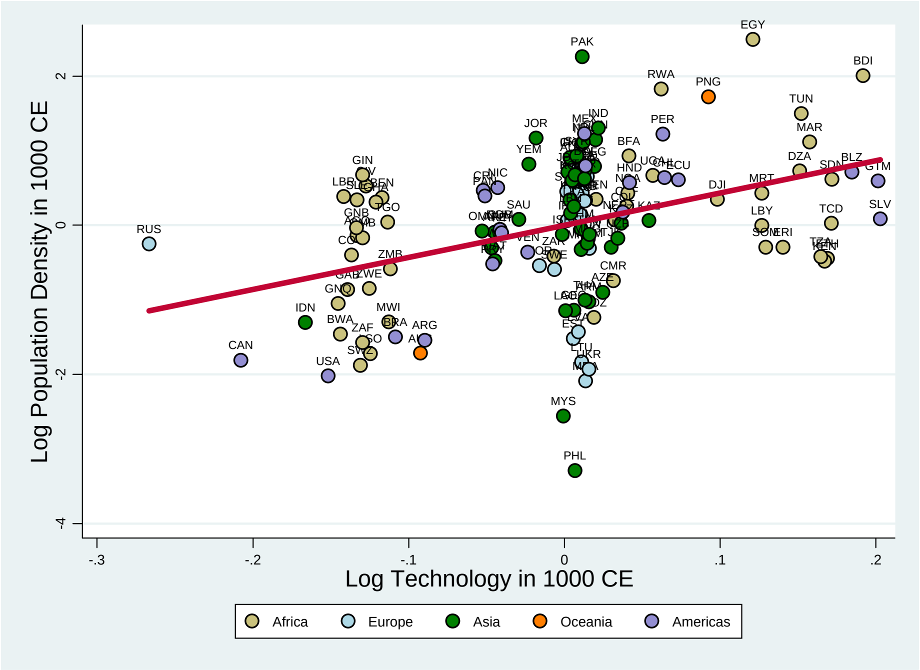

Figure 14a: Technology and Population Density in 1000 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

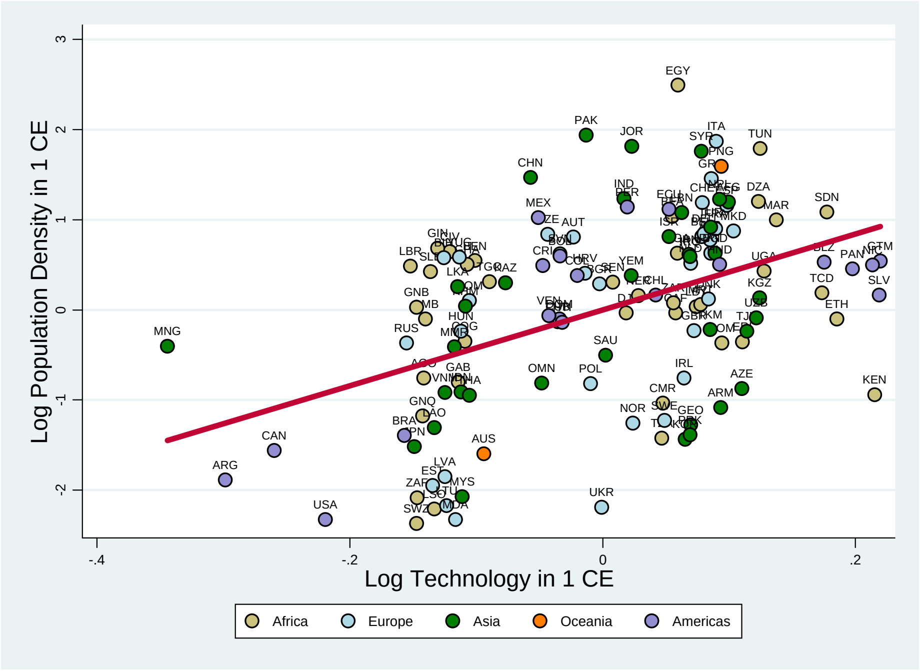

Figure 14b: Technology and Population Density in 1 CE

Conditional on Land Productivity, Geographical Factors and Continental Fixed Effects

Foreshadowing the qualitative robustness of the empirical 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 effects of technological sophistication on population density in the two time periods. To interpret the magnitude of these effects, a 1% increase in the level of technological sophistication in the years 1000 CE and 1 CE raises 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. Figures 14a-b depict the partial regression lines associated with these findings. In addition, Columns 1-2 also indicate that the effects of land productivity on population density remain largely stable in comparison to estimates presented in Tables 2-3.

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 effect of technological sophistication on population density is not only highly statistically significant, but at least an order of magnitude larger than its corresponding effect on income per capita. Indeed, the effect on 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 across regions, not as variations in the standard of living.

4.5 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 story. 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. Such a story would also imply, however, that changes in the level of technology should be positively associated with changes in the standard of living. This runs contrary to the Malthusian prediction that changes in the level of technology should ultimately translate into changes in population density, leaving income per capita constant at the subsistence level. Thus, examining the effect of changes on changes, as opposed to levels on levels, constitutes a more discriminatory test of the Malthusian model.

Moreover, the results of the level regressions in Table 5, indicating the significant positive effect of the level of technology on population density but its neutrality for income per capita, may simply 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.

Table 6: Robustness to First Differences

	(1)	(2)
	OLS	OLS
	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^{***} (1.771)	0.522 (0.573)
Constant	0.216^{*} (0.110)	-0.045 (0.036)
Observations	26	26
R-squared	0.36	0.03

Notes – (i) the absense of controls from both regressions is justified by the removal of country fixed effects through the application of the first difference methodology; (ii) robust standard error estimates reported in parentheses; (iii) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

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. In particular, the analysis compares the results from estimating the following empirical models:

$$\begin{aligned} \Delta \ln P_{i,t} &= \mu_0 + \mu_1 \Delta \ln A_{i,t} + \phi_{i,t}, \qquad (11) \\ \Delta \ln y_{i,t} &= \nu_0 + \nu_1 \Delta \ln A_{i,t} + \psi_{i,t}, \qquad (12) \end{aligned}$$

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 respectively. These models are simply the first-difference counterparts of (8) and (9) when $\ln A_{i,t}$ is used in lieu of $\ln T_i$ in those specifications.

Table 6 presents the results from estimating equations (11) and (12). 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 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 results from the first-difference estimation strategy adopted here lend further credence to the Malthusian interpretation of the level regression results presented earlier.

4.6 Long-Run Population Dynamics

Table 7 presents the results of regressions examining the Malthusian prediction of conditional convergence in the 1-1000 CE and 1000-1500 CE time horizons. In particular, the empirical model specified in equation (10) is estimated and the qualitative robustness of the regression results is verified, first, in subsamples eliminating the influence of potential outliers, and second, when the indices of technological sophistication in the years 1000 CE and 1 CE are employed in lieu of the timing of the Neolithic Revolution.

Table 7: Long-Run Population Dynamics

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS Full Sample	OLS No Outliers	OLS No Outliers	OLS Full Sample	OLS No Outliers	OLS No Outliers
	Average Rate of Population Growth, 1 CE - 1000 CE			Average Rate of Population Growth, 1000 CE - 1500 CE		
Log Initial Population Density	-0.219*** (0.043)	-0.162*** (0.029)	-0.199*** (0.031)	-0.161*** (0.033)	-0.174*** (0.031)	-0.192*** (0.029)
Log Years since Neolithic Transition	-0.101 (0.121)	-0.101 (0.099)		-0.151* (0.089)	-0.117 (0.081)	
Log Initial Technology Index			0.375* (0.225)			0.145 (0.234)
Log Land Productivity	0.113*** (0.032)	0.079*** (0.028)	0.107*** (0.026)	0.146*** (0.023)	0.148*** (0.023)	0.149*** (0.024)
Log Absolute Latitude	-0.198*** (0.057)	-0.241*** (0.045)	-0.244*** (0.042)	-0.127*** (0.029)	-0.135*** (0.028)	-0.134*** (0.028)
Mean Distance to Nearest Coast or River	-0.128* (0.075)	-0.071 (0.059)	-0.074 (0.061)	-0.025 (0.058)	-0.035 (0.056)	-0.018 (0.058)
% Land within 100 km of Coast or River	0.290 (0.199)	0.019 (0.125)	0.044 (0.107)	0.144 (0.120)	0.110 (0.116)	0.171 (0.109)
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	128	125	126	142	141	139
R-squared	0.49	0.62	0.63	0.48	0.51	0.48

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) in regressions (2)-(3), the set of outliers omitted from the sample include Japan, North Korea and South Korea; (iii) the outlier omitted in regressions (5)-(6) is Japan; (iv) a single continent dummy is used to represent the Americas, which is natural given the historical period examined; (v) robust standard error estimates reported in parentheses; (vi) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

Columns 1 and 4 establish the conditional convergence of population density across countries during the 1-1000 CE and 1000-1500 CE time horizons, employing, for each time span, the full sample of countries for which population growth rates can be calculated from the data available on population levels.

Specifically, a statistically significant negative effect of initial population density on the rate of population growth is revealed in each of the historical time spans examined. The estimated OLS coefficients indicate that, conditional on the timing of the Neolithic, land productivity, geographical factors, and continent fixed effects, a 1% increase in population density in the years 1 CE and 1000 CE is respectively associated with a 0.22% decrease and a 0.16% decrease in the average rate of population growth during the 1-1000 CE and 1000-1500 CE time horizons.

Interestingly, the productivity of land confers significant positive effects on population growth in the two time spans, suggesting, consistently with the theory, the existence of upward pressures on conditional Malthusian steady states due to higher productivity. On the other hand, and perhaps contrary to priors, the number of years elapsed since the Neolithic transition has a negative, but generally insignificant, effect on population growth in each time horizon. This finding, however, is entirely consistent with the assertion that the process of development initiated by the Neolithic Revolution was characterized by diminishing social gains over time.[26]

To ensure that the convergence results from Columns 1 and 4 were not being driven by the influence of outliers, the empirical models for population growth in the two time spans were re-estimated using samples eliminating these outliers.[27] The results from these regressions are revealed in Columns 2 and 5. Reassuringly, the results continue to confirm the convergence hypothesis through highly statistically significant negative effects of initial population densities on subsequent population growth rates. In particular, a 1% increase in population density in the years 1 CE and 1000 CE is associated with a 0.16% decrease and a 0.17% decrease in the average rate of population growth during the 1-1000 CE and 1000-1500 CE time horizons respectively, conditional on the timing of the Neolithic, land productivity, geographical factors, and continent fixed effects. The partial regression lines reflecting these relationships between initial population densities and the subsequent rates of population growth are depicted in Figures 15a-b.

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[26] Despite the importance of access to waterways in determining population levels, the explanatory power of these variables appears to be negligible for population growth rates, suggesting that the beneficial effects of trade and technological diffusion, as captured by these variables, remained fixed over time, at least during the 1500-year period examined in this study. However, the finding that absolute latitude has a significant negative effect on the rate of population growth in each time span is consistent with complementarity between technological diffusion and the level of development, as suggested in Footnote 24.

[27] Sample outliers were identified by examining partial scatter plots for each explanatory variable in the baseline specification and selecting those observations that were consistently located at a disproportionately large distance from the partial (covariate-adjusted) regression lines. The outliers identified in the 1-1000 CE analysis were Japan, North Korean and South Korea, whereas Japan was the only identifiable outlier in the 1000-1500 CE analysis.

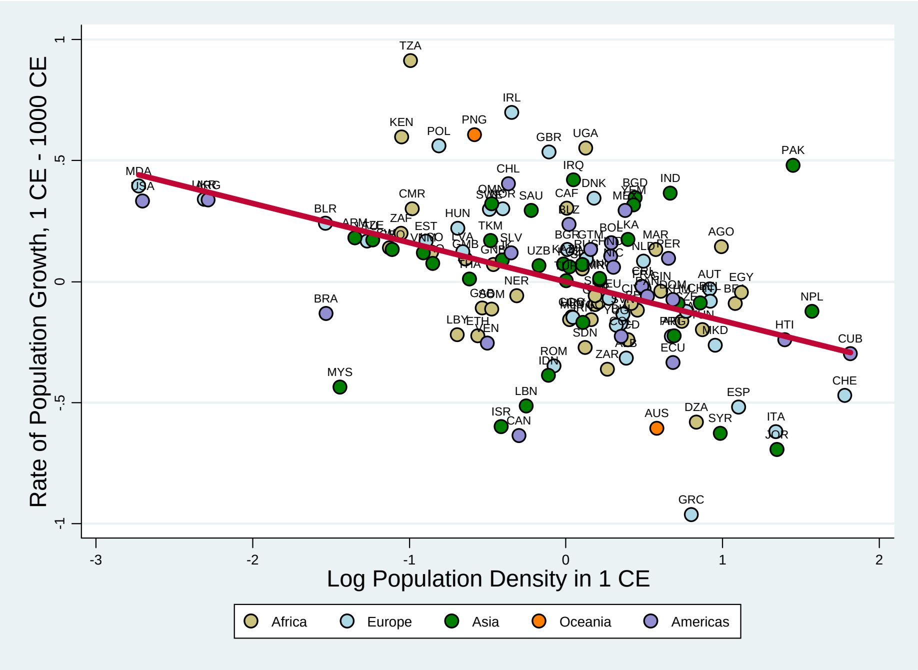

Figure 15a: Initial Density and Population Growth, 1-1000 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

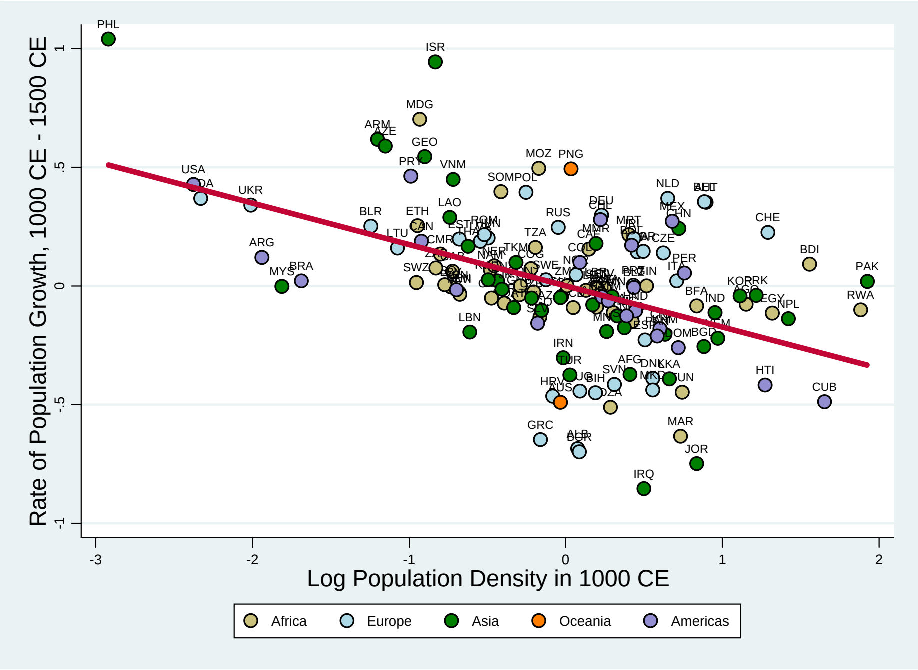

Figure 15b: Initial Density and Population Growth, 1000-1500 CE

Conditional on Transition Timing, Geographical Factors and Continental Fixed Effects

Finally, Columns 3 and 6 demonstrate the robustness of the findings from earlier columns when the indices for technology in the years 1000 CE and 1 CE are employed by the analysis. Specifically, the negative relationship between initial population density and the subsequent rate of population growth, in each time horizon, is largely unaffected when accounting for initial productivity with a more direct measure of the degree of technological sophistication. It is also interesting to note that, in general, the estimated coefficients on initial population density in the two time spans examined are not significantly different from one another. This suggests that on average societies were as far from their respective steady states in the year 1 CE as they were in 1000 CE, a finding consistent with the notion that Malthusian steady-states were implicitly admitting larger populations due to technological progress that occurred in pre-industrial times.

5 Concluding Remarks

This paper empirically tests the predictions of the Malthusian theory regarding population density, income per capita, and population dynamics in the pre-Industrial Revolution 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. Technologically superior economies ultimately had denser populations but their standard of living did not reflect the degree of their technological advancement. Thus, a region's population density, as opposed to its income per capita, would have largely reflected its carrying capacity, determined by the effective resource constraints that were binding for that region.

The theory is therefore tested in several dimensions, including (i) the notion that population density in the Malthusian epoch was constrained by the availability of *natural* resources, but income per capita was independent of it, and (ii) the role of technological progress in expanding *effective* resources and, thus, population density, while leaving income per capita unchanged in the long run. Specifically, since resource constraints were slacker for regions naturally blessed by greater land productivity, they would have sustained larger populations, given the level of technological advancement. On the other hand, given land productivity, societies with more advanced technologies, as reflected by their cumulative experience with the agricultural production paradigm since the Neolithic Revolution, would have sustained higher population densities. However, societies that experienced an earlier onset of the Neolithic Revolution, or those characterized by higher land productivity, would not have enjoyed higher standards of living.

The Malthusian theory predicts that regional variation in population density in the long run would ultimately reflect variations in land productivity and biogeographic attributes. Thus, for a given technological environment, greater land productivity, such as a higher arable percentage of land, better soil quality, and a favorable climate, would enable society to sustain a larger population. 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 via trade and the implementation and diffusion of agricultural technologies. The variations in land productivity and biogeographic factors, however, would not be manifested as significant differences in income per capita across regions.

Consistent with the predictions of the Malthusian theory, 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. These results are shown to remain robust to controls for other geographical factors such as absolute latitude and access to waterways, which historically played a major role in facilitating trade and technological diffusion, and to biogeographic instrumental variables, employed to establish causality. In contrast to their effects on historical population density, and in full compliance with the Malthusian theory, the effects of land productivity and timing of the Neolithic Revolution on income per capita in the years 1500 CE, 1000 CE and 1 CE are indeed not significantly different from zero. The empirical findings also reveal, in line with the Malthusian prediction of conditional convergence, statistically significant negative relationships between initial population density and the average rate of population growth in the 1-1000 CE and the 1000-1500 CE time horizons. These results remain 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.

Interestingly, the empirical analysis also dispels a non-Malthusian story, consistent with the level regression results. In a world admitting 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. Labor inflows in response to technological improvements in a given region, however, 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 was, in fact, unaffected by technological improvements during this period as suggested by the Malthusian theory.

Data Appendix

Population Density in 1, 1000, 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 Development Indicators online database. The cross-sectional unit of observation in McEvedy and Jones 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.

Population Growth Rate, 1-1000 CE and 1000-1500 CE: The average rate of population growth in a given time interval is calculated as the difference in log population density between the ending and starting years of the time interval, using the data described above.

Income Per Capita in 1, 1000, and 1500 CE: The level of income per capita in a given year, as reported by Maddison (2003). More details available on the author's website.

Years since Neolithic Transition: The time elapsed (in thousands of years) since the Neolithic transition to agriculture, as reported by Putterman (2006). This dataset was compiled using a wide variety of country and region-specific sources from the Archaeological literature. A detailed description of Putterman's data and original data sources is available in the public domain at the author's website.

Technology Index in 1 and 1000 CE: The index of technology for a given year is calculated as the cross-sectoral average of sector-specific levels of technology, reported on a 3-point scale by Peregrine (2003). Following the methodology adopted by Comin et al. (2007), the index employs technology data on four sectors, including communications, ceramics and metalworks, transportation, and agriculture, and is normalized to take a value on the [0,1] interval. 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. Since spatial delineations in Peregrine 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 borders of a given country. For more details on the underlying data and methodology employed to compute this index, see Peregrine (2003) and Comin et al. (2007).

Land Productivity: Land productivity is composed of the arable percentage of land, as reported by the World Development Indicators database, and an agricultural suitability index of land, based on soil pH levels and temperature, as reported 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 World Factbook available online.

Mean Distance to Nearest Coast or River: The expected distance (in thousands of km) from any GIS grid point within a country to the nearest ice-free coastline or sea-navigable river, as reported in the physical geography dataset available online from the Center for International Development.

Land within 100 km of Coast or River: The percentage of a country's land area located within 100 km of the nearest ice-free coastline or sea-navigable river, as reported in the physical geography dataset available online from the Center for International Development.

Plants and Animals (used as instruments for Years since Transition): 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).

	Obs.	Mean	S. D.	Min.	Max.
Log Population Density in 1500 CE	148	0.880	1.491	-3.817	3.842
Log Population Density in 1000 CE	143	0.464	1.437	-4.510	2.989
Log Population Density in 1 CE	128	-0.068	1.538	-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	148	8.349	0.594	5.991	9.259
Log Technology Index in 1000 CE	142	0.572	0.160	0.118	0.693
Log Technology Index in 1 CE	142	0.528	0.164	0.061	0.693
Log Land Productivity	148	0.067	1.212	-4.344	1.657
Log Absolute Latitude	148	2.985	0.966	-0.693	4.159
Mean Distance to Coast or River	147	0.353	0.458	0.014	2.386
Land w/in 100 km of Coast or River	147	0.435	0.367	0.000	1.000

Table A1: Summary Statistics of the Sample used in Level Regressions

	1	2	3	4	5	6	7	8	9	10	11	12
Log Population Density in 1500 CE	1.000											
Log Population Density in 1000 CE	0.963	1.000										
Log Population Density in 1 CE	0.875	0.937	1.000									
Log Income Per Capita in 1500 CE	0.762	0.642	0.670	1.000								
Log Income Per Capita in 1000 CE	0.128	0.238	0.253	0.106	1.000							
Log Income Per Capita in 1 CE	0.225	0.323	0.453	0.337	0.485	1.000						
Log Years since Neolithic Transition	0.507	0.566	0.649	0.561	0.463	0.415	1.000					
Log Technology Index in 1000 CE	0.593	0.575	0.577	0.646	0.303	0.329	0.709	1.000				
Log Technology Index in 1 CE	0.509	0.541	0.573	0.635	0.283	0.380	0.593	0.828	1.000			
Log Land Productivity	0.521	0.435	0.393	0.408	-0.115	-0.051	-0.004	0.008	-0.104	1.000		
Log Absolute Latitude	0.106	0.103	0.302	0.320	-0.363	-0.302	0.324	0.343	0.284	0.130	1.000	
Mean Distance to Coast or River	-0.308	-0.337	-0.376	-0.387	0.173	-0.123	-0.027	0.003	-0.042	-0.231	-0.059	1.000
Land w/in 100 km of Coast or River	0.386	0.366	0.400	0.452	-0.417	0.002	0.117	0.103	0.109	0.327	0.263	-0.670

Table A2: Pairwise Correlations in the Sample used in Level Regressions

	Obs.	Mean	S. D.	Min.	Max.
Population Growth, 1000-1500 CE	143	0.499	0.395	-0.696	1.609
Population Growth, 1-1000 CE	128	0.648	0.541	-0.693	2.708
Log Population Density in 1000 CE	143	0.464	1.437	-4.510	2.989
Log Population Density in 1 CE	128	-0.068	1.538	-4.510	3.170
Log Years since Neolithic Transition	143	8.365	0.587	5.991	9.259
Log Technology Index in 1000 CE	137	0.580	0.154	0.118	0.693
Log Technology Index in 1 CE	138	0.533	0.159	0.061	0.693
Log Land Productivity	143	0.085	1.221	-4.344	1.657
Log Absolute Latitude	143	2.989	0.959	-0.693	4.127
Mean Distance to Coast or River	142	0.360	0.464	0.014	2.386
Land w/in 100 km of Coast or River	142	0.435	0.370	0.000	1.000

Table A3: Summary Statistics of the Sample used in Growth Regressions

	1	2	3	4	5	6	7	8	9	10
Population Growth, 1000-1500 CE	1.000									
Population Growth, 1-1000 CE	0.291	1.000								
Log Population Density in 1000 CE	-0.112	-0.084	1.000							
Log Population Density in 1 CE	-0.165	-0.428	0.937	1.000						
Log Years since Neolithic Transition	-0.201	-0.385	0.566	0.649	1.000					
Log Technology Index in 1000 CE	-0.010	-0.146	0.575	0.577	0.727	1.000				
Log Technology Index in 1 CE	-0.176	-0.152	0.541	0.573	0.613	0.813	1.000			
Log Land Productivity	0.362	-0.007	0.435	0.393	-0.010	0.001	-0.109	1.000		
Log Absolute Latitude	0.011	-0.446	0.103	0.302	0.356	0.347	0.278	0.124	1.000	
Mean Distance to Coast or River	-0.056	0.028	-0.337	-0.376	-0.045	-0.020	-0.059	-0.240	-0.059	1.000
Land w/in 100 km of Coast or River	0.160	-0.081	0.366	0.400	0.148	0.118	0.110	0.326	0.255	-0.675

Table A4: Pairwise Correlations in the Sample used in Growth Regressions

	(1)	(2)	(3)
	1500 CE Sample	1000 CE Sample	1 CE Sample
	Log Years since Neolithic Transition		
Excluded Instruments:			
Domesticable Plants	0.012**	0.013**	0.012**
	(0.005)	(0.005)	(0.006)
Domesticable Animals	0.067**	0.064**	0.048*
	(0.029)	(0.028)	(0.029)
Second-Stage Controls:			
Log Land Productivity	0.040	0.025	-0.011
	(0.049)	(0.049)	(0.037)
Log Absolute Latitude	-0.127***	-0.127***	-0.083*
	(0.042)	(0.043)	(0.044)
Mean Distance to Nearest Coast or River	0.127	0.103	0.094
	(0.141)	(0.140)	(0.156)
% Land within 100 km of Coast or River	-0.165	-0.190	-0.227
	(0.137)	(0.136)	(0.136)
Continent Dummies	Yes	Yes	Yes
Observations	96	94	83
R-squared	0.68	0.70	0.71
Partial R-squared (Excl. Instr.)	0.27	0.28	0.25
F-statistic (Test of Excl. Instr.)	14.65	15.10	10.85

NOTES – (i) robust standard error estimates reported in parentheses; (ii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided tests.

Table A5: First-Stage Regressions of Instrumented Transition Timing

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