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THE TWO REVOLUTIONS, LANDED ELITES, AND EDUCATION DURING THE INDUSTRIAL REVOLUTION

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Understanding the causes of the Industrial Revolution, namely the process of transition from a Malthusian equilibrium to modern economic growth, has been the subject of passionate debate. This paper contributes to insights into the process of industrialization and the demographic transition that followed. We present a model that proposes a mechanism behind the claim that landed elites had strong incentives to block education reforms. By applying the theory of interest groups to landownership, landowners could delay education. However, they could not prevent its introduction indefinitely since gains for the landed elites derived from education would at some moment surpass the costs associated with them. We also sustain that improvements in agricultural productivity prior to the Industrial Revolution may have induced a positive impact on the landowners' decision to educate the population, which led to an earlier introduction of education reforms. The conclusions fit the patterns of the late boom of industrialization and demographic transition and help explain why some countries (e.g., Britain and The Netherlands) had accelerated education reforms and a faster process of industrialization than most continental countries. A theoretical model is presented, and numerical simulations are exhibited to illustrate our claims.

Keywords: Industrial and Agricultural Revolution, Demographic Transition, Education, Interest Groups

1. INTRODUCTION

Human-capital formation has been regarded as one of the main forces in the transition from Malthusian stagnation to a sustained economic growth period [Galor (2005, 2011)]. In particular, as was established in the seminal contributions of

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Galor and Moav (2006) and Galor et al. (2009), the rise in the demand for human capital in the process of industrialization, and the presence of capital-skill complementarity, induced the industrial elite to support the provision of human capital from the masses so as to sustain their profit rates while inducing the landed aristocracy to block the proposed education reforms. Maintaining this line of argumentation, this study focuses on the decision process of the landed aristocracy, and how events such as the rise in agricultural productivity in the dawn of the Industrial Revolution and the improvements in the flow of technology from the industrial to the agricultural sector created incentives to make landed aristocracy support public education reforms and, hence, human-capital formation. We claim that landowners' incentives to support education depend mostly on the benefits for their own land rents and that the above events led to the increase of these benefits, opening the way to unblocking earlier education reforms by the elites. These decision processes are essential to reconcile the events that occurred during and after the Industrial Revolution, namely the earlier process of education reforms in countries like Britain and The Netherlands and the acceleration of the Industrial Revolution after the second half/end of the 19th century. We sustain that historical delays in agricultural productivity improvements in some countries or lower spillovers from the industrial to the agricultural sector are causes for an initial blocking of the proposed education reforms (lower contributions to education), negatively affecting the timing of both the process of demographic transition and the acceleration of the industrialization process.

Using tools from Unified Growth Theory (UGT), we model the process of industrialization as its timing and posterior acceleration are directly dependent on the countervailing incentives faced by landowners to support education reforms. On the one hand, land rents would increase due to the industrial sector's spillovers. On the other hand, it is also suggested that due to competition from the industrial sector, landowners' revenues could decrease significantly [Bourguignon and Verdier (2000) and Galor et al. (2009)]. Landowners consider the economic gains and losses from the introduction of education reforms to decide whether to support them or not. We argue in this study that gains are associated with early agricultural productivity improvements, and the spillovers of technology innovations from the rising industrial sector at some point in time create enough economic incentives to make landowners want to support education.

Similarly to Galor et al. (2009), we show that despite the initial incentives for blocking education reforms, landowners eventually end up supporting education. As shown by Galor et al. (2009) and Bourguignon and Verdier (2000), this paper suggests that landowners aimed to prevent education during the onset of the Industrial Revolution. But, instead of focusing on land concentration, we propose a more general approach that concentrates on the fear of losing revenues caused by a higher return of education in the industrial sector. We suggest a mechanism that leads to a switch in their decisions to support education reforms, namely future gains from spillovers of industrial technology fostered by human capital that become sufficiently high enough to make the landowners' decision to support educational reforms profitable. This mechanism explains the initial delay in the industrialization, human capital accumulation process verified in, for instance, Britain before the 1870s, and the accelerated process of education and rise in human capital that occurred afterwards along with a faster demographic transition process. The resulting analysis is consistent with the importance of landowners contributing to school boards in the mid-late 1800s Britain [Stephens (1998) and Goni (2016)] and the delayed process of education verified in history: the Industrial Revolution commenced in the late 1700s and education only spread from the mid to late 1800s, leading to the faster course of the demographic transition [Flora et al. (1983) and Brown (1991)].

Besides the gains from spillovers from the industrial sector, agricultural productivity prior to the Industrial Revolution plays an important role in landowners' decisions and, hence, on the Industrial Revolution process. Many researchers point out the large improvements on agriculture previous to the Industrial Revolution [Allen (1988) and Clark (1993)], while others regard them as insignificant. In contrast to the latter theories, this paper advances the idea that the improvement in agricultural processes contributed to accelerating the process of industrialization and that landowners were more favorable toward education reforms due to the lower risk of losing rents and their share of the economy because they could still rely on the higher productivity of land, compensating the loss caused by the financial support provided to educate the population and the loss of workers to the industrial sector[1] [Engerman and Sokoloff (2000), Galor et al. (2009), and Litina (2016)]. This claim helps explain why some countries (e.g., Britain and The Netherlands) had accelerated their education reforms and later the process of industrialization in the middle 1800s, prior to most continental countries where agricultural improvements were not so prominent. Moreover, as Thompson (1968) poses, a Second Agricultural Revolution[2] breaks the closed-circuit system and transforms agricultural production in a more similar way to the industrial one, where machinery, fertilizers, and other discoveries are introduced in the main processes of production. These externality gains improved the productivity of agriculture and made it rise exponentially. Our model, as is shown below, captures both empirical facts, which are crucial to our theory on the process of industrialization and education reforms.

To sum up, our paper adds a distinctive explanation to the extant literature for the later rise of education and consequent demographic transition, as well as differences between countries. Nonetheless, the paper is also in line with the Malthusian, post-Malthusian, and Modern-Growth trends inherent in this period, proposing a complementary perspective of landownership according to the UGT. Finally, it contributes to the discussion regarding the positive/negative impacts of the First Agricultural Revolution on landowners' decisions and, consequently, on education. Few papers promote a theoretical model of possible effects of higher or lower levels of agricultural productivity on the Industrial Revolution. We fill this gap by providing a model, which is then simulated.

The paper is organized as follows: in Section 2, we present the related literature and how our paper complements it. A historical overview of the periods before and during the Industrial Revolution is then presented in Section 3. In Section 4, the setup of the model is defined together with the main assumptions. Section 5 shows the dynamics of the development process and how the economy evolves from a preindustrial to an Industrial equilibrium. Section 6 provides the analysis of the main predictions of the model and a numerical discussion of these same predictions. Concluding remarks are in Section 7.

2. RELATED LITERATURE

The Great Divergence, which started two centuries ago, has been one of the main research challenges economists have been facing in the fields of Growth and Development Economics. Many hypotheses have been put forward to explain the transition from a Malthusian to a post-Malthusian era and then to today's Modern-Growth era. UGT offers some explanations about the behavior of economies in this time. Theories of comparative economic development have considered the role of geographical, institutional, cultural, and human characteristics [Diamond (1997), Landes (1998), Ashraf and Galor (2011b), Acemoglu and Robinson (2012), Ashraf and Galor (2013), and Galor and Özak (2016)]. Meanwhile, the processes of declining fertility, educational and human capital formation, and agricultural transformation were pivotal for the onset of the Industrial Revolution [Galor and Weil (2000), Galor and Moav (2006), and Voigtländer and Voth (2006)].

The role of human-capital formation is highlighted as a key element in the transition from stagnation to growth. This line of research is supported by the UGT through different approaches [Galor and Weil (2000), Galor and Moav (2002), Cervellati and Sunde (2005), and Galor (2011)]. This theory links the rise in the demand for human capital in the emergence of industrialization and the onset of the demographic transition, leading to the transition from stagnation to growth [Galor and Weil (2000)]. Galor and Moav (2006) suggest that the importance of human capital in production increased the incentives for capitalists to support the provision of state education triggering the demise of the existing class structure, whereas Galor et al. (2009) argue that inequality in the distribution of landownership negatively affected the emergence of human-capital-promoting institutions. This paper contributes to this line of research with an analysis on the willingness of landowners to support education during the Industrial Revolution and combining this theory with those on the role of institutions.

Modern institutional theories had their historical birth with North and Thomas (1973), Greif (1989), and North (1990) and were then followed in a more empirical fashion by La Porta et al. (1999), Rodrik et al. (2004), Banerjee and Iyer (2005), and Jones and Romer (2010) among others. In accordance to the institutional literature, the processes of political and social conflict are at the center of discussion [Olson (1982), Mokyr (1990), Bourguignon and Verdier (2000), and Acemoglu and Robinson (2006)]. Some authors have shown that small interest groups put up an obstructive front against new technologies and better institutions in order to maintain their own power and rent income [Olson (1982)]. Regarding the effect of these elite groups on education, Bourguignon and Verdier (2000) argue that if education determines political participation, elites may not find it beneficial to subsidize universal public education although there are positive externalities from human capital. While Grossman and Kim (2003) show that predation is mitigated by education, Lizzeri and Persico (2004) argue that the elite use the provision of public services in their own interest so that the extension of franchise redirects resources from wasteful redistribution to public goods. Goni (2016) also shows that landed elites, when land concentration is high, provide fewer funds to education, thus limiting the development of human capital after the 1870s.

This paper combines both UGT and the institutional theories referred previously and models the process of the decision faced by landowners on whether to support education reforms, which directly affects the timing and acceleration of the Industrial Revolution and demographic transition. Since only very few theoretical models exist on the impact the First Agricultural Revolution had on the way landowners supported education reforms, this paper also contributes to the literature by accurately studying the impact of this rise on agricultural productivity prior to the Industrial Revolution on landowners' decisions on education reforms and its effects on human-capital formation and demographic transition.

3. HISTORICAL OVERVIEW

The divergence of income that began during the Industrial Revolution marked the end of the Malthusian era and pointed toward the Modern-Growth regime. For this process to occur, several events took place at different moments in time. Firstly, the First Agricultural Revolution played a crucial role. Although there is some controversy in the literature, the real dimension of the First Agricultural Revolution is larger for some than the Industrial Revolution itself. Independent of this position, it is argued that long before the Industrial Revolution, British farmers were already quite productive [Mokyr (2009)]. Between 1700 and 1850, output both per acre and per worker increased to levels far above those verified for the Middle Ages [Clark (1993)]. Looking at the estimate of rents in different studies for Britain, the majority of the results present an upsurge of rents at the beginning of the 17th century and a slower growth in rents up to the beginning of the 19th century [Allen (1988) and Clark (2002)]. Two factors are considered to allow for the increase in output: intensity and efficiency in the usage of land [Brown (1991), Clark (1993), and Mokyr (2009)]. The enclosure movement, which took place mostly in England, led to higher land productivity due to better organization of land, easier agreements on new production techniques,

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and an increase in the size of the average agricultural holding [Mokyr (2009)]. Nevertheless, there is an ongoing debate regarding its real effects prior to the Industrial Revolution [McCloskey (1972), Clark (1993), and Allen (2009)].

During the Industrial Revolution, it is also claimed that agricultural production improved substantially due to technology spillovers from the industrial sector. As Allen (1999) remarks, depending on the measures used, the strength of such dynamics is not always visible, which generates some controversy. Notwithstanding this, both "revolutions" are captured by empirical data collected from several sources [Allen (1999, 2009) and Thomas and Dimsdale (2017)]. From Figures A1–A3 in Appendix A.1 of the Supplementary Material, we see the increase in output growth in the period before 1750, some stagnation until 1800, and then a new surge on agriculture output during the onset of the Industrial Revolution.

Secondly, education was already regarded as an asset in the 18th century although it played a minor role during the first phase of industrialization. Only after the mid-1800s, when demand for education was reaching fever pitch, did it start to grow and become essential for the definitive take-off of the industrial sector. In the first phase of industrialization, demand for skilled workers was low because the requirements for work in industry were still very basic. As industrialization grew apace, industrial work became more and more demanding and a higher level of education was required. Despite some education reforms, the most important ones, those leading to a real increase in the workers' educational level, only emerged in the late 19th century. This was pernicious for the economy since despite the high demand for education and capital formation, each country proceeded at its own pace in instituting education reforms [Cubberley (1920) and Galor (2011)].

In Prussia, the first education laws came into force in the early 1700s. But, they were met with resistance and implemented slowly since there was no willingness by either the population, in general, or landowners, in particular, to cope with the financial burden [Cubberley (1920)]. The same happened in Italy and France. Soon after the end of the French Revolution, education declined due to the imposition of restrictions on state schools and the enhancement of church and private schools [Cubberley (1920) and Green (1990)]. As for Britain, the strong educational progress began in the 1850s[3] when several reforms were effective in promoting education among children, as, for example, the 1870 Forster's Education Act claimed for the provision of elementary education [Flora et al. (1983), Green (1990), and Mokyr (1990)]. School boards were created, and these would raise the funds necessary to run the schools. The majority of these funds were demanded from the landed aristocracy, who avoided having to contribute to them by controlling school boards and, hence, reducing education provided to the minimum possible [Stephens (1998) and Goni (2016)]. These facts highlight the power of landed aristocracy regarding education reforms and reinforce the need to study the mechanism of landowners' decisions on contributions to education.

A third emerging force during this period was the decline in fertility rates, which has characterized the demographic transition in most countries throughout the last two centuries. In Western countries, it started in the late 19th century and continued throughout the last century and led fertility rates to the replacement level [Lee (2003)]. One of the main causes for this decline in fertility was the investment in education whose negative correlation is associated with the trade-off between child quantity and quality. Becker et al. (2010, 2012) found evidence of this trade-off in 19th-century Prussia, while Murphy (2010) found evidence for it in France in the late 19th century.

Finally, a fourth powerful force in this period was the landowners. As a small interest group in preindustrial societies, they were extremely powerful and their initial incentives were to block any progress in education and hence the full take-off of the Industrial Revolution [Galor et al. (2009)]. On this group, the state relied to finance education. After the Forster's Act in England, when education was considered a state duty for the first time, most of its resources came through property taxes directly from landed elites [Stephens (1998)]. Their power and their unwillingness to support education were the main reasons for the conflict between landowners and the emerging capitalist class. The fight for more education during this period was one of the main points of divergence between these two groups: industrialists wanted a better educated working class to boost their production and landowners wanted workers farming and so were staunchly opposed to their education. The power of landowners in this period was strong enough to delay, or even prevent, the dissemination of education. As they were the largest and richest group, their financial influence implied that most monarchs' and rulers' decisions depended on them [Ekelund and Tollison (1997) and Lizzeri and Persico (2004)]. In fact, the dependence of rulers on landowners' money for warfare and other expenses made it easy for the latter to extract from the former the concession of monopolies, private businesses, patents, and other advantageous deals, whereby a less widely disseminated form of public education could be included [Ekelund and Tollison (1997)].

4. MODEL SETUP

We consider an overlapping-generations economy operating over infinite discrete time according to Galor et al. (2009), Ashraf and Galor (2011a), and Litina (2016). In the preindustrial era, the economy produces a single homogeneous good using land and labor as inputs. After the emergence of the industrial sector, the economy produces agricultural goods using land and labor and manufactured goods using only labor as input. The supply of land is exogenous and fixed over time. The number of efficiency units of labor is defined by households' decisions in the preceding period regarding the human-capital level of their children and how many children they have.

The model comprises two types of individuals: workers and landowners. Workers reproduce themselves asexually, whereas landowners have one child each. In each period t, a generation of a continuum of L_t identical workers enters the labor force, and landowners do not take part in the productive process. Individuals of generation t live for two periods.

4.1. Production

To produce a good, each worker inelastically supplies one unit of labor in each period. The aggregate supply of workers evolves over time at the endogenously determined rate of population growth. In the early Malthusian phase, the agricultural sector is the only operating sector since the industrial sector is not yet economically viable. As technology in the industrial sector evolves over time, there comes a point at which the productivity threshold is reached, the industrial sector emerges, and both sectors operate in the economy.

4.1.1. Production in both sectors. The output of the agricultural sector is produced according to a constant-returns-to-scale technology. In period t, Y_t^A is determined by quantity of land, X_t, by labor employed in the agricultural sector, L_t^A, and by agricultural technology, A_t^A, determined endogenously.

$$Y_t^A = (A_t^A X_t)^{\alpha} \left(L_t^A\right)^{1-\alpha} \text{ for } 0 < \alpha < 1, \tag{1}$$

where $L_t^A = (1 - \lambda_t)\, L_t$, $(1 - \lambda_t)$ is the share of workers in the agricultural sector, and $\lambda_t \epsilon\ (0, 1)$ is set to zero until the emergence of the industrial sector.

The production function of the industrial sector after the onset of the industrial revolution is given by equation (3). However, to allow for the characterization of the period before the emergence of the industrial sector, a latent production function is assumed in equation (2). This production function does not directly affect the dynamics of the model since it only captures the latent production improvements in the industrial sector, which is closed. Equation (3), on the other hand, represents the actual production function when both agricultural and industrial sectors are open.[4] Subsequently, in the preindustrial era, the latent production function is a linear production function[5] relying on technology A_t^I and on efficient labor H_t, at each t:

$$Y_t^I = A_t^I H_t, \tag{2}$$

with $H_t = \lambda_t h_t L_t$, where h_t is the human-capital level. After the emergence of the industrial sector, constant returns to scale are assumed in the production function. A typical Cobb–Douglas production function whose marginal gains on labor are decreasing is assumed leading to equilibrium in the labor market so that both sectors are open and remain open. The elements of technology and efficient labor are maintained:

$$Y_t^I = \left(A_t^I\right)^{1-\theta} (H_t)^{\theta} \text{ for } 0 < \theta < 1. \tag{3}$$

Finally, the total labor force is given by the sum of workers in each sector:

$$L_t = L_t^A + L_t^I, \tag{4}$$

where $L_t^I = \lambda_t L_t$.

4.1.2. Factor prices, labor market and the technology threshold. Workers receive wages according to their productivity. Landowners, as the owners of property

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rights, receive rents from land. Thus, the returns from land are not zero. Further, property rights are not transmissible; they are inherited by the child of each landowner.

Rents are determined as the marginal gains for each unit of land held by landowners. We assume that landowners have the same share of land, and the rent received by each one is

$$\rho_t = \alpha\left(A_t^A\right)^{\alpha}(X_t)^{\alpha-1}\left(L_t^A\right)^{1-\alpha}. \tag{5}$$

From the above, rents are positively related to technology, and the number of workers allocated to the agricultural sector while negatively related with land: $\rho_A\left(A_t^A, X_t, L_t^A\right) > 0$, $\rho_X\left(A_t^A, X_t, L_t^A\right) < 0$, and $\rho_{L^A}\left(A_t^A, X_t, L_t^A\right) > 0$ for any $A_t^A, L_t^A > 0$.

The market for labor is perfectly competitive, and thus, wages are given by the marginal productivity of labor in each sector. Given (1), the marginal product and hence the inverse demand for labor in the agricultural sector is

$$w_t^A = (1-\alpha)\left(A_t^A\right)^{\alpha}(X_t)^{\alpha}[(1-\lambda_t)L_t]^{-\alpha}, \tag{6}$$

where w_t^A is the wages of agriculture workers.

From (2), before the take-off of the industrial sector, workers could supply h_t efficient units to the industrial sector and earn the potential wage:

$$w_t^I = A_t^I h_t. \tag{7}$$

After the take-off, marginal productivity is calculated using (3):

$$w_t^I = \theta\left(A_t^I\right)^{1-\theta}(\lambda_t L_t)^{\theta-1}(h_t)^{\theta} \tag{8}$$

From (6) and (7), we conclude that the marginal productivity of the industrial sector is finite and initially low (considering initial low technology values for industrial technology), while the marginal productivity in the agricultural sector tends to infinity, the share of workers in that sector tends to zero. Thus, the agricultural sector is open in every period, and the industrial sector emerges only when its labor productivity exceeds that of the agricultural sector, in the case when its entire labor force is employed. After the onset of the industrial sector, (6) and (8) govern the dynamics of the model and must be equal to guarantee the perfect labor mobility assumption. Lemma 1 establishes the necessary conditions for the emergence of the industrial sector:

LEMMA 1. *If wages are determined by (6) and (7), there is a threshold value for industrial technology $\hat{A}_t^I$ from which the industrial sector is economically viable*[6]:

$$\hat{A}_t^I > \frac{(1-\alpha)\left(A_t^A X_t\right)^{\alpha}}{L_t^{\alpha} h_t}.$$

See the Proof in Appendix B.1 of the Supplementary Material.

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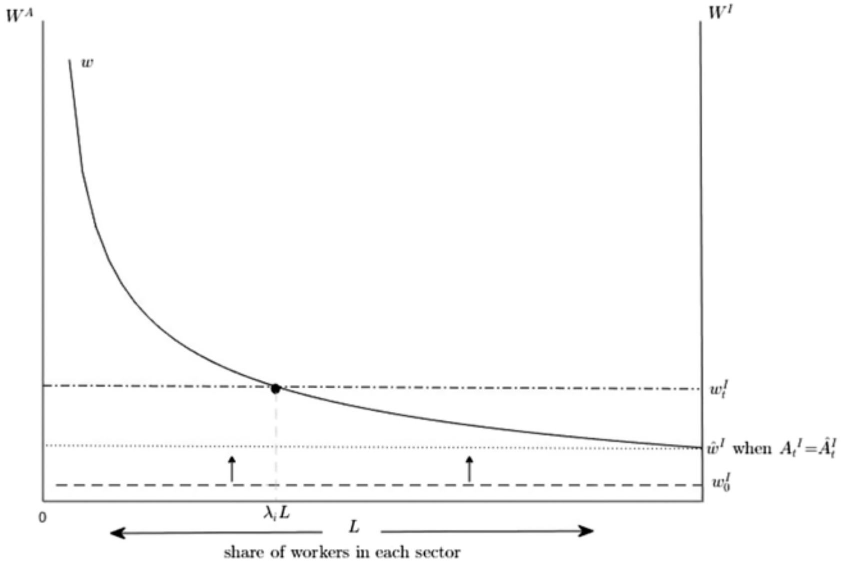

FIGURE 1. Dynamics of labor market equilibrium.

In Figure 1, the dynamics of Lemma 1 are depicted. In the preindustrial period, latent wages in the industrial sector are lower (for instance, w_0^I) and $A_t^I < \hat{A}_t^I$. From Lemma 1, wages are set equal to the marginal product of the agricultural sector $w_t = w_t^A$.

When the industrial technology increases and when the economy is in the Malthusian equilibrium such that agricultural technology and population are in steady state, latent wages will increase and become more competitive. This will imply a shift upwards of the w_0^I line until A_t^I reaches the threshold $\hat{A}_t^I$ and wages are $\hat{w}_t^I$. When the threshold is exceeded, the industrial sector emerges and $w_t = w_t^A = w_t^I$ and wages are set to be equal to the marginal product of both industrial and agricultural sectors—(6) and (8).

The equilibrium labor share between the two sectors at time t is[7]

$$\lambda_t = \begin{cases} 0 \; if \; A_t^I < \hat{A}_t^I \\ \frac{A_t^I (h_t)^{\frac{\theta}{\alpha}}}{A_t^A X_t + A_t^I (h_t)^{\frac{\theta}{\alpha}}} \; if \; A_t^I \geq \hat{A}_t^I, \end{cases} \tag{9}$$

and

$$w_t = \begin{cases} w_t^A = (1-\alpha)\left(A_t^A\right)^{\alpha} (X_t)^{\alpha} [(1-\lambda_t) L_t]^{-\alpha} \; if \; A_t^I < \hat{A}_t^I \\ w_t^I = w_t^A \; if \; A_t^I \geq \hat{A}_t^I \end{cases}. \tag{10}$$

When the two sectors are open ($A_t^I \geq \hat{A}_t^I$), a share of the workers employed in the agricultural sector will move to the industrial sector to benefit from higher wages until equilibrium is established between the two sectors.

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4.1.3. Technology dynamics. The level of each type of technology is affected by its level in the previous period.[8] Agricultural technology at time *t+1* is affected by three elements: the externality of the "learning-by-doing effect," the general knowledge effect of the population on technology, and the external effect from the gains from educating youngsters in the period along with the existing level of industrial technology. This latter effect allows for interconnections between technology and education and the current working population and level of agricultural technology. The law of motion of agricultural technology is such that:

$$A_{t+1}^{A} = (1 + e_{t+1}(A_t^I)^b)(L_t)^{\varepsilon}\left(A_t^A\right)^{\delta}, \quad \mathbf{(11)}$$

where $(L_t)^{\varepsilon}\left(A_t^A\right)^{\delta}$ captures the "learning-by-doing effect" and general externalities of the growing population in agricultural technology. The factor $e_{t+1}(A_t^I)^b(L_t)^{\varepsilon}\left(A_t^A\right)^{\delta}$ is the external effect of industrial technology and education. These dynamics are dependent on the imperfect intergenerational transmission of knowledge. We assume that $\varepsilon > 0$ and $\delta > 0$ and $\varepsilon + \delta < 1$, which implies that the population has a decreasing effect on knowledge creation, and implies a "fishing out" effect, namely the negative effect of past discoveries on those being made today. In addition, $b > 0$ so that when people are educated, externalities of industrial technologies spill over to technology in agriculture. These externalities are the mechanism which captures the patterns of the Second Agricultural Revolution. When education is allowed and all workers acquire higher skills to understand new methods and techniques, technological know-how produced in the industrial sector can be transferred to the agricultural sector. This improves production techniques in agriculture, which boosts productivity levels as observed in the data.

Evolution in industrial technology is given by the past period level of technology and the improvement in knowledge driven by the working population, measured by its human capital. The higher the human capital and the more workers in the economy, the higher the gains to industrial technology driven by "learning-by-doing" and externalities associated with human capital.

$$A_{t+1}^{I} = \left(1 + h_t L_t^{\Delta}\right)^{\zeta} A_t^I, \quad \mathbf{(12)}$$

where $\zeta \epsilon (0, 1)$ as well as $\Delta \epsilon (0, 1)$. Equation (12) shows that industrial technology advances according to the expansion of the existing level of technology due to increasing population and human capital but with diminishing returns.

4.2. Workers

Workers are raised by their parents in the first period of their lives (childhood) and may acquire human capital (education). In the second period of their lives (adulthood), they supply their efficiency units of labor and allocate the resulting wage income. The preferences of members of generation t (those born in $t-1$) are defined over consumption above a subsistence level $\tilde{c} > 0$ and over the potential aggregate income of their children—that is, the number of their children, their

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acquired human capital, and their correspondent wages (observed in $t+1$). They are represented by the utility function:

$$u_t = c_t^{\gamma}(h_{t+1}n_t)^{1-\gamma} \text{ for } 0<\gamma<1, \tag{13}$$

where c_t is consumption, h_{t+1} is the human-capital level of each child, and n_t is the number of children of members of generation t. Following Galor and Weil (2000), the individual's function is strictly monotonically increasing and strictly quasi-concave, satisfying the conventional boundary conditions that ensure that, for sufficiently high income, there is an interior solution for the utility maximization problem. For a sufficiently low level of income, the subsistence consumption constraint is binding. Let $z_t = w_t h_t$ (where for $e_{t+1}=0, \ \ h_{t+1}=1$) be the level of potential income per worker, which is divided between expenditure on child-rearing (quantity as well as quality) and consumption. We define $\tilde{z}$ as the level of potential income below which subsistence consumption is binding.

Let $\tau^r>0$ be the time endowment cost faced by a member of generation t for raising a child, regardless of quality, and let $g(\tau^e, T_t)>0$ be the time endowment cost necessary for each unit of education per child, that is, decreasing in T_t and increasing in τ^e. The latter is the fixed cost of educating children, and the former is the amount of resources raised by landowners among themselves that are transferred to workers to reduce the cost of education to motivate parents (workers) to educate their children defined by $T_t(.)=\frac{t_t b_t}{1+t_t b_t}$. It is an increasing, concave function in b_t (the amount of bequest available to contribute to education) and t_t (the share of resources to be allocated). According to what was previously described, we can sketch time endowment costs as $g(\tau^e, T_t)=\left(\frac{1}{\tau^e}+T_t(.)\right)^{\phi}$, where $-1<\phi<0$. Thus, $g(.)$ is decreasing in t_t and b_t.

Human capital in the second period of life is determined by the units of education received during childhood. It is an increasing and concave function of education.[9]

$$h_{t+1}=h(e_{t+1})=(1+e_{t+1})^{\beta}, \tag{14}$$

with $0<\beta<1$. $h(0)=1$, $\lim_{e\to\infty} h'(e_{t+1})=0$, $\lim_{e\to 0} h'(e_{t+1})=\beta$. In the absence of education, individuals possess basic skills—one efficiency unit of human capital.

We can now sketch the budget constraint faced by parents in the second period:

$$c_t + w_t h_t n_t[\tau^r + g(\tau^e, T_t)\, e_{t+1}] \le w_t h_t, \tag{15}$$

4.2.1. Optimization. The members of generation t maximize utility subject to the budget constraint. They choose the number of children and the level of education of each child and their own consumption. Substituting (15) with (13), the optimization problem for a member of generation t reduces to

$$(n_t, e_{t+1}) = \text{argmax}\ \{w_t h_t(1-n_t[\tau^r + g(\tau^e, T_t)\, e_{t+1}])\}^{\gamma}\{(h_{t+1}n_t)\}^{1-\gamma}, \tag{16}$$

subject to

$$w_t h_t (1 - n_t[\tau^r + g(\tau^e, T_t)\, e_{t+1}]) \geq \tilde{c},$$
$$n_t, e_{t+1} \geq 0.$$

It follows from the optimization process that:

$$n_t = \begin{cases} \frac{1-\frac{\tilde{c}}{w_t h_t}}{\tau^r + g(\tau^e, T_t) e_{t+1}} & \text{if } z_t < \tilde{z} \\ \frac{1-\gamma}{\tau^r + g(\tau^e, T_t) e_{t+1}} & \text{if } z_t \geq \tilde{z} \end{cases}. \quad \textbf{(17)}$$

For a binding consumption constraint $z_t < \tilde{z}$, the optimal number of children for a member of generation t is an increasing function of individual t's income. This mimics one of the fundamental features of the Malthusian era: the individual consumes the subsistence level $\tilde{c}$ and uses the rest of the time level for child-rearing. The higher the wage the individual earns, the lower the time allocated to labor, and the time spent rearing children increases.

From above, population dynamics L_{t+1}, follow straightforward:

$$L_{t+1} = L_t n_t = \begin{cases} \frac{1-\frac{\tilde{c}}{w_t}}{[\tau^r + g(\tau^e,\, t_t) e_{t+1}]} L_t & \text{if } z_t < \tilde{z} \\ \frac{1-\gamma}{[\tau^r + g(\tau^e,\, t_t) e_{t+1}]} L_t & \text{if } z_t \geq \tilde{z} \end{cases}. \quad \textbf{(18)}$$

Regarding education decisions, the optimization with respect to e_{t+1} shows that the units of education for each child only depend on the relative weight of raising costs and educating costs, independently of the time division between consumption and child-rearing. While the raising costs are constant, the educating costs rely on the willingness of landowners to devote resources to fostering education. The higher the resources devoted to education by landowners, the higher the units of education given to children as referred to in Lemma 2.

LEMMA 2. *If (B.2), in Appendix B.2 of the Supplementary Material, is satisfied, then for the specific set of equations of* $g\,(.)$, $n_t\,(.)$ *, and* $h_t\,(.)$*, the level of education of generation t is a nondecreasing function of* T_t.

$$e_{t+1} \begin{cases} = 0 \text{ if } T_t = 0 \\ > 0 \text{ if } T_t > 0 \end{cases} \text{ and } e'_{t+1}\,(T_t) > 0 \text{ for } T_t > 0.$$

Note that $T_t \geq 0$*, by definition of* t_t *and* b_t.

From Lemma 2 and (17), we can draw some conclusions regarding the behavior of education and the number of offspring.

PROPOSITION 1.

(A) *The number of offspring and level of education are affected by the level of* T_t *. An increase in* T_t *results in a decline in the number of offspring and in an increase in their level of education:* $\frac{\partial n_t}{\partial T_t} < 0$ *and* $\frac{\partial e_{t+1}}{\partial T_t} > 0$ *(see the Proof in Appendix B.3 of the Supplementary Material).*

(B) *The number of offspring is affected by changes in the potential income of parents if the subsistence consumption constraint is binding, while the level of education*

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is not affected. Otherwise, none of the two variables are affected—from (17) and Lemma 2.

$$\begin{cases} \frac{\partial n_t}{\partial z_t} > 0 \text{ and } \frac{\partial e_{t+1}}{\partial z_t} = 0 \text{ if } z_t < \tilde{z} \\ \frac{\partial n_t}{\partial z_t} = \frac{\partial e_{t+1}}{\partial z_t} = 0 \text{ if } z_t \geq \tilde{z} \end{cases}.$$

4.3. Landowners

Landowners (elites) are raised by their parents during childhood and receive their parents' bequest. They then decide whether to allocate a share to contribute to education or to leave it to be spent in adulthood on consumption, and to bequest it to their future offspring. Hence, in adulthood, landowners divide the value of rent from land and the amount of bequest left from childhood into consumption and the bequest to their children. The preferences of members of generation t (those born in period $t-1$) are defined over consumption as well as over the bequest left to their children. They are represented by

$$u_t = c_{t+1}^{\mu}(b_{t+1})^{1-\mu} \text{ for } 0 < \mu < 1, \tag{19}$$

where c_{t+1} is consumption in the second period, b_{t+1} is the bequest for the child. Landowners' function is again strictly monotonically increasing and strictly quasi-concave, satisfying the conventional boundary conditions. We assume that $\mu = \gamma$.

The available income to use as consumption and bequest is defined by the second period rent and the remains of the bequest after deducting the amount to support education. This amount (T_t) is deducted in the first period when the bequest is received. The bequest maintains the same value throughout both/all periods, and the interest rate equals zero. A boundary on the gains of increased spending is plausible to avoid infinite gains. The rent depends on the amount of land each landowner has.

We can now sketch the budget constraint faced by a landowner in the first period:

$$c_{t+1} + b_{t+1} \leq \rho_{t+1} + (1-t_t)b_t. \tag{20}$$

4.3.1. Optimization. Members of generation t maximize utility, subject to the budget constraint. They choose the tax level, the consumption in the next period, and the next period's bequest for their children. Substituting (20) into (19), the optimization problem for a member of generation t reduces to

$$(t_t, b_{t+1}) = \text{argmax } \{\rho_{t+1} + (1-t_t)\, b_t - b_{t+1}\}^{\gamma} \{(b_{t+1})\}^{1-\gamma}, \tag{21}$$

subject to

$$b_{t+1} \geq 0 \text{ and } t_t \in [0, 1].$$

It follows from the optimization process that

$$b_{t+1} = (1-\gamma)\left[\rho_{t+1} + (1-t_t)b_t\right]. \tag{22}$$

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Landowners spend $(1-\gamma)$ of their income in providing a bequest for their children. Using (5) and (21), the optimization with respect to t_t shows this as an implicit function $G(.)$:

$$G\left(A_t^A, A_t^I, L_t, t_t\right) = \frac{d\rho_{t+1}}{dt_t} - b_t = 0. \tag{23}$$

There are different effects that influence the decision of landowners which are reflected in $G(.)$. The primary effect is the "bequest effect." The higher the bequest, the higher is the amount transferred to support education. This effect is always negative. The "rent effect" can be divided into two main effects: the "technology effect" and the "workers effect." The technology effect is positive since a higher amount spent on supporting education increases the externality of industrial technology on agricultural technology. The sign of the worker effect, however, is ambiguous. With more education, the agricultural share can increase due to externalities that increase productivity in this sector, while the industrial sector can benefit from more human capital, which also increases marginal productivities in this sector. Thus, depending on the strength of forces, the share of workers either in industry or in agriculture may increase. Now, since the landowners' decision relies on an implicit function and $t_t \in [0, 1]$, when $G(.)$ does not equal zero, an increase in t_t either increases the utility at a maximum of $t_t = 1$ or decreases the utility so that the best choice is $t_t = 0$. Otherwise, $t_t \in (0, 1)$ so that the best choice is an interior solution.[10]

4.3.2. Political mechanism. Landowners in this model are a central force on education reforms. We define a stable political system which does not depend on changes in the economy, but whose decisions will affect the way education develops over time. Economic development and the structure of the economy, whether only the agricultural sector is open or both sectors are open, change landowners' economic incentives and their decisions regarding education.

As seen above, improvements in technology in the agricultural sector depend not only on population resources available in the economy but also on spillovers from the industrial sector when workers are sufficiently educated [see equation (11)]. Landowners understand the possible rent gains when productivity and production in the agricultural sector increase—see landowners' optimization. Given this perception of not only future gains with education but also of losses due to the competition of another sector, the decision of whether to support education is not *a priori* defined. Depending on whether an additional unit of transferences—t_t—leads to enough positive gains in rents such that $G(.)$ is positive, landowners decide on positive transfers to workers, which fosters education among the population in general. If the gains are not sufficient, then landowners do not transfer any amount and taxes are set to zero.

LEMMA 3. *The decision to set taxes at a higher rate than zero depends on the value of the implicit function. Since* $t_t \in [0, 1]$ *then:*

If for the entire interval [0, 1]*:*

$$\begin{cases} G(.) < 0, & \Rightarrow t_t = 0 \\ G(.) > 0, & \Rightarrow t_t = 1 \end{cases}.$$

If in the interval [0, 1]*:*

$$G(.) = 0, \Rightarrow t_t \in [0, 1].$$

See the Proof in Appendix B.4 of the Supplementary Material.

From the Proof of Lemma 3 in the Appendix B.4 of the Supplementary Material, we observe that landowners' decisions will be dependent on the stage of development of the economy. Before the Industrial Revolution, the decision of landowners regarding education relied on the technology effect as a positive force and on the "worker effect" and bequest effect as negative forces (see Lemma 4 in Appendix B.6 of the Supplementary Material). Since technology of the industrial sector is at first very low, as we are still in the pre-Industrial Revolution period, $G(.)$ will be negative and taxes zero, only becoming positive if technology in the industrial sector becomes attractive enough such that spillovers from this sector increase rents in the agricultural sector. After the onset of the industrial sector, there is an additional effect—the "population effect." This effect relates to education. The more education workers receive, the less time endowment they have to raise their children, beginning the quantity–quality trade-off (see Lemma 5 in Appendix B.7 of the Supplementary Material). Depending on the strength of these effects, landowners define when to contribute to education. These decisions rely on the macroeconomic environment and main variables such as agricultural and industrial technology and on population dynamics. As shown later, at some point in time, the gains attained by landowners will be large enough for them to set transfers t_t higher than zero.

5. DYNAMICS OF THE DEVELOPMENT PROCESS

In this section, we examine how the structure of the economy and agents' decisions shape the path of the development process. We show how the economy can evolve from a preindustrial equilibrium to a state of sustained economic growth and how agricultural technology and landowners' decisions affect the economic equilibrium during different states.

5.1. Before the Industrial Revolution

This subsection presents the endogenous evolution from a Malthusian era and the endogenous transition to industrialization. It is shown that the transitional process depends on agricultural technology and on landowners' contributions to education. During the Malthusian era, the economy is governed by the dynamics of equations (11), (12), and (18) which, bearing in mind the initial values $\left(A_0^A, A_0^I, L_0\right)$, yield the sequence of state variables $\left\{A_t^A, A_t^I, L_t\right\}_{t=0}^{\infty}$.

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Following Ashraf and Galor (2011a), the preindustrial equilibrium can be analyzed by the behavior of the two variables $\{A_t^A, L_t\}$ and the distance to the Industrialization Frontier. The industrial technology variable does not affect the preindustrial equilibrium since until the emergence of the industrial sector, it is just a latent variable. It must also be stressed that in the preindustrial era, the economy is under the Malthusian regime; that is, it evolves under the assumption that the subsistence consumption constraint is binding and so fertility depends on the income of workers. Thus, the economy under steady-state equilibrium is trapped in the Malthusian regime and with the binding consumption constraint.

5.1.1. The Industrialization Frontier. The Conditional Industrialization Frontier (*CIF*) gives the frontier between the agricultural economy and the industrial economy. Once the economy's trajectory crosses the frontier, the industrial sector becomes operative. The *CIF* is then given by

$$CIF|A_t^I \equiv \left\{\left(A_t^A, L_t\right):\ L_t = \hat{L}(A_t^A, A_t^I)\right\}, \tag{24}$$

and we can establish the following lemma:

LEMMA 6. *If $\{A_t^A, L_t\}$ belongs to the CIF, then, for a given A_t^I,*

$$L_t = \frac{(1-\alpha)^{\frac{1}{\alpha}} A_t^A X}{\left(h_t A_t^I\right)^{\frac{1}{\alpha}}},$$

where $\frac{\partial \hat{L}(A_t^A,\, A_t^I)}{\partial A_t^A} > 0$ *and* $\frac{\partial \hat{L}(A_t^A,\, A_t^I)}{\partial A_t^I} < 0$.

Proof. This follows directly from Lemma 1, and equations (6), (7), and (24). ■

The *CIF* is upward sloping. In the region strictly below the frontier, agriculture is the only open sector, whereas in the region above, both sectors are open. The higher A_t^I, the closer we are to the trigger and to surpassing the *CIF*.

The agricultural technology locus is set, for all the pairs $\{A_t^A, L_t\}$, such that A_t^A is in steady state.

$$AA \equiv \left\{\left(A_t^A, L_t\right):\ A_{t+1}^A - A_t^A = 0\right\}. \tag{25}$$

LEMMA 7. *If $\{A_t^A, L_t\}$ belongs to AA, then*

$$L_t = \left(A_t^A\right)^{\frac{1-\delta}{\varepsilon}} \equiv L^{AA}\left(A_t^A\right),$$

where $\frac{\partial L^{AA}\left(A_t^A\right)}{\partial A_t^A} > 0$ *and* $\frac{\partial^2 L^{AA}\left(A_t^A\right)}{\partial \left(A_t^A\right)^2} > 0$.

Proof. This follows from equation (11), using the steady-state condition, and (25). ■

The AA locus is a convex, upward-sloping curve. Above L^{AA} the number of workers is large enough to ensure the expansion of the technology frontier, overcoming the erosion effects of imperfect intergenerational transmission of knowledge. Below the L^{AA}, workers are too few to overcome the latter effect and shrink the technology level.

The population locus (LL) is the set of all pairs $\left\{A_t^A, L_t\right\}$ such that L_t is in steady state.[11]

$$LL \equiv \left\{ \left(A_t^A, L_t\right): L_{t+1} - L_t = 0 \,\middle|\, L_t < \hat{L}; z_t < \tilde{z} \right\}. \tag{26}$$

LEMMA 8. *If $\left\{A_t^A, L_t\right\}$ belongs to LL, then*

$$L_t = \left[\frac{(1-\tau^r)(1-\alpha)}{\tilde{c}}\right]^{\frac{1}{\alpha}} A_t^A X \equiv L^{LL}, \left(A_t^A\right)$$

where $\frac{\partial L^{LL}\left(A_t^A\right)}{\partial A_t^A} > 0$ *and* $\frac{\partial^2 L^{LL}\left(A_t^A\right)}{\partial \left(A_t^A\right)^2} = 0.$

Proof. This follows from (18), using the steady-state equilibrium condition and (26). ■

Hence, the LL locus is an upward sloping linear function. L_t grows over time below the LL locus ($L_{t+1} > L_t$), when for a lower population size wages increase, allowing for fertility above replacement. Otherwise, wages are lower, and, due to the consumption constraint, resources available for fertility are reduced ($L_{t+1} < L_t$). The relationship between the LL locus in Lemma 8 and the CIF in Lemma 6 is as follows.

LEMMA 9. *For* $A_t^I > 0$ *and for all* A_t^A *such that* $[A_t^A, \hat{L}(A_t^A, A_t^I)] \in CIF|A_t^I$ *and* $\left[A_t^A, L^{LL}\left(A_t^A\right)\right] \in LL$

$\hat{L}(A_t^A, A_t^I) \gtreqless L^{LL}\left(A_t^A\right)$ *if and only if* $A_t^I \lesseqgtr \frac{\tilde{c}}{(1-\tau^r)h_t}$.

Proof. This follows from comparing $\hat{L}\left(A_t^A, A_t^I\right)$ in Lemma 6 with $L^{LL}\left(A_t^A\right)$ in Lemma 8. ■

5.1.2. Equilibrium and global dynamics. If we consider the preindustrial Malthusian equilibrium, we must ensure that the condition $A_t^I < \frac{\tilde{c}}{(1-\tau^r)h_t}$ in Lemma 9 is verified and the subsistence consumption constraint is binding, $z_t < \tilde{z}$. Following these conditions, the Malthusian steady state is characterized by a globally stable steady-state equilibrium $\left\{A_{ss}^A, L_{ss}\right\}$—see Appendix B.8 of the Supplementary Material. By ruling out the unstable equilibrium at the origin *($L_0 > 0$* and *$A_0^A > 0$)*, the globally stable equilibrium $\left\{A_{ss}^A, L_{ss}\right\}$ is conserved. At the initial stages of development, agriculture is the pervasive sector since the latent industrial sector has a very low level of productivity and is thus not sufficiently attractive. The economy then operates exclusively in the agricultural sector. Thus, the CIF locus is located above the $\boldsymbol{LL}$ locus, and the above-mentioned dynamics

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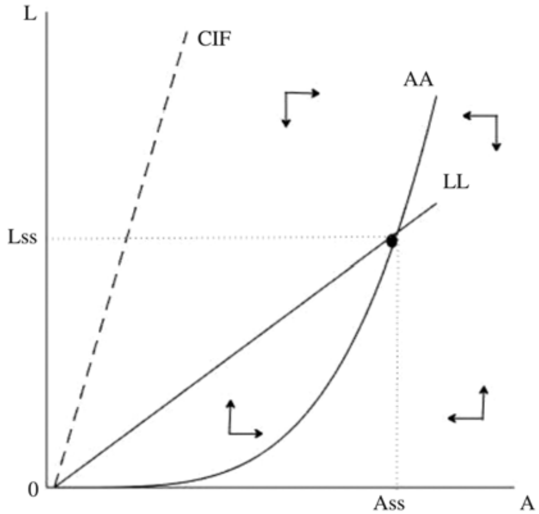

FIGURE 2. Preindustrial equilibrium.

of L_t and A_t^A are valid (see Figure 2). Proposition 2 describes the stability of the dynamic system and the convergence to the steady state.

PROPOSITION 2. *For $A_t^I < \frac{\tilde{c}}{(1-\tau^r)h_t}$, the equilibrium in the dynamical system is globally stable and the convergence to the steady state is monotonically stable since the necessary conditions hold under the parameterization assumed in Subsection 6.1 (see also Appendix B.8 of the Supplementary Material).*

From the analytical solution of the dynamical system, the Malthusian equilibrium is not generally globally stable. In Appendix B.8 of the Supplementary Material are shown the necessary conditions for the dynamical system in the Malthusian equilibrium to be globally stable. The global stability conditions hold under the parameterization assumed in Subsection 6.1. We also ensure that during this regime, the subsistence consumption constraint remains binding so that $z_t \left| A_{ss}^A, L_{ss} = w_{ss}h_t \right. < \tilde{z}$, for an initial $h_t = 1$. With only the agricultural sector operative, all workers are employed in this sector. Thus, it follows from (1) and the globally stable steady-state values that, in line with the dynamics in the Malthusian era, in the long run, the level of income is independent of the technology level and is stable.

As the economy evolves during the Malthusian era within the preindustrial steady state, the latent and endogenous process of industrialization implies that the take-off to a state of sustained economic growth will take place sooner. The driving force behind the transition from an agricultural society to an industrial one, which will force the exit from the Malthusian trap, stems from the growth of productivity in the (latent) industrial sector. In (12), we can observe the typical mechanism that leads to an increase in the initially latent productivity of the industrial sector. The higher the human capital and the higher the number of

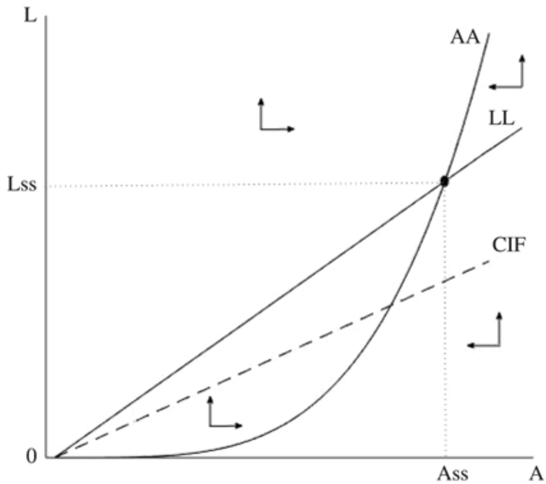

FIGURE 3. Onset of industrialization.

workers in the economy, the higher the gains to industrial technology driven by "learning-by-doing" and externalities associated with human capital. In the process of development, increases in the industrial productivity (A_t^I) rotate the CIF as we can observe in Figure 2.

As A_t^I continues to increase and gets closer to the trigger of the industrial sector, the CIF locus rotates clockwise (Figures 2 and 3). As productivity of the industrial sector surpasses the trigger level, $A_t^I > \frac{\tilde{c}}{(1-\tau^r)h_t}$, this sector becomes operative and the CIF will be below the LL locus, as in Figure 3. As the economy moves from an agricultural to an industrial economy, the globally stable Malthusian steady state ceases to exist. The model predicts the transition to a sustained growth under the right ranges of parameters (see Section 6).

5.2. The Industrial Revolution

When the industrial sector takes off, two regimes can emerge—both of which are shown in Appendix B.9 of the Supplementary Material. In the first regime, the subsistence consumption constraint is still binding. Nevertheless, as the previous steady-state equilibrium vanishes, wages increase and so the subsistence constraint will also vanish in time. In the second regime, the subsistence constraint is no longer binding. Population grows at a constant level that will only be affected by worker education choices. The transition between the two regimes is given by the distance to the Malthusian Frontier (MF). As previously explained, the economy departs from the first regime when potential income, z_t, exceeds that level. Thus, $\left\{A_t^A, A_t^I, L_t\right\}$ belongs to the Malthusian Frontier according to

$$MF \equiv \left\{\left(A_t^A A_t^I, L_t\right): \theta\left(A_t^I\right)^{1-\theta}\left(\lambda_t(A_t^A, A_t^I, L_t)L_t\right)^{\theta-1}(h_t)^{\theta} = \frac{\tilde{c}}{1-\gamma}\right\}. \quad \textbf{(27)}$$

From this condition, we can define Lemma 10:

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LEMMA 10. *The economy leaves the Malthusian regime if*

$$w_t^I \geq \frac{\tilde{c}}{1-\gamma}.$$

Proof. This follows directly from (8), the definition of z_t and $\tilde{z}$, and (27). ■

The take-off from the Malthusian regime is achieved through the process of industrialization and the increase on human-capital intensity in the industrial sector that makes wages increase over time. Since $\frac{\tilde{c}}{1-\gamma}$ is a constant, at some point in time the trigger will be reached, and the Malthusian regime will cease to exist, moving to the post-Malthusian regime. The forces behind the passage of one regime to another are the same ones linked to the industrialization process. As the population increases, the gains from "learning-by-doing" and the latent effects of a greater number of ideas sprouting from a larger number of individuals foster the latent industrial development that will become the engine of future increases in wages and technology. At some point, this process will be strong enough to overcome the Malthusian forces and lead the economy to exit the Malthusian trap.

As the economy enters the industrial era, the globally stable Malthusian regime in the A_t^A, L_t space no longer applies. Upon leaving the Malthusian trap, the analytical solution becomes intractable, meaning that a definite conclusion regarding the dynamics of the new regime can only be described by the numerical simulation in Section 6. In the long run, under the parameterization of the numerical example below, the economy gradually moves to a steady state where education and fertility levels are constant. The economy enters an era of sustained endogenous growth, where the growth of income per worker is driven mostly by the growth of industrial productivity, which also tends to the equilibrium. As shown in Appendix B.10 of the Supplementary Material, this solution may not always occur but is stable for a large range of parameter values.

6. FROM THE MALTHUSIAN ERA TO THE MODERN-GROWTH ERA

In this section, we build a numerical example, using the above model, to examine the dynamics of the model along the different regimes and periods of time. Since the model is analytically intractable, we resort to the numerical analysis to show the dynamics and all the necessary proofs regarding the effects from the main variables on landowners' and households' decisions. The first part of the numerical analysis will be concerned with the relationship between landowners' decisions and education as well as impacts on the process of industrialization and demographic transition. The second part will be dedicated to showing how an earlier improvement of agricultural techniques, namely the "First Agricultural Revolution," has an impact on landowners' incentives to contribute to education and then proceeding to shedding light on a possible connection between the revolutions (Industrial and Agricultural). From here, we can draw the two main hypotheses advanced in this paper, shown in Subsections 6.2 and 6.3:

TABLE 1. Parameter calibration

Parameter	Values	Sources
Land share (α)/labor share ($1-\alpha$)	0.35/0.65	Hansen and Prescott (2002) and Galor (2011)
Human-capital share (θ)	0.65	Voigtländer and Voth (2006) and Elgin (2012)
Land (X)	1	Normalization
Weight on fertility in utility function ($\gamma=\mu$)	0.635	Lagerlöf (2006)
Fixed time cost of raising children (τ^r)	0.35	Assumption
Time cost of educating children (τ^e)	0.097	Lagerlöf (2006) and Galor (2011)
Subsistence consumption ($\tilde{c}$)	1	Normalization
Degree of concavity of human-capital function (β)	0.35	Assumption
Time endowment cost concavity (ϕ)	−0.9	Assumption
Weight of population on agricultural "learning by doing effect" (ε)	0.04	To target trends in the model
Weight of agricultural technology on agricultural "learning by doing effect" (δ)	0.10	To target trends in the model
Externality of industrial technology (b)	0.89	To target trends in the model
Weight of population on industrial "learning by doing effect" (Δ)	0.05	To target trends in the model
Diminishing returns effect on the industrial dynamic path (ζ)	0.06	To target trends in the model

HYPOTHESIS 1. *The emergence of education, and hence the demographic transition, relies on the decision of landowners: they delay the emergence of education even after the onset of the Industrial Revolution;*

HYPOTHESIS 2. *The First Agricultural Revolution positively affects the emergence of education.*

6.1. Model Calibration

Although our focus here is to show the expected dynamics in a numerical example, we parametrize our model such that it resembles the patterns observed in this period of modern history as closely as possible. Subsequently, we closely follow Hansen and Prescott (2002), Lagerlöf (2006), Voigtländer and Voth (2006), Galor (2011), and Elgin (2012) who provide quantitative analyses of UGT models and use some of the resulting parameterization on our model. The baseline parameters are depicted in Table 1. The typical values from labor share were taken from Hansen and Prescott (2002) and Galor (2011). Human-capital share is set to

TABLE 2. Initial conditions

Parameter	Values	Sources
Population (L_0)	0.076	Steady-state
Agricultural productivity (A_0^A)	0.8918	Steady-state
Industrial productivity (A_0^I)	0.6	Assumption (see Lemma 1)
Fertility (n_0)	1	Normalization
Education (e_0)	0	Assumption
Share of workers in the industrial sector (λ_0)	0	Assumption (see Lemma 1)
Bequest (b_0)	1	Initial assumption

0.65 as in Voigtländer and Voth (2006) and Elgin (2012) —see also Afonso and Magalhães (2018) and Neto et al. (2018). The fixed time costs of raising children and education costs are set to 0.35 and 0.097. These cost values are needed to guarantee that the conditions in Appendices B.2 and B.8 of the Supplementary Material are conserved. In Lagerlöf (2006), a smaller value is assumed for fixed time costs. Here, we found a compromise that, on the one hand, does not deviate too much from Lagerlöf's values but, on the other hand, still guarantees that fertility growth rates in the post-Malthusian era do not turn population growth too high and oscillatory. Regarding β and ϕ, we choose parameters that meet the properties of the human-capital function, $g(.)$ and condition (B.2), which are achieved by a degree of concavity of human-capital formation of 0.35 and a negative concavity of 0.9 of time endowment costs. The technology dynamics parameters are specified to capture the trends observed in terms of demographic and technology observed in this period. Indeed, as we demonstrate in our sensitivity analysis in Appendix B.10 of the Supplementary Material, the choice of these parameters for a reasonable range of values does not lead to instability of the model. Hence, we target them such that these trends are captured in the model. Without loss of generality, we assume a fixed quantity for land $X_t = X = 1$.

Moreover, in Table 2, the initial conditions of the model are given by the steady-state equilibrium values for the preindustrial period of A_0^A and L_0 (shown in Appendix B.8 of the Supplementary Material) as well as by the initial values on fertility, education, and bequests.

The preindustrial steady-state values of A_0^A and L_0 will rely on parameters in Table 1, as shown in the Appendix B.8 of the Supplementary Material. We choose A_0^I such that at the beginning, Lemma 1s condition does not hold. Given this, the share of workers in the industrial sector is also set to 0%.

6.2. Landowners, Education and Demographic Transition

The economy evolves from the Malthusian era to the Modern-Growth era, passing through the post-Malthusian era and the demographic transition. This path derives from Section 5 and the two regimes explained in Subsection 5.2.

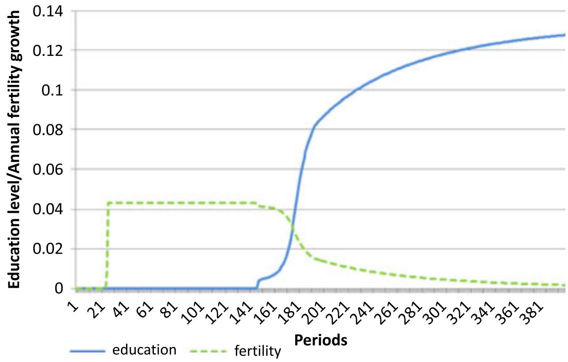

FIGURE 4. Quantitative analysis of calibrated model—education and fertility.

In the long run, all variables tend to stabilize, as is possible to observe in the period-extended figures of Figures 4B and 5B in Appendix B.10 of the Supplementary Material. As referred to above, due to the intractability of the model, it is not possible to analytically show the stability of the model, but in our numerical simulation and under the parameterization assumed at the beginning of this section, our model converges to a stable solution.[12]

As the economy is trapped in the preindustrial equilibrium, population is small and agricultural technology is stagnant. Initially, education is not supported by landowners' contributions, and thus, workers provide no education to their offspring. As depicted in Figure 4, the preindustrial Malthusian era remains until the beginning of the industrial phase. At the onset of the industrialization, population growth rates increase and remain high until the demographic transition takes place. Consistent with the empirical evidence, the demographic transition occurs after about 100 periods, when landowners start contributing to education and education starts increasing over time. Prior to that, education levels are always zero. In the preindustrial Malthusian era, fertility has a positive correlation with and depends on workers' income. Even in the pre-Malthusian era, landowners can support education among workers. However, as seen in Lemmas 3 and 4, it only occurs if the gains in rents are such that $G(.)$ is positive. As shown in Lemma 4, this never happens since it is dependent on the evolution of the industrial technology that is very low during the Malthusian period. Hence, the spillovers from the industrial sector to the agricultural sector would not be attractive enough to make landowners support education, and so, the education level is zero during the Malthusian era.

Nevertheless, the preference of landowners to have no education changes after the onset of the industrial sector. When the industrial technology is high enough, the industrialization takes place and the Malthusian forces vanish. Population starts to grow over time, and, from equations (11) and (12), there is a scale effect on both technologies and an interconnection between variables since both an increased population and more technology lead to higher wages. Thus, according

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to Lemma 2 and Proposition 1, the more income available, the less restrictive the budget constraint is. Hence, consumption increases over time. In response to increasing disposable income, the subsistence consumption constraint vanishes. As this occurs, the economy moves to the second regime where fertility no longer depends on income and is only dependent on the quality–quantity trade-off. In Figure 4, these patterns are visible at the point where fertility rates increase from 0% to around 4%—the subsistence constraint is no longer binding when the industrialization process takes off.

In this new regime, new circumstances arise and with them the willingness of landowners to either provide education or not to the young people. Landowners, again, can influence workers' provision of education through tax contributions (see Lemma 2 and Proposition 1). In the beginning, we observe that education levels remain low while fertility rates are very high. Since rents of landowners are still high enough and growing, there is no interest of landowners to encourage education via transfers (t_t) to workers. While the industrialization of the economy develops and the industrial technology grows faster, workers become more numerous in the industrial sector. As this is happening, the growth rate of rents decreases over time. As a counter reaction to this trend, landowners begin to make transfers to workers so that they educate their children because now both technologies (agricultural and industrial) are connected via a spillover effect from the industrial sector to the agricultural one [see equations (11) and (12)]. Therefore, as human capital increases spillovers from the industrial sector to the agricultural sector, rents' growth rates will increase again, benefiting landowners. This benefit to landowners can also be seen analytically. As shown in Lemmas 3 and 5, as industrial technology increases over time, the marginal gains from the technology effect at some point exceed the "workers effect" and the population effect. As this condition applies, the overcoming of the bequest effect, which is negatively affected by growing industrial technology, soon follows.

This education process boosts education levels in the economy and negatively affects fertility since individuals start to dedicate more of their time to education and less to raising a larger number of children [see equation (18)]. That is why we observe in Figure 4 a simultaneous decrease in fertility rates with an increase in education levels. From the patterns in Figure 4, we can observe the same trends as in the empirical data regarding the process of demographic change—first an increase in fertility rates due to the break of the Malthusian era and later an increase in education rates accompanied by a decrease of fertility rates. These patterns can be explained through landowners' preferences regarding the support of education. The delayed response of landowners in supporting education will cause a period of high fertility rates, as is observed at the beginning of the 1800s, and then be followed by a constant fall of these rates when they begin supporting education.

But, the decisions of landowners do not only affect fertility rates and education levels. Regarding the paths of technology and income, Figure 5 depicts a continuous increase in agricultural and industrial productivities along with population

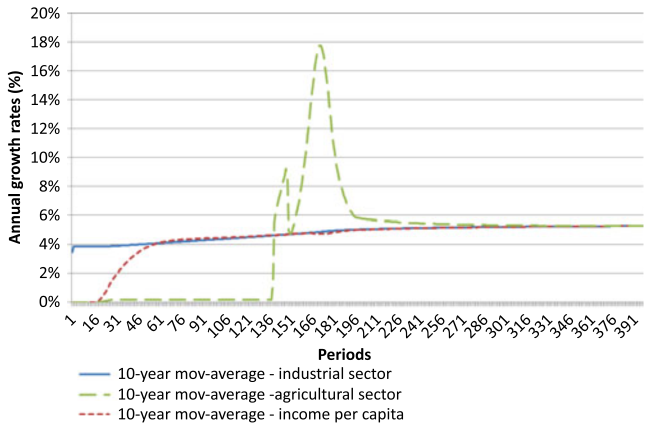

FIGURE 5. Quantitative analysis of the calibrated model—productivity rates and income per capita.

after the preindustrial Malthusian equilibrium.[13] Both production sectors are now open and profit from spillovers of population growth and education. As previously discussed, there is a migration of workers from the agricultural sector to the industrial sector as observed in the empirical data. Gains obtained in productivity and increasing levels of human capital among the population make the industrial sector more attractive. From (9), the share of workers in the industrial sector depends positively (negatively) on the technology of the industrial (agricultural) sector. As Figure 5 shows, productivity growth in the industrial sector will, in the long run, always be higher than productivity growth in the agricultural sector. Therefore, the share of workers in the industrial sector will tend to increase over time, which is now observable in developed countries where the share of workers in the agricultural sector is quite minimal. According to Broadberry et al. (2013), the sectoral distribution of the labor force between three sectors (agriculture, industry, and services) shows a permanent decrease on the share of labor in the agricultural sector. It declines from 58.1% in 1522 to approximately 16.9% in 1871, while the industrial sector share of workers increased from 22.7% to 47.1% (see Figure A4 in Appendix B.3 of the Supplementary Material). In our simulation, the share of workers in the industry sector after the onset of the Industrial Revolution reaches values of around 65% in the short-run and increases to 93% of workers employed in the industrial sector in the medium run and in the long run. Our model does not have a service sector, so if we only account for the ratio between agriculture and industry sectors, the weight of the industry sector in comparison with the agriculture sector changes from 28% in 1522 to 74% in 1871 and is equivalent to our short-run estimates. Our medium-run estimates would correspond to today's percentages of the sectoral distribution of labor force (close to 95% in developed countries).

In this process, both sectors' productivities increase because of education. In fact, agricultural productivity reaches a peak after the start of educational

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provision with high growth rates in this period, while industrial productivity undergoes a small increase, but maintains its almost constant ascending path. The volatility observed in a few periods of the simulation for the agricultural technological progress is associated with gains obtained at the time of the emergence of education in the economy (see Figure 5). As we can see from equation (11), agricultural technological progress depends on education. Because there is no education provided before the Industrial Revolution, when it is provided and human capital increases, the growth rate of technology in the agricultural sector expands. This boost on the dynamics of agricultural technology makes technological progress grow stronger and the growth rate jump suddenly, creating this volatile profile. After stabilizing, the growth rate is then higher for all later projected periods due to the efficiency gains obtained by more education provided and technology spillovers. This pattern well describes the dynamics inherent in the Second Agricultural Revolution. Externalities from the industry sector lead to a surge on productivity and output growth as depicted in Figures A1–A3 where some spikes are visible at the beginning of the second half of the 19th century. This Second Agricultural Revolution is different from the First Agricultural Revolution before the Industrial Revolution because here productivity gains in agriculture stem from endogenous transfers of knowledge between sectors as a result of landowners' decision to invest in education [see equation (11)]. Over time, both sectors' technologies and income per capita continue to grow at stable rates, although agricultural productivity grows at a slightly slower pace than industrial productivity as externalities from the latter sector are not totally absorbed by the former one. A sensitivity analysis on the level of externalities is undertaken in Appendix B.10 of the Supplementary Material.

It is the combined effect of technology development and externalities between production sectors that influence landowners' decisions and their incentives to promote education. Since technology gains from the industrial sector will happen independently of the landowners' decision, the support of education by landowners will eventually happen since they cannot afford to lose their rents (Lemma 5). Still, this decision will be delayed as much as possible and will affect the rise of human capital in the economy and, subsequently, the enhancement of the industrial sector. From the above explanations and previously referred lemmas, we arrive at the following proposition:

PROPOSITION 3. *The aversion of landowners to education does not persist over time. Their decision to support education on their own occurs at some point in time. Landowners may delay education but do not prevent its growth indefinitely.*

Proof. This follows from Lemmas 3, 4, and 5. ■

Industrial sector growth and the subsequent rise in education have a virtuous effect. Workers' higher earnings mean a better quality of children and lead to cumulative effects of a rising use of technology and, hence, increase productivity

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levels of workers in both sectors. This increased productivity raises earnings, implying more income available for consumption and child-rearing.

Thus, in contrast with many theoretical contributions [Mokyr (1990), Bourguignon and Verdier (2000), Acemoglu and Robinson (2006), and Galor et al. (2009)], it is possible that landowners had an incentive to support educational progress. Nevertheless, in line with those same theories, they also had the power to prevent the emergence of education sooner due to their own interests. This means that although they eventually decided to support education, they only made that decision later in time, which is historically consistent with the delayed process of education: the Industrial Revolution commenced in the late 1700s but education only spread in the mid to late 1800s [Flora et al. (1983) and Brown (1991)]. Thus, this delay can be traced to the power of landowners. If, as it is argued in previous sections, landowners were a small interest group, which had the power to decide people's education, then they also had the power to block education reforms. Hence, they had incentives to block education during industrial emergence, but they also had incentives to support it afterwards when it became economically beneficial for them. In line with the literature, it can be shown that landowners were not always against education and industrial enhancement.

6.3. Landowners' Decisions and the Agricultural Revolution

The second hypothesis advanced in this paper suggests that increasing technology in agriculture leads landowners to be more disposed to supporting education.

Contrary to the Second Agricultural Revolution described in the last subsection, the main concern in this subsection is to explain how an agricultural revolution preceding the Industrial can affect landowners' education decisions and, hence, affect the timing of the take-off of industry and education. The First Agricultural Revolution can be seen more like a shock to agricultural productivity in previous years and on methods and production techniques that increase agricultural productivity. As the sensitivity analysis in Appendix B.5 of the Supplementary Material shows, larger levels of agricultural technology influence positively $G(.)$. Consequently, the First Agricultural Revolution can create greater incentives on landowners to allow for education. These higher levels of agricultural productivity mean higher initial rents for landowners. Notwithstanding the bequest effect, which increases, the technology effect now becomes greater than the former since gains from externalities of industry boost an already higher level in the recipient technology. In other words, the higher level of agricultural technology enhances the effect of the industrial externalities on the agriculture technology. Thus, experiencing shocks relating to agricultural productivity would trigger a speedier positive decision of landowners regarding education and exert a negative effect on the period of industrialization. From Lemmas 1, 4, and 5, we can show that the higher the value of agricultural technology (A_t^A) on the onset of industrialization, the more likely it is that the take-off will take place sooner (see Appendices B.4–B.7 of the Supplementary Material). This stems from the

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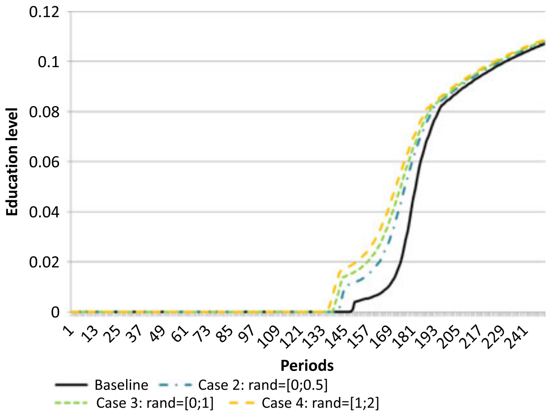

FIGURE 6. Period of take-off of education for different scenarios of shocks in technology of agriculture.

fact that higher productivities induce higher levels of rents and higher bequests that will increase incentives of landowners to contribute more toward education via transference of their wealth. The following proposition can then be advanced:

PROPOSITION 4. *The First Agricultural Revolution has a positive impact on landowners' decision to educate the population. The higher agricultural productivity during the process of industrialization, the more prone are landowners to support education.*

Proof. It follows from Lemmas 1 and 3–5 (see Appendix B.11 of the Supplementary Material). ■

Proposition 4's conclusions are obtained from the numerical analysis conducted in the Appendix B.5 of the Supplementary Material regarding $G(.)$ and its derivatives, for the range of parameters considered in the model. But additionally, we can show these same conclusions by simulating exogenous shocks on agricultural technology before the industrialization and taking these technologic advancements through the industrialization period. To undertake these simulations, we replicate the model using several different positive random shocks with a uniform distribution (cases 2, 3, and 4 in Figure 6). We then test if landowners support earlier education among workers. From Figure 6, it is clear that higher shocks have a positive impact on the early onset of education. Overall, shocks in agriculture affect the decision of landowners to support education and the take-off of the industrial sector with higher agricultural technology shocks.

From the model, in a Malthusian equilibrium, the gains of a single shock vanish over time—equilibrium is globally stable—so there is no effective impact on the outcomes in the economy. However, if there are shocks such that the population level and agricultural technology increase consistently above the equilibrium levels at the time of take-off, then this implies that there is an effect on rents and on bequests, thus, on the willingness of landowners to provide education. There is a virtuous circle in the economy that will then imply a faster economic boost due to more education and, thus, higher industrial and agricultural technology growth rates. This means that countries that underwent an agricultural revolution, mainly Britain and some continental countries, benefited from an earlier take-off of education and an earlier economic boom. The other countries lagged behind, which may have contributed to the divergence process in industrialization and which was verified in this period [Galor (2011)].

Regarding a contribution to the ongoing debate about the role of the First Agricultural Revolution on the onset of education and expansion of the Industrial Revolution, we argue that the literature backing the Agricultural Revolution theories in the 1700s may be correct in pointing to this revolution as relevant to the Industrial Revolution development debate. From our results, it is also clearer to see why the take-off of the industrial sector and education took place earlier in countries such as Britain and the Netherlands. The argument followed in this section points to the fact that a consistent level of ongoing improvements in agricultural techniques and on agricultural production during the 1700s was essential for the occurrence of a stronger industrial revolution and an early escape to modern economic growth.

7. CONCLUDING REMARKS

We argue that both agricultural productivity improvements prior to the Industrial Revolution and technology spillovers from the industrial to the agricultural sector are determinants for lifting the blockage of landed aristocracy to education reforms and human-capital formation, both of which play a major role in the transition from Malthusian stagnation to a sustained economic growth period. By modeling the process of the decision of landowners on whether to support education reforms or not given the future gains on rents and future competition from the industrial sector, we show that only at later stages of the Industrial Revolution when the agricultural sector begins to be less profitable and to suffer from a too strong competition by the industrial sector did landowners have sufficient incentives to support education reforms and to incentivize them. This change in decision is dependent firstly on the spillover of technology that the agricultural sector benefits from due to better educated individuals and gains from innovation in machinery and production technology that only later compensate the harder competition from the industrial sector once education reforms occur.

We demonstrate how landed elites can block the process of education reforms but, ultimately, end up supporting them due to their own interests in benefiting from gains in land rents derived from increasing human capital and innovation during the Industrial Revolution. We also contribute to the UGT by providing a deeper analysis on the role of the improvements on agricultural productivity prior to the Industrial Revolution and on the anticipation of the landowners' decisions supporting education reforms since higher land productivity lowers the risk of losing rents and their share of the economy. The conclusion that the First Agricultural Revolution may have contributed to the early onset of the Industrial Revolution and to a faster process of education of the masses is an important new contribution to the debate currently taking place in the literature. It further explains and gives strength to the theories of why and how Britain developed earlier than other countries in Europe.

The numerical simulations presented herein just show the pattern in which a higher and stronger rise in agricultural productivity leads to an earlier unblocking of education reform policies by the landed aristocracy. In line with the UGT, it is possible to conclude that landowners had a big role in the main events during the period of industrialization and that the occurrence of an agricultural revolution in the previous century positively influenced both industrialization and education reforms on the onset of the Industrial Revolution.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/S1365100518000937.

NOTES

1. Besides this main effect related to education, there are also positive effects highlighted in the literature such as the provision of more and cheaper goods, as well as the migration of labor to the urban population [Overton (1996) and Allen (2009)]. Still, the increase in marginal gains for farm workers compared to urban workers contributes to a slower pace of migration from the countryside to urban areas.
2. We will keep the definition of "First Agricultural Revolution" to the rise in agricultural productivity prior to the Industrial Revolution and leave the "Second Agricultural Revolution" definition as a reference to further improvements in the agricultural sector concomitant with the Industrial Revolution.
3. Some earlier British educational efforts should, however, be mentioned, for example, the push in the 1830s and 1840s and the charity schools.
4. For a detailed explanation on the reasons for the methodological approach assumed, please see Appendix B.2 of the Supplementary Material.
5. Capital is important in the production process. Nevertheless, due to the focus on human capital we do not incorporate it in the production function and we follow the Litina (2016) approach instead.
6. When only the agricultural sector is open, compare the gains in this sector with the supposed gains in the industrial sector, given by (7).
7. Note that for the easy tractability of the equilibrium we will assume that $\theta = 1 - \alpha$.
8. The dynamic paths are inspired by Litina (2016) and Ashraf and Galor (2011a).
9. We follow, for instance, Galor et al. (2009) and Galor and Moav (2006), although there are other interesting approaches such as linking human capital to the growth rate of technology or linking it to teachers' wages although this is beyond the scope of this paper.

10. We show by numerical simulation that $G(.)$ is a decreasing function with respect to t_t. See the sensitivity analysis in Appendix B.5 of the Supplementary Material for proof.

11. Although population increased during some periods of the Malthusian era [Maddison (2003)], the model regards this period on a steady-state level.

12. In Appendix B.10 of the Supplementary Material, we show that the convergence for a stable solution occurs for a large range of parameter values although not all values.

13. Some empirical evidence on the period considered in the analysis suggests that the productivity of agricultural and industrial sectors in the UK have been growing at similar rates [Broadberry et al. (2013)].

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