JOURNAL OF ECONOMICS TEACHING

A Malthusian Model for Undergraduates

This article presents a simplified Malthusian growth model that is appropriate for undergraduate classes not requiring calculus. The model stresses the role of fixed factors of production and preferences for net fertility, which are the focus of academic research in this area. The Malthusian model can be heuristically derived from the Solow model. The connection to the Solow model helps reinforce key methodological tools, like phase diagrams and steady states, that are often difficult for new students in economics. The connection to the Solow model also allows students to think about how an economy might transition from a Malthusian world to a more modern regime captured by the Solow model. This transition plays a key role in academic growth theory, but is rarely covered in undergraduate classes.

Gregory Casey†

†Williams College

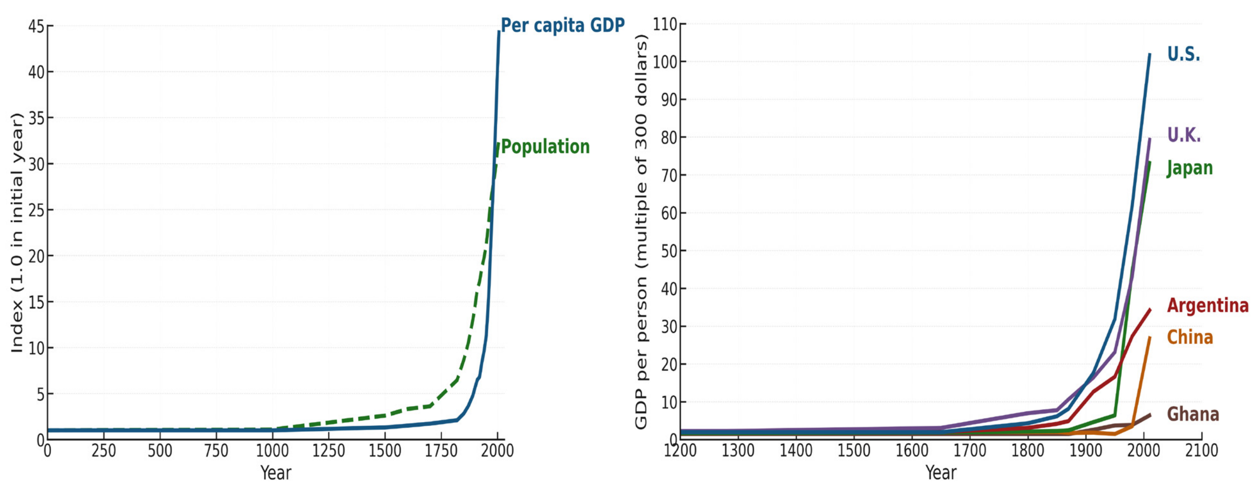
1. Introduction

Acemoglu (2013) argues that undergraduate economics education would benefit from an increased focus on long-run growth and development, especially early in the major. This paper takes a step toward this goal by introducing a simple version of the Malthusian growth model that can be used in undergraduate classes that do not require calculus. The model builds directly on cutting-edge academic research, specifically Ashraf & Galor (2011). It provides simple explanations for striking empirical results that students may find counterintuitive, demonstrating the value of simple models.

The Malthusian model presented here can be heuristically derived from a simplified pedagogical version of the Solow model found in intermediate macroeconomics textbooks from N. Gregory Mankiw (e.g., Mankiw & Ball, 2011; Mankiw, 2019). This simple model has two key benefits. First, it allows for a simple discussion of how an economy might transition from a Malthusian regime with constant income per capita to a more modern regime characterized by continuous economic development. Research in economic growth stresses this transition as a key determinant of historical growth rates and therefore contemporary differences in income per capita across countries (e.g., Galor & Weil, 2000; Hansen & Prescott, 2002; Lucas, 2018). A second benefit of the model is that it reinforces the important methodological tools that students learn via the Solow model, phase diagrams, and steady states, which often represent a difficult departure from the static diagrams that students are used to seeing.

2. Historical Context

Figure 1: Historical Data on Long-Run Growth



(a) Growth in the 'West'

(b) Great Divergence

Figure 1 recreates two important figures on long-run economic development from Jones (2016). The original data are from Maddison (2008). Panel (a) shows the evolution of population and income per capita in the 'West' as defined by Maddison (2008). Exponential growth in income per capita and population is a relatively recent phenomenon. Economic history is characterized by long periods of relatively constant income and population. The rapid take-off in income per capita that occurred in the late 1700s and early to mid-1800s was a break from historical experience, and it transformed living standards for millions of people.

The models taught in macroeconomic courses, the Solow model and sometimes endogenous growth extensions, are valuable tools for characterizing and analyzing the relatively recent phenomenon of sustained economic growth. Malthusian models aim to capture the earlier period of stagnation (Ashraf & Galor, 2011). The name refers to the influential work of Malthus (1798) who argued that population growth explained the ongoing historical stagnation in income per capita and that such stagnation would likely continue.

Given the far-reaching consequences of the shift from a world of Malthusian stagnation to one of exponential growth, scholars have long studied the factors that led to this change (Galor, 2011). Although the exact causes are still debated, the original take-off coincided with the Industrial Revolution, and many believe that the two are closely linked (Lucas, 2004; Clark, 2014).

Panel (b) of Figure 1 shows that this rapid increase in income per capita in some areas also led to a significant increase in global inequality. Thus, studying the transition from stagnation to growth is relevant for understanding comparative development.[1]

3. Model

The model is based on the work of Ashraf & Galor (2011), but does not require calculus, making it accessible to a wide range of students in economics. The model stresses two key forces: (i) the role of fixed production factors (i.e., land) and (ii) preferences for net fertility.[2]

A. Background

To start, consider a standard undergraduate-level presentation of the Solow model due to Mankiw (2019):

$$\underset{\text{change in k}}{\Delta \mathrm{k}} = \underset{\text{new k}}{sf(k)} - \underset{\text{lost k}}{(n+\delta+g)k}, \tag{1}$$

where k is capital per effective worker, s is the savings rate, $f(k)$ is the output per effective worker, n is population growth, δ is the depreciation rate, and g is the growth rate of productivity (i.e., technology). The level of productivity will be represented by A and is introduced to the students in the course of learning the Solow model.

There are parts of this equation that warrant further discussion. First, there is a slight mixing of discrete and continuous time, since Δk is usually presented as the change in the capital/labor ratio over one year, but the dynamic equation here is only exactly correct in continuous time. This presentation simplifies both the math and the graphical presentation. Second, the presentation uses the general functional form $f(k)$, rather than a specific functional form such as Cobb-Douglas.[3] Third, this presentation includes technological progress, implying

[1] The model discussed here will not speak directly to differences in take-off timing across countries. However, the connection to global inequality is still helpful for motivating the topic in undergraduate courses. In my courses, I follow the class on Malthus with a class on comparative development and use the evidence on the differential timing of take-offs to set up a discussion of the relationship between historical and geographic factors and contemporary economic outcomes.

[2] For teachers not wishing to stress demographic preferences, the model is compatible with a more reduced form approach to population dynamics, while still capturing the key role of land.

[3] I have found the translation from general functional forms to Cobb-Douglas to be an informative problem set question.

that $k = K/(AL)$. Including technological progress can be useful because technology plays a role in the transition from stagnation to growth. However, it is straightforward to start with a version of the Solow model that does not include technology. Finally, in my classes, I often use the Solow model to discuss human capital, which can be created through education and health spending, much like physical capital can be created through investment. This introduction to human capital is helpful for thinking about the transition from Malthusian to Solowian settings.

B. A Heuristic Derivation

Table 1: Malthusian Model: Variables and Parameters

Symbol	**Description**
X	Land
L	Population
Y	Output
$\bar{A}$	Productivity level
y	Income per capita ($y = Af(x)$)
x	Land per person
n	Net population growth rate ($n = n(y)$)
$\bar{n}$	Income sensitivity of n
$\bar{c}$	Subsistence income

Now, we will derive the dynamics of a Malthusian economy from the Solow model. The variables and parameters are listed in Table 1. We will rely on three key differences between these time periods. In the historical period:

1. technological progress was erratic and did not exhibit the sustained growth assumed in the Solow model.
2. fixed factors of production (e.g., land) played a greater role.
3. population growth increased with income.

I will use X to represent land.

Since there is no technological progress, we can set $g = 0$. The level of technology is a constant exogenous parameter, which we denote with $\overline{A}$.[4] Drawing on insights from the Solow model without technology, students will know that it is possible to write:

$$Y = \overline{A}F\left(X, L\right) \tag{2}$$

and

$$y \equiv \frac{Y}{L} = \overline{A}f\left(x\right), \tag{3}$$

where Y is total output and $x \equiv X/L$ is land per person. So, we need an equation to keep

[4] This maintains consistency with the notation from Mankiw (2019), who also uses bars to denote constant quantities.

track of how land per person evolves. Thus, the starting point for the rest of the derivation is

$$\underbrace{\Delta x}_{\text{change in x}} = \underbrace{s\overline{A}f\Big(x\Big)}_{\text{new x}} - \underbrace{(n+\delta)x}_{\text{lost x}} \tag{4}$$

Then, we note that land cannot be accumulated, unlike physical capital that can be reproduced through investment. So, $s = \delta = 0$ and

$$\Delta x = -nx. \tag{5}$$

The growth rate of land per capita, and therefore income per capita, is determined by the rate of population growth. Income per capita growth is greater than zero if and only if the growth rate of the population is negative. This intuition is crucial for understanding the phase diagram.

In a Malthusian setting, the growth rate of the population is increasing with income. This can be captured with the following equation:

$$n = \overline{n}(y - \bar{c}) \tag{6}$$

Since n is bounded below by -1, we assume $\overline{n}\bar{c} \leq 1$, which implies that $n \geq -1$ when $y = 0$. Parameter $\bar{c}$ is the 'subsistence consumption' level, i.e., the level of consumption consistent with zero population growth. Parameter $\overline{n} > 0$ captures preferences for fertility. When $\overline{n}$ is large, parents place a high weight on having children relative to supporting their own consumption. Importantly, $\overline{n}$ is the *net* population growth rate. It accounts for how fertility decisions respond to the mortality rate. These two forces, subsistence constraints and preferences for net fertility, are the driving forces in leading growth models that explain the Malthusian population dynamics (e.g., Galor & Weil, 2000; Ashraf & Galor, 2011).

Putting everything together,

$$\Delta x = -\overline{n}\Big(\overline{A}f\Big(x\Big) - \bar{c}\Big)x. \tag{7}$$

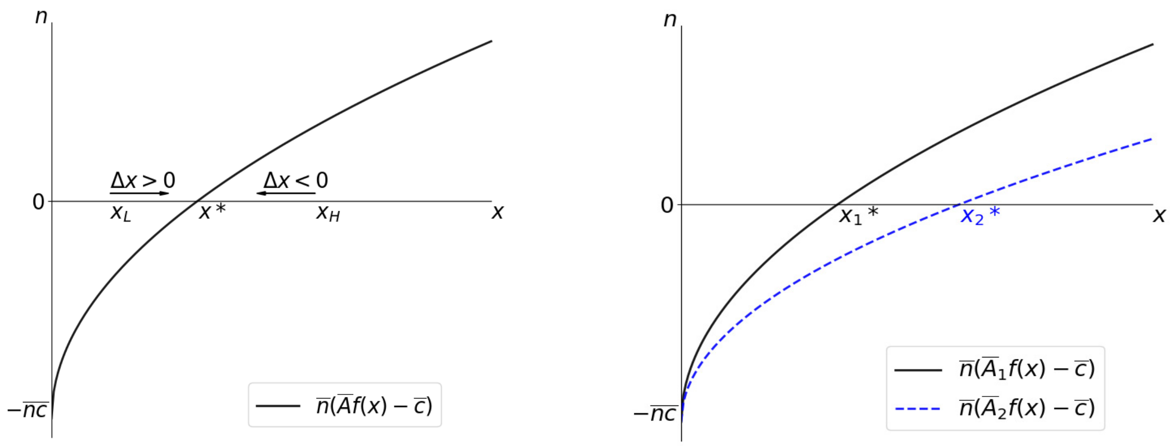
The term $xf(x)$ is more complicated than students are used to seeing, but the exact shape of this product is not relevant for understanding the predictions of the model. Since $\overline{n}x > 0$, the sign of Δx only depends on whether income per capita is above or below the subsistence consumption level:

$$\Delta x > 0 \Longleftrightarrow \overline{A}f\Big(x\Big) < \bar{c}. \tag{8}$$

This equation is simply an alternate way of saying that endogenous changes in the land-labor ratio (and income per capita) are determined solely by changes in population. As in the Solow model, it is straightforward for students to find the steady state:

$$y^* = Af(x^*) = \bar{c}. \tag{9}$$

Figure 2: Malthusian Steady State



(a) Stability

(b) Comparative Statics

This equation highlights one of the main predictions of the Malthusian model: income per capita is always pushed to the 'subsistence' level that is consistent with zero population growth.

To analyze the stability of the steady state, we can focus on whether population growth is positive or negative. In the context of the Solow model, students have already studied the shape of *f(x)*, making it straightforward to analyze:

$$n\left(x\right) = \overline{n} - A\left(\bar{f}\left(x\right) - \bar{c}\right). \tag{10}$$

The term $\overline{n}A\bar{f}\left(x\right)$ has the same shape as *sf(k)* in the Solow model, and the term $-\overline{n}\bar{c}$ just changes the intercept.

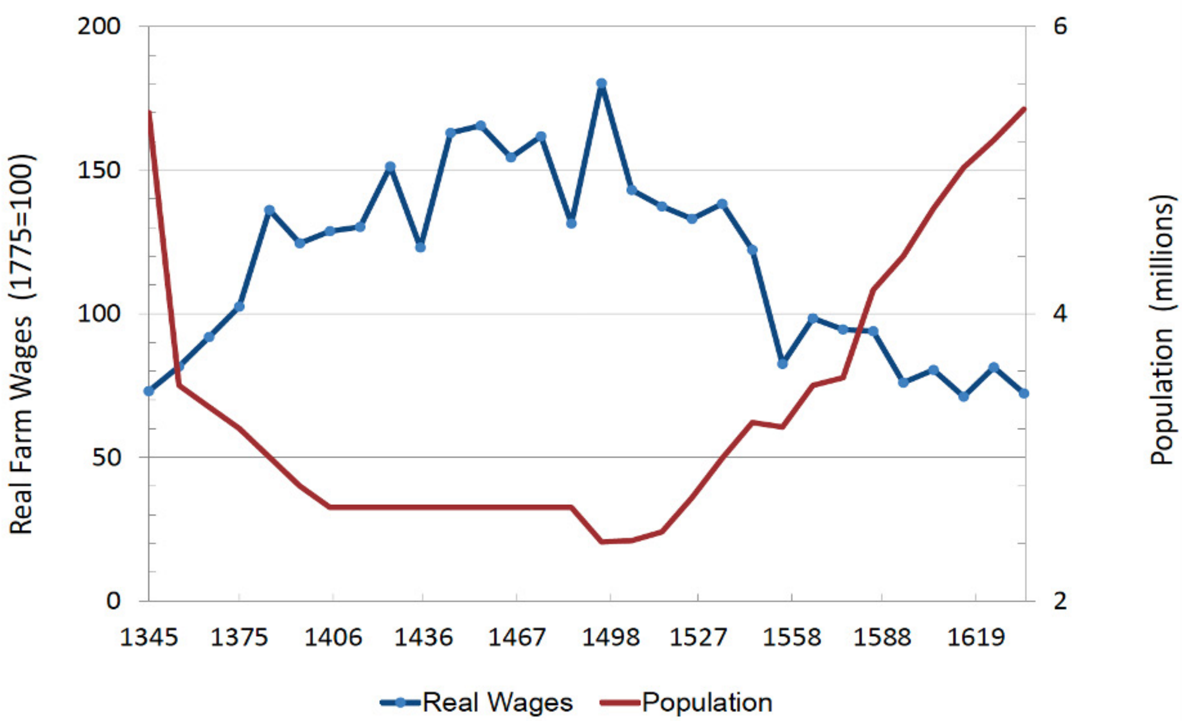
Figure 2 shows the simple phase diagram. The horizontal axis is the phase space for *x* and the vertical axis shows *n(x)*, which determines the sign of Δx. Panel (a) demonstrates the stability of the steady state. The steady state land-labor ratio *(x*)* occurs when population is constant *(n = 0)*. Point x_L shows an economy that starts with a land-labor ratio below the steady state. In this case, population growth is negative, which means that $\Delta x > 0$ and the economy moves right toward the steady state. Point x_H shows an economy that starts with a land-labor ratio above the steady state. In this case, population growth is positive, which means that $\Delta x > 0$ and the economy moves left toward the steady state. Thus, the steady state defined by $\overline{A}f\left(x^*\right) = \bar{c}$ is globally stable. Panel (b) compares the steady states for two economies that differ only in their level of productivity: $\overline{A}_1 > \overline{A}_2$. It is straightforward to consider comparative statics with changes in $\overline{n}$ and $\bar{c}$ as well.

C. Connection to Data

This section discusses how the simple Malthusian model described in the previous section can explain counterintuitive stylized facts about economic growth in the Malthusian era. This description can help students better understand (i) the power of simple economic models to generate surprising insights about the world and (ii) some of the basic contours of economic history.

We begin by analyzing two striking facts motivating the work of Ashraf & Galor (2011). The key cross-sectional results are presented in Appendix Figures A1 and A2. The first striking fact is that, in pre-industrial times, places with relatively fertile land and better technology did not have higher income per capita. They did have higher population density. According to Malthusian logic, this occurred because, away from the steady state, high productivity is channeled into high population growth, which pushes down the land-labor ratio and decreases income per capita. The fact that the steady state level of income per capita is independent of productivity is shown in equation (9). The theoretical impact of productivity on population density – which is the inverse of the land-labor ratio – is shown in panel (b) of Figure 2.

Figure 3: Impacts of the Black Death in England. Source: Galor (2019). [Reproduced with Permission]



The second striking fact is about comparative dynamics, rather than comparative statics. As shown in Figure 3, the Black Death actually increased wages in England at the same time that it decreased population. In the context of the model, we can think of this as a one-time exogenous decrease in L, or equivalently, an exogenous increase in $x = X/L$. In the context of panel (a) in Figure 2, this is equivalent to suddenly moving the economy from x^* to x_H and then letting the Malthusian dynamics continue. Immediately after the plague, the land-labor ratio is above the steady state level, implying that income per capita is also above the steady state level. The increase in income per capita leads to an increase in the population growth rate, which drives x and y back to their original steady state levels. It is also straightforward to note that the population level must have returned to its original level, because X has not changed.

4. Discussion

A. Malthus to Solow

The previous sections provided a heuristic derivation that connects the Solow and Malthusian models. This connection can be the starting point for a classroom discussion of how economies transition from a Malthusian world to one with continued economic growth. There is an ongoing debate about the exact mechanisms that drove this transition. But all theories seek to explain important empirical facts, such as changes over time in the (1) rate of technological progress, (2) population growth patterns, and (3) the importance of land in the production process. The heuristic derivation highlights these differences and can therefore be a useful starting point for discussing any (or several) of the leading theories.

In my intermediate macroeconomics course, I focus on theories of an endogenous evolution between growth regimes. More specifically, I discuss theories that fall under the umbrella of Unified Growth Theory (e.g., Galor & Weil, 2000; Galor, 2011) and the closely related explanations that have been stressed by other prominent growth theorists (e.g., Jones & Romer, 2010; Lucas, 2018).[5] Below, I summarize that discussion, which introduces students to additional important concepts in economic growth and development.

First, consider technology. While there was no sustained technological progress during the Malthusian era, there were occasional advancements in productivity, often associated with learning-by-doing or institutional improvements (Mokyr, 2005). As shown in panel (b) of Figure 2, such improvements lead to increases in population, rather than income per capita, in a Malthusian economy. The Boserup (1965) effect suggests that larger populations have faster technological progress, potentially due to greater scope for learning-by-doing (see also, Kremer, 1993). Thus, we can think of a reinforcing cycle where sporadic technological improvements lead to a higher population, and the higher population causes these technological improvements to happen more frequently.

Next, consider the connection between population growth, income, and human capital investment. Parents have finite time and finite income, and they face a trade-off between activities that require both time and money: raising children and investing in the human capital (i.e., education, health) of each child. In economics, this is known as the 'quantity-quality' trade-off (Becker & Lewis, 1973). Given the production technologies available in the Malthusian era, there was little return to education or health spending. As a result, parents used income for their own consumption and to have children, creating the positive link between income and net fertility. The lack of investment in human (or physical) capital implied that fixed factors, like land, were central to production. Today, however, education and health spending provide significant benefits to children. As a result, parents often use higher income to make human capital investments.[6] This breaks the connection between higher income and higher net fertility and introduces non-fixed factors of production to the economy.

To bring everything together, we introduce one additional observation: education helps people adapt to changing economic circumstances. This is a type of skill-biased technical change, where the rate - rather than the level - of technological progress increases the return to education. Together, these modeling elements – skill-biased technical change, the quantity-

[5] Recent work by Galor (2022) discusses long-run growth in a context that is accessible to students early in the economic education.

[6] Of course, other factors break the link and are interesting to discuss in class. For example, changes in the labor market opportunities for women likely have a significant impact on fertility (Galor & Weil, 1996).

quality trade-off, and the Boserup effect — explain how an economy can transition away from a Malthusian equilibrium. The occasional productivity advances in the Malthusian era led to larger and larger populations. As the population increases, the Boserup (1965) effect implies that productivity advancements also happen more frequently. This feedback between population size and technological advancement continues until eventually there is sustained economic progress. This progress induces parents to substitute away from child quantity and toward child quality, breaking the link between income and population growth. In addition, the investment in education leads to even faster technological progress. The end result is a more 'modern' economic growth regime with continued economic progress and investment in human capital.

The theory just presented closely follows Galor & Weil (2000) and stresses the relationship between technological progress, fertility, and human capital accumulation.[7] The connection between the Malthusian and Solow models is even more direct in approaches that posit an exogenous technological advancement that creates opportunities for investment in physical capital. In the language of Hansen & Prescott (2002), these are models where technology pushes the economy from 'Malthus to Solow'. These models are similar to the theory that the Enlightenment started a continued process of scientific advancement that eventually led to a technological revolution that made it possible to build useful capital equipment (Mokyr, 2005). Cervellati et al. (2022) link these models to Unified Growth Theory by suggesting that capital-skill complementarity could drive the quantity-quality trade-off. Regardless of the precise mechanisms, the Malthusian model presented here draws a direct connection between different growth regimes and can serve as the basis for discussing how the world managed to transition from one regime to another, fundamentally altering the growth rate of living standards.

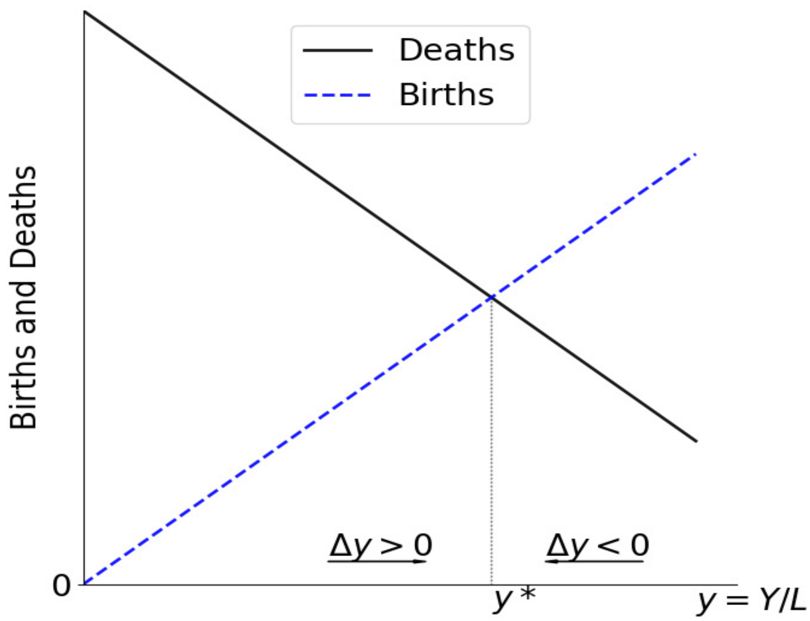
B. Comparison to Existing Approaches

<u>i. Births and Deaths Model</u>

When Malthusian dynamics are taught in undergraduate classes, it is often with a 'births and deaths' Malthusian model (see Clark (2008) for a more complete discussion of this model). In this model, births are an increasing function of income per capita, and deaths are a decreasing function of income per capita. Implicitly, there is a fixed factor of production so that population increases lead to decreases in income, generating a stable steady state with zero population growth. These relationships can be motivated by purely biological considerations. This model is presented in Figure 4.

[7] See also Cervellati & Sunde (2005), who present a similar model focused on health investments and mortality, and Lucas (2018).

Figure 4: 'Births and Deaths' Malthusian Model



The 'births and deaths' model is a constructive pedagogical tool, but it has a few shortcomings in undergraduate education relative to the model presented in Section 3. First, and most importantly, it is difficult to use the births and deaths model to explain how an economy might transition from a Malthusian setting to one with continued economic growth. As discussed in the previous section, deriving a Malthusian model from the Solow model draws these connections more explicitly. Second, the births and deaths model does not focus on the forces that underlie cutting-edge research. It relies mainly on biological relationships. It does not account for the fact that fertility decisions can depend on death rates and only implicitly models fixed factors of production. The research in this area stresses fixed factors of production and preferences for net fertility, both of which are represented more explicitly in the model presented in this paper. Third, since the model presented in this paper incorporates production technology, it can be used to analyze the impact of differences in technology and land productivity across space, a central focus of Ashraf & Galor (2011).

ii. Jones & Vollrath (2002)

An alternate approach to teaching Malthusian models comes from Jones & Vollrath (2002). Their approach differs from the model discussed here mainly in terms of mathematical complexity. In particular, they present a model focusing on differential equations that is similar to models that students see in first-year graduate courses. This model is a helpful presentation for advanced students, and it follows naturally from the continuous time growth models developed earlier in their book. However, it is inaccessible to students early in their economic studies, and it cannot be readily connected to the simple Solow model that students encounter in introductory or intermediate macroeconomics. As discussed by Acemoglu (2013) and below in Section 4.C, there is great benefit to teaching the intuition of long-run growth to students early in their economic education.

C. The Importance of Teaching Malthus

This paper presents a simple approach to teaching Malthusian growth theory. Before concluding, it is worth quickly discussing the benefits of teaching Malthusian models. Teaching Malthusian models is fairly standard in growth electives, but not in principles or core intermediate-level macroeconomics classes. If required macroeconomic classes discuss growth at all, it is usually in the context of the Solow model. While important, the Solow model focuses on the role of capital accumulation, a force that has been de-emphasized in recent work on economic growth, which instead focuses on endogenous fertility, technology, and human capital (Jones & Romer, 2010). Moreover, the Solow model is only intended to capture the recent growth experiences, implying that it is unable to explain growth over most of human history (Galor & Weil, 2000; Jones & Romer, 2010). For these reasons, the Solow model presents a limited framework for understanding economic growth. Without complementary models or other resources, it does not provide students with an accurate picture of how economists think about growth. Acemoglu (2013) presents a more in-depth discussion of the importance of teaching long-run growth, specifically in the context of a principles class. Similar to arguments made in this paper, he discusses how to use the framework of the Solow model to help guide further discussions.

In addition to covering an important topic, greater emphasis on long-run economic growth early in the major may also increase student interest in economics. As Lucas (1988) famously stated, '[o]nce one starts to think about [economic growth], it is hard to think about anything else' (p. 5). Given that long-run growth combines history, demography, and economics, it may be particularly interesting for students with multi-disciplinary interests or for students who may not pursue further economics classes. For these reasons, Malthusian models might be particularly useful in a liberal arts setting or when teaching introductory classes or low-level electives.

D. Possible Uses in an Environmental Economics Class

While this paper focuses on economic growth, Malthusian dynamics are also relevant in environmental economics, especially when it comes to the 'limits to growth' debate.[8] Such discussions necessarily go beyond the discussion of externalities to think about dynamics and about the natural resources that serve as inputs to production and are necessary to sustain income per capita. Such natural resources include land, the most obvious connection to the Malthusian model, but the discussion could also be extended to incorporate other natural resources, such as air quality and even the 'carbon budget'.[9]

A simplified Malthusian model can therefore be useful in environmental economics classes as a tool to make discussions of economic growth more concrete. The environmental message of the model is somewhat mixed. On the negative side, it suggests that resource scarcity prevents changes in long-run growth in income per capita. Students who have learned about the transition from Malthus to Solow can have an informed debate about whether this transition was temporary or permanent. For example, will climate change eventually put an end to economic growth, implying that the modern regime was only a temporary deviation from the Malthusian steady state? On the more positive side, it suggests that population

---

[8] See Sabin (2013) for an interesting overview of this debate that is accessible for undergraduates early in the economics education.

[9] The carbon budget is a tool from natural science that explains how carbon dioxide can be emitted before some environmental threshold is crossed (e.g., global average surface temperature rising $1.5^{\circ}C$ above pre-industrial levels).

growth responds to resource availability. Since population growth is a major driver of human environmental impact, endogenous fertility responses might decrease the likelihood of an environmental disaster driven by resource use or climate change. A broader discussion of growth theory could also incorporate ideas from endogenous growth theory to explore the direction of technical change and its potential to conserve natural resources and reduce emissions as in recent academic papers by Acemoglu et al. (2012) and Hassler et al. (2021). Students can discuss variables other than population that might respond endogenously to changes in environmental conditions or to environmental policy.

5. Teaching Materials

To aid instructors wishing to use this material, the supplementary content for this paper includes a set of slides used to teach the model. It takes about an hour to go through the slides in an intermediate macroeconomics class. The slides contain two practice questions related to the discussion in Section 3.C.

6. Conclusion

Prior to the industrial revolution, income per capita grew very slowly and was relatively equal across the globe. Since then, the vast improvements in economic well-being over time, as well as the disparities in income per capita across countries, are related to the 'escape' from this Malthusian 'trap' (Galor, 2011). Despite the fundamental importance of the Malthusian period, it is usually ignored when teaching economic growth to undergraduates. As a result, undergraduates are missing key insights that drive contemporary academic thinking about how historical economic growth, the legacy of which may still affect contemporary income levels and, by extension, global inequality. This paper builds a simple Malthusian model that does not require calculus, is closely related to the Solow model that serves as the core of undergraduate growth education, and captures the forces in cutting-edge academic research. It explains the counterintuitive dynamics observed in Malthusian economies, demonstrating the power of simple theory to students. Hopefully, it will also make teaching Malthusian theory easier and more attractive in macroeconomics classes.

References

Acemoglu, D. (2013). Economic growth and development in the undergraduate curriculum. *The Journal of Economic Education*, 44(2), 169–177. DOI: 10.1080/00220485.2013.770344

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1), 131–166. DOI: 10.1257/aer.102.1.131

Ashraf, Q. & Galor, O. (2011). Dynamics and stagnation in the malthusian epoch. *American Economic Review*, 101(5), 2003–2041. DOI: 10.1257/aer.101.5.2003

Becker, G. S. & Lewis, H. G. (1973). On the interaction between the quantity and quality of children. *Journal of Political Economy*, 81(2, Part 2), S279–S288.

Boserup, E. (1965). *The conditions of agricultural growth: The economics of agrarian change under population pressure*. Routledge, 2014.

Cervellati, M., Meyerheim, G., & Sunde, U. (2022). The empirics of economic growth over time and across nations: a unified growth perspective. *Journal of Economic Growth*, (pp. 1–52). DOI: 10.1007/s10887-022-09216-2

Cervellati, M. & Sunde, U. (2005). Human capital formation, life expectancy, and the process of development. *American Economic Review*, 95(5), 1653–1672. DOI: 10.1257/000282805775014380

Clark, G. (2008). *A farewell to alms: a brief economic history of the world*, volume 25. Princeton University Press.

Clark, G. (2014). The industrial revolution. In P. Aghion & S. Durlauf (Eds.), *Handbook of Economic Growth*, volume 2 chapter 5, (pp. 217–262). Elsevier. DOI: 10.1016/B978-0-444-53538-2.00005-8

Galor, O. (2011). *Unified Growth Theory.* Princeton University Press.

Galor, O. (2019). The Malthusian hypothesis. Lecture Notes, available at https://www.odedgalor.com/_files/ugd/5c20f9_d8e341d3eb934e1198cca8b2cd816835.pdf.

Galor, O. (2022). *The journey of humanity: The origins of wealth and inequality*. Penguin.

Galor, O. & Weil, D. N. (1996). The gender gap, fertility, and growth. *American Economic Review*, 86(3), 374–387.

Galor, O. & Weil, D. N. (2000). Population, technology, and growth: From malthusian stagnation to the demographic transition and beyond. *American Economic Review*, (pp. 806–828). DOI: 10.1257/aer.90.4.806

Hansen, G. D. & Prescott, E. C. (2002). Malthus to Solow. *American Economic Review*, 92(4), 1205–1217. DOI: 10.1257/00028280260344731

Hassler, J., Krusell, P., & Olovsson, C. (2021). Directed technical change as a response to natural resource scarcity. *Journal of Political Economy*, 129(11), 3039–3072. DOI: 10.1086/715849

Jones, C. I. (2016). The facts of economic growth. *Handbook of Macroeconomics*, 2, 3–69. DOI: 10.1016/bs.hesmac.2016.03.002

Jones, C. I. & Romer, P. M. (2010). The new Kaldor facts: Ideas, institutions, population, and human capital. *American Economic Journal: Macroeconomics*, 2(1), 224–45. DOI: 10.1257/mac.2.1.224

Jones, C. I. & Vollrath, D. (2002). *Introduction to Economic Growth*. W. W. Norton & Company Inc. NY.

Kremer, M. (1993). Population growth and technological change: One million BC to 1990. *Quarterly Journal of Economics,* 108(3), 681–716. DOI: 10.2307/2118405

Lucas, Robert E., J. (2004). The industrial revolution: Past and future. *Economic Education Bulletin*, 44(8), 1–8.

Lucas, R. E. (1988). On the mechanics of economic development. *Journal of Monetary Economics*, 22(1), 3–42. DOI: 10.1016/0304-3932(88)90168-7

Lucas, R. E. (2018). What was the industrial revolution? *Journal of Human Capital*, 12(2), 182–203. DOI: 10.1086/697243

Maddison, A. (2008). Statistics on world population, gdp and per capita gdp, 1–2006 ad. https://www.rug.nl/ggdc/historicaldevelopment/maddison/. Downloaded on December 4, 2008.

Malthus, T. R. (1798). *An Essay on the Principle of Population*. London: J. Johnson.

Mankiw, N. G. (2019). *Macroeconomics*. Macmillan, 10th edition.

Mankiw, N. G. & Ball, L. (2011). *Macroeconomics and the Financial system*. Macmillan.

Mokyr, J. (2005). Long-term economic growth and the history of technology. In *Handbook of Economic Growth*, volume 1 (pp. 1113–1180). Elsevier. DOI: 10.1016/S1574-0684(05)01017-8

Sabin, P. (2013). *The bet: Paul Ehrlich, Julian Simon, and our gamble over Earth's future*. Yale University Press.

Appendix

Figure A1: Source: Ashraf & Galor (2011). [Copyright American Economic Association; reproduced with permission of the American Economic Review]

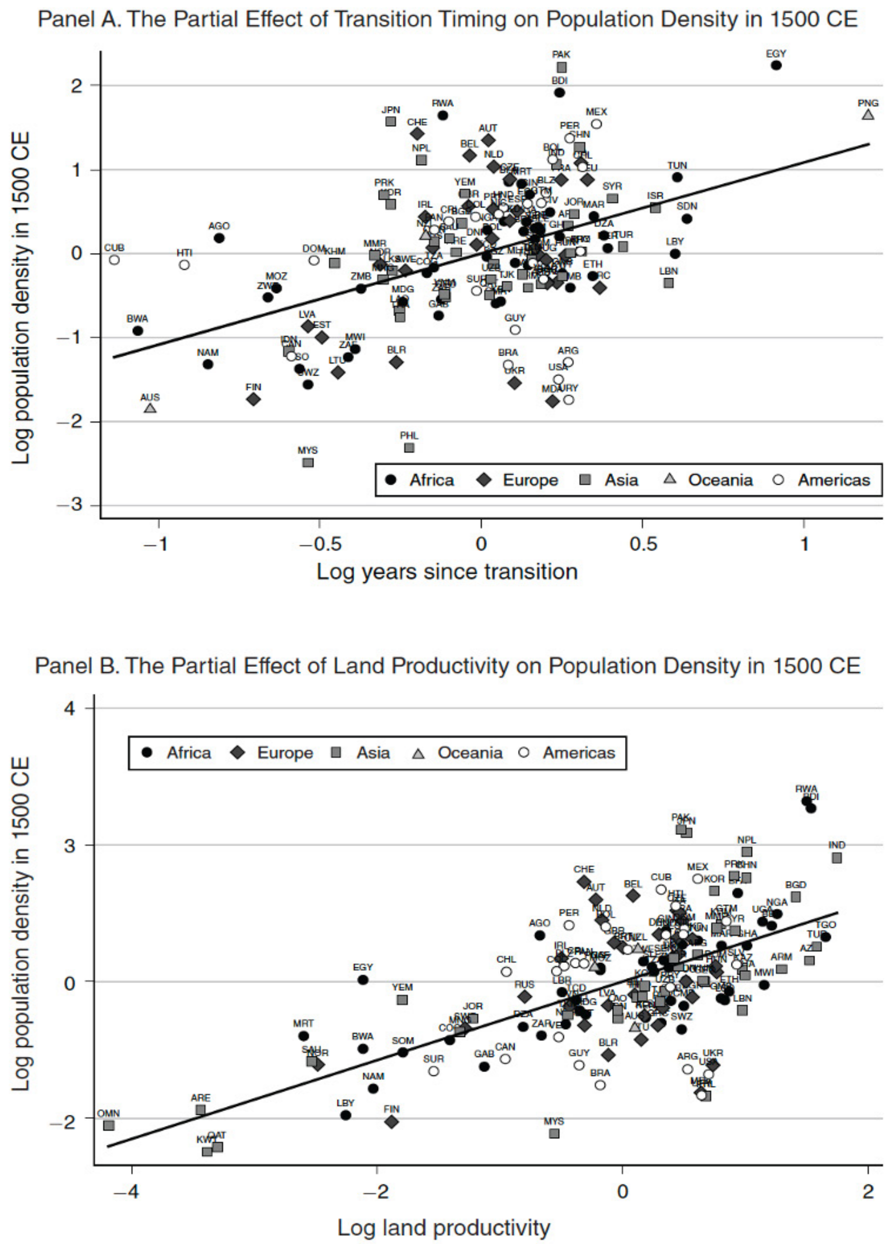


FIGURE 3. TRANSITION TIMING, LAND PRODUCTIVITY, AND POPULATION DENSITY IN 1500 CE

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

Figure A2: Source: Ashraf & Galor (2011). [Copyright American Economic Association; reproduced with permission of the American Economic Review]

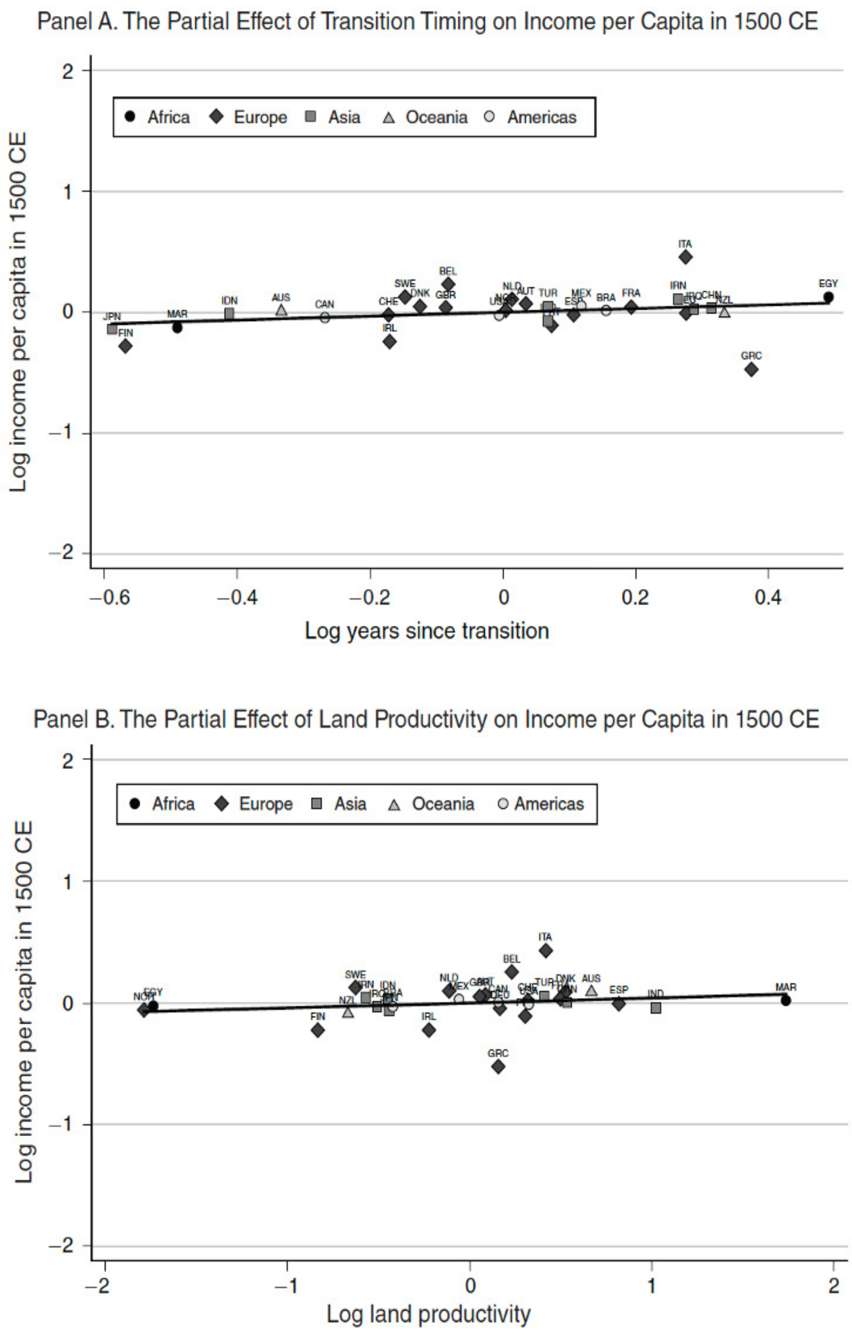


Figure 4. Transition Timing, Land Productivity, and Income per Capita in 1500 CE

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