

ARTICLE

# From Neolithic Revolution to industrialization

Angus C. Chu and Rongxin Xu

Department of Economics, University of Macau, Macau, China

**Corresponding author:** A. C. Chu; Email: [angusccc@gmail.com](mailto:angusccc@gmail.com)

## Abstract

This study develops a Malthusian model for the evolution of human society from hunting-gathering to agriculture and from agriculture to industrial production. Human society evolves across these stages as the population grows. However, under endogenous population growth, the population may stop growing at any stage. If it fails to reach the first threshold, the population remains as hunter-gatherers. If it reaches the first threshold, an agricultural society emerges. Then, if the population fails to reach the industrial threshold, it remains in an agricultural Malthusian trap without experiencing industrialization. Interestingly, high agricultural productivity triggers not only the Neolithic Revolution but also the subsequent industrialization. Using cross-country data to test this result, we employ an index of prehistoric biogeographic conditions that affect agricultural productivity as an instrument for the timing of transitions to agriculture and find that an earlier transition to agriculture has a positive effect on industrialization in the modern era.

**Keywords:** Neolithic revolution; industrialization; endogenous population growth

**JEL Classification:** O13; O14; J11

## 1. Introduction

Archaeological evidence suggests that *Homo sapiens* emerged in Africa as early as about 300,000 years ago.<sup>1</sup> For most of its history, humans were hunter-gatherers. Then, the Neolithic Revolution (the transition from hunting-gathering to agriculture) occurred in the Fertile Crescent about 12,000 years ago and then in other parts of the world.<sup>2</sup> In the late 18th and early 19th century, the Industrial Revolution (the transition from agriculture to the manufacturing of goods) took place in Britain and then in continental Europe and the USA.<sup>3</sup> Are these transitions in the economic evolution of human society inevitable? If not, what are the different conditions that could have potentially made the transitions more or less likely to occur?

This study develops a Malthusian model that captures the economic evolution of human society from hunting-gathering to agriculture and then from agriculture to an industrial economy. In our model, human society evolves across these stages as the size of the population grows. However, under endogenous population growth determined by the fertility decisions of optimizing agents in our microfounded model, the population may stop growing at any stage and never reach the next threshold. If it fails to reach the first threshold, then the population remains in a hunting-gathering Malthusian trap. If the population size reaches the first threshold, then an agricultural society emerges; therefore, both the Boserupian and Malthusian forces are present in our model.<sup>4</sup> The Neolithic Revolution occurs under the following conditions: a high level of agricultural productivity, a low cost of fertility, and a strong preference for fertility. In the main text, we discuss the intuition of these results and their relation to existing hypotheses. We also provide empirical evidence that high agricultural productivity leads to an earlier transition to agriculture.

After an agricultural society emerges, the economy eventually becomes completely agricultural until it reaches the next threshold. If it fails to reach the next threshold, the economy remains in an agricultural Malthusian trap and does not experience industrialization. Industrialization is influenced by the same conditions as the Neolithic Revolution (namely, a high level of agricultural productivity, a low cost of fertility, and a strong preference for fertility) and also other conditions: a high level of industrial productivity and a low fixed cost of industrial production. Therefore, the conditions (e.g., a high level of agricultural productivity) that trigger the Neolithic Revolution also trigger the subsequent industrialization, but not necessarily vice versa. Here, the importance of the population size on industrialization is due to its increasing returns to scale (i.e., having a large enough market to cover the fixed costs associated with industrial production) as in Murphy et al. (1989), whereas the importance of the population size on the Neolithic Revolution is due to the decreasing returns to scale in hunting-gathering as in North and Thomas (1977). If the population reaches the industrial threshold, then a modern economy emerges and exhibits positive steady-state population growth.

Empirically, we use cross-country data to examine our key theoretical result that high agricultural productivity triggers not only the Neolithic Revolution but also the subsequent industrialization. We follow previous empirical studies, such as Olsson and Hibbs (2005), Ashraf and Galor (2011), and Ang (2015), to consider an index of prehistoric biogeographic conditions that affect agricultural productivity and explore how it affects the transition to agriculture. Specifically, we use the index of biogeographic conditions as an instrument for the timing of transitions to agriculture and find that an earlier transition to agriculture has a positive effect on the degree of industrialization in the modern era.

This study relates to the literature on the economic modeling of the transition from hunting-gathering to agriculture,<sup>5</sup> see Smith (1975) and North and Thomas (1977) for early studies and Weisdorf (2005) for an excellent review of this literature.<sup>6</sup> A subsequent study by Locay (1989) develops a dynamic general equilibrium model with endogenous fertility to explore the transition of the human population from nomadic hunter-gatherers to a sedentary agricultural society, see also the interesting studies by Olsson (2001) and Weisdorf (2003).<sup>7</sup> Baker (2008) estimates an extended version of the Locay model using historical data on the incidence of agriculture and finds empirical support for the model. Weisdorf (2011) explores the case in which the agricultural transition is caused by an exogenous discovery of agricultural technology.<sup>8</sup> Recent studies by Dow et al. (2009) and Dow and Reed (2015, 2022) consider climate change as a cause of the transition to agriculture, whereas Bowles and Choi (2019) explore the origins of private property as a reason for adopting agriculture.

Our model is based on Locay (1989) and Baker (2008) with the introduction of an industrial economy as the third stage of the economic evolutionary process, without which the population remains either in a hunting-gathering or an agricultural Malthusian trap in the long run. An important finding is that the transition from hunting-gathering to agriculture and the transition from agriculture to industrial production are both endogenous and share a similar set of determinants. For example, high agricultural productivity triggers not only the Neolithic Revolution but also the subsequent industrialization.<sup>9</sup> Ashraf and Galor (2011) provide empirical evidence that agricultural productivity has a significant positive effect on population density in the preindustrial era. Olsson and Hibbs (2005) also provide evidence to show that prehistoric biogeographic conditions that are favorable to agriculture can trigger the Neolithic Revolution and the subsequent development in the industrial era. Using an index of biogeographic conditions as instruments, Ang (2015) finds that the timing of transitions to agriculture has a significant effect on technology adoption from 1000 BC to 1500 AD. Our empirical analysis follows the footsteps of these studies but instead examines the effects of agricultural productivity on the timing of transitions to agriculture and the degree of industrialization in the modern era.

This study also relates to the literature on unified growth theory, see Galor and Weil (2000) for the seminal study and Galor (2005, 2011) for a comprehensive review. Studies in this literature

explore the endogenous transition of an agricultural economy in a Malthusian trap to a modern industrial economy with technological progress and long-run economic growth. This study complements the interesting studies in this literature by developing a simple unified model that captures both the first transition from hunting-gathering to agriculture and the second transition from agriculture to a modern industrial economy. In the spirit of Diamond (1997), Olsson and Hibbs (2005) also model both of these important transitions in human history using a theoretical framework that focuses on the causal relationship between initial biogeographic conditions and the subsequent development of the economy. Specifically, they assume that a better biogeographic endowment causes a higher growth rate of productive knowledge, which in turn triggers the transitions once productive knowledge reaches certain exogenous thresholds. We take a more microfounded approach in which population growth is endogenously determined by optimizing agents and the transitions occur only when population size crosses thresholds that are also endogenously determined within the model. As a result, the transition from hunting-gathering to agriculture and the transition from agriculture to industry may not always occur depending on parameter conditions in our model.

The rest of this study is organized as follows. Section 2 presents the static model with exogenous population. Section 3 develops the dynamic model with endogenous population. Section 4 presents the empirical evidence. Section 5 concludes.

**2. A static model of economic evolution**

Our model is based on Locay (1989) and Baker (2008). We extend the Locay model to introduce an industrial economy as the third stage of economic evolution. In the first stage, the population engages in hunting-gathering. In the second stage, an agricultural society emerges. In the third stage, an industrial economy emerges. The population consists of  $N$  identical agents. Each agent is endowed with  $l$  units of labor, which can be allocated to hunting-gathering  $l_H$ , farming  $l_F$ , or industrial production  $l_Y$ . Therefore, the labor constraint faced by each agent is

$$l_H + l_F + l_Y = l. \tag{1}$$

In the preindustrial era, industrial production does not yet exist, and hence, the constraint simplifies to  $l_H + l_F = l$ . There is also a fixed amount of land denoted as  $Z$ , which can be used for hunting-gathering or farming.

**2.1. Hunting-gathering**

Hunting-gathering takes place in available land that is not occupied for farming. We use  $\bar{l}_H$  to denote the average amount of labor endowment devoted to hunting-gathering. Then, total food production from hunting-gathering is given by

$$H = \theta(\bar{l}_H N)^\gamma (Z_H)^{1-\gamma}, \tag{2}$$

where  $\bar{l}_H N$  and  $Z_H \leq Z$  are, respectively, the total amount of labor and land devoted to hunting-gathering. The parameters  $\theta > 0$  and  $\gamma \in (0, 1)$  measure, respectively, the productivity and labor intensity of the hunting-gathering process. An agent, who contributes  $l_H$  units of labor to hunting-gathering, receives  $h$  units of food production given by

$$h = \frac{l_H}{\bar{l}_H N} \theta(\bar{l}_H N)^\gamma (Z_H)^{1-\gamma}, \tag{3}$$

in which the agent takes  $\bar{l}_H$  and  $Z_H$  as given.

**2.2. Agriculture**

Farming also requires both labor and land. The farming production of an agent, who devotes  $l_F$  units of labor to farming, is

$$f = \varphi(l_F)^\alpha z^{1-\alpha}, \tag{4}$$

where the parameters  $\varphi > 0$  and  $\alpha \in (0, 1)$  measure, respectively, the productivity and labor intensity in agriculture.  $z$  is the amount of land used by the agent. We follow Baker (2008) to assume a fixed ratio  $\rho$  of land to farming labor given by

$$z = \rho l_F \tag{5}$$

when agricultural land is not scarce (i.e.,  $\rho \bar{l}_F N < Z$ ); in this case,  $f = \varphi \rho^{1-\alpha} l_F$ . Weisdorf (2005) argues that the temporary constant returns to farming labor, which is also present in the analysis of North and Thomas (1977), are a reasonable assumption when there is abundant agricultural land. When agricultural land becomes scarce, it is equally divided between agents, that is,

$$z = Z/N. \tag{6}$$

In this case, there is no more land available for hunting-gathering (i.e.,  $Z_H = 0$ ), see North and Thomas (1977) for a discussion that with communal property rights on agricultural land, farmers have better access to land than hunter-gatherers.

**2.3. Industrial production**

As in Murphy et al. (1989), the operation of modern industrial production requires a fixed cost  $\delta > 0$  under which total industrial output is given by<sup>10</sup>

$$Y = A(\bar{l}_Y N - \delta), \tag{7}$$

where  $\bar{l}_Y N$  is the total amount of labor devoted to industrial production, and the parameter  $A > 0$  determines the level of industrial productivity. The fixed cost is shared by all agents when the industrial economy operates. Then, the output of industrial production received by an agent, who devotes  $l_Y$  units of labor, is

$$y = A(l_Y - \delta/N). \tag{8}$$

Due to the fixed cost  $\delta$ , the industrial market would not operate unless the population size  $N$  is sufficiently large.

**2.4. From Neolithic Revolution to industrialization**

In this section, we explore the evolution of the economy and impose the following parameter assumption:  $A > \varphi \rho^{1-\alpha} > \theta \rho^{1-\gamma}$ . The population begins as hunter-gatherers and evolves into an agricultural society before an industrial economy emerges. We will impose parameter restrictions to ensure the realistic scenario in which industrialization takes place only after the complete transition from hunting-gathering to agriculture.

We begin by assuming that each agent maximizes consumption given by

$$c = x + y = h + f + y. \tag{9}$$

Here, we make a simplifying assumption that there is perfect substitutability between food production  $x$  and industrial production  $y$  in the consumption of agents. This assumption helps to keep our analysis tractable and is not entirely unrealistic because industrial production includes modern methods of food production that requires fixed investment.

In the initial stage, there is no industrial production, so we have  $l_Y = 0$ . An agent's decision is to choose labor allocation between hunting-gathering  $l_H$  and farming  $l_F$  to maximize food production  $x$  given by

$$x = h + f = \frac{l_H}{\bar{l}_H N} \theta (\bar{l}_H N)^\gamma (Z_H)^{1-\gamma} + \varphi (l_F)^\alpha z^{1-\alpha} = (l - l_F) \theta \left( \frac{Z_H}{\bar{l}_H N} \right)^{1-\gamma} + \varphi \rho^{1-\alpha} l_F, \tag{10}$$

where we have used the resource constraint on labor  $l_H + l_F = l$  and the fixed ratio of land to farming labor  $z = \rho l_F$ . The first-order condition is given by

$$\frac{\partial x}{\partial l_F} = -\theta \left( \frac{Z_H}{\bar{l}_H N} \right)^{1-\gamma} + \varphi \rho^{1-\alpha} = -\theta \left[ \frac{Z - \rho l_F N}{(l - l_F) N} \right]^{1-\gamma} + \varphi \rho^{1-\alpha}, \tag{11}$$

where we have invoked symmetry  $\{l_H, l_F\} = \{\bar{l}_H, \bar{l}_F\}$  and also used the resource constraint on land  $Z_H = Z - \rho l_F N$ . In (11),  $\varphi \rho^{1-\alpha}$  is the marginal product of farming labor  $l_F$ , whereas  $\theta \left[ \frac{Z - \rho l_F N}{(l - l_F) N} \right]^{1-\gamma}$  is the average product of hunting labor  $l_H = l - l_F$ . In the following subsections, we first compare these two objects under different population levels.

2.4.1. Stage 1: Hunting-gathering

Equation (11) implies that if the following inequality holds:

$$N < \left( \frac{\theta}{\varphi \rho^{1-\alpha}} \right)^{1/(1-\gamma)} \frac{Z}{\bar{l}}, \tag{12}$$

then  $\partial x / \partial l_F < 0$  even at  $l_F = 0$ . In this case, all labor is allocated to hunting-gathering  $l_H = l$  and the per capita output of food production is given by

$$x = h = \theta l^\gamma \left( \frac{Z}{N} \right)^{1-\gamma}, \tag{13}$$

which is increasing in hunting productivity  $\theta$ , labor supply  $l$ , and the amount of land  $Z$  but decreasing in the population size  $N$  due to the decreasing returns to labor in hunting-gathering.

2.4.2. Stage 2: From hunting-gathering to agriculture

Equation (11) and  $\rho l_F N < Z$  imply that if the following inequalities hold:

$$\left( \frac{\theta}{\varphi \rho^{1-\alpha}} \right)^{1/(1-\gamma)} \frac{Z}{\bar{l}} < N < \frac{Z}{\rho \bar{l}}, \tag{14}$$

then  $\partial x / \partial l_F = 0$  at some interior values of  $\{l_F, l_H\} \in (0, l)$ . In this case, the transition from hunting-gathering to agriculture begins. The first inequality shows that a reduction in hunting productivity  $\theta$  or an increase in population size  $N$  could trigger this transition. In our static model, the reduction in hunting productivity  $\theta$  can capture the extinction of large herding animals analyzed in Smith (1975),<sup>11</sup> whereas an exogenous increase in population size  $N$  can capture the population pressure theory discussed in Cohen (1977). However, as we will show, these results would be quite different in our dynamic model with endogenous population growth.

During the gradual transition from hunting-gathering to agriculture, the per capita output of food production is given by

$$x = h + f = (l - l_F) \theta \left( \frac{Z_H}{\bar{l}_H N} \right)^{1-\gamma} + \varphi \rho^{1-\alpha} l_F = \varphi \rho^{1-\alpha} l, \tag{15}$$

which uses  $\theta \left[ Z_H / (\bar{l}_H N) \right]^{1-\gamma} = \varphi \rho^{1-\alpha}$  from (11). Equation (15) shows that  $x$  is increasing in labor supply  $l$  and agricultural productivity  $\varphi \rho^{1-\alpha}$ .

2.4.3. Stage 3: Complete transition to agriculture

When  $N > Z/(\rho l)$ , the transition from hunting-gathering to agriculture is complete (i.e.,  $l_F = l$ ) because  $Z_H = 0$ . At this stage of the economy, an industrial market still does not emerge if the population size is insufficient to cover the fixed cost  $\delta$ . This threshold value of  $N$  is implicitly determined by the following equality:

$$\varphi l^\alpha \left( \frac{Z}{N} \right)^{1-\alpha} = A \left( l - \frac{\delta}{N} \right), \tag{16}$$

in which the left-hand side is farming output per capita when  $l_F = l$  and decreasing in  $N$ , whereas the right-hand side is the industrial output per capita when  $l_Y = l$  and increasing in  $N$ . A simple graphical analysis would confirm that there exists a unique cutoff value of  $N$  for the emergence of an industrial economy, which is denoted as  $N_I$  and has the following comparative statics:

$$N_I(\varphi, Z, \delta, A, l). \tag{17}$$

$\begin{matrix} + & + & + & - & - \end{matrix}$

This implies that by making agriculture more productive, higher agricultural productivity  $\varphi$  delays industrialization, which contradicts the evidence discussed in Nurkse (1953).<sup>12</sup> As we will show, this counterfactual result will be overturned under endogenous population growth.

In summary, if the following inequality holds:<sup>13</sup>

$$\frac{Z}{\rho l} < N < N_I, \tag{18}$$

then the agents would be better off allocating all their labor to farming (i.e.,  $l_F = l$ ). In this case, the level of output per capita is given by

$$x = f = \varphi l^\alpha \left( \frac{Z}{N} \right)^{1-\alpha}, \tag{19}$$

which is increasing in agricultural productivity  $\varphi$ , labor supply  $l$ , and the amount of land  $Z$  but decreasing in the population size  $N$  due to the decreasing returns to labor in farming when agricultural land is scarce.

2.4.4. Stage 4: Industrial economy

If  $N > N_I$ , then the transition from agriculture to an industrial economy occurs. In this case, the level of output per capita is given by

$$y = A \left( l - \frac{\delta}{N} \right), \tag{20}$$

which is increasing in industrial productivity  $A$ , labor supply  $l$ , and population size  $N$  but decreasing in the fixed cost  $\delta$  of industrial production. Equation (20) is obtained by setting  $l_Y = l$  in (8). When the population size is sufficiently large, the agents would immediately allocate all their labor to industrial production because the marginal product of industrial labor is greater than the marginal product of agricultural labor,<sup>14</sup> that is,

$$A > \varphi \rho^{1-\alpha} > \varphi (l_F)^{\alpha-1} \left( \frac{Z}{N} \right)^{1-\alpha} > \alpha \varphi (l_F)^{\alpha-1} \left( \frac{Z}{N} \right)^{1-\alpha}$$

for  $l_F > Z/(\rho N)$ .<sup>15</sup> Naturally, we assume that it is infeasible for humans to return to hunting-gathering at this stage.<sup>16</sup>

2.4.5. Summary

In this section, we summarize the level of consumption per capita at different levels of population as follows:

$$c = x + y = \begin{cases} h = \theta l^\gamma \left(\frac{Z}{N}\right)^{1-\gamma} & \text{for } N < \left(\frac{\theta}{\varphi \rho^{1-\alpha}}\right)^{1/(1-\gamma)} \frac{Z}{l} \\ h + f = \varphi \rho^{1-\alpha} l & \text{for } \left(\frac{\theta}{\varphi \rho^{1-\alpha}}\right)^{1/(1-\gamma)} \frac{Z}{l} < N < \frac{Z}{\rho l} \\ f = \varphi l^\alpha \left(\frac{Z}{N}\right)^{1-\alpha} & \text{for } \frac{Z}{\rho l} < N < N_I \\ y = A \left(l - \frac{\delta}{N}\right) & \text{for } N > N_I \end{cases} \quad (21)$$

Equation (21) presents the level of per capita consumption  $c$  as population  $N$  increases. In summary,  $c$  is initially falling due to the decreasing returns to labor in hunting-gathering. Then,  $c$  reaches to a stationary level (from above) when the gradual transition from hunting-gathering to agriculture begins. Therefore, before the transition to agriculture, hunter-gatherers enjoy a higher level of consumption than the later farmers, which is consistent with archaeological evidence, see, for example, Cohen and Armelagos (1984). However, our model implies that the hunter-gatherers would have experienced a subsequent fall in consumption if they did not adopt farming due to the decreasing returns to labor in hunting-gathering. When the transition from hunting-gathering to agriculture is complete,  $c$  becomes falling again due to the decreasing returns to labor in farming when agricultural land is scarce. When the industrial economy emerges,  $c$  becomes rising due to the increasing returns to scale in the presence of a fixed cost of industrial production and converges toward a steady-state level given by  $y^* = Al$  as  $N \rightarrow \infty$ .

3. A dynamic model with endogenous population growth

The previous section presents a static model with an exogenous level of population. This section extends the model into a dynamic setting with endogenous population growth. We follow Locay (1989) and Baker (2008) to consider overlapping generations of agents. Each agent lives for two periods. Each adult agent at time  $t$  has the following utility function:

$$u_t = (1 - \sigma) \ln c_t + \sigma \ln n_{t+1}, \quad (22)$$

where the parameter  $\sigma \in (0, 1)$  measures the preference for fertility and  $n_{t+1}$  is the agent’s number of children, who then become adults at time  $t + 1$ . Raising children is costly, and the level of consumption net of the fertility cost is given by

$$c_t = x_t + y_t - \beta n_{t+1}, \quad (23)$$

where the parameter  $\beta > 0$  determines the cost of fertility. Substituting (23) into (22), we derive the utility-maximizing level of fertility  $n_{t+1}$  as

$$n_{t+1} = \frac{\sigma}{\beta} (x_t + y_t) \quad (24)$$

and  $c_t = (1 - \sigma)(x_t + y_t)$  in which the agent maximizes  $x_t + y_t$  as in Section 2. Each adult agent has  $n_{t+1}$  children, and the number of adult agents at time  $t$  is  $N_t$ . Therefore, the law of motion for the adult population size (i.e., the labor force) is given by

$$N_{t+1} = n_{t+1} N_t = \frac{\sigma}{\beta} (x_t + y_t) N_t, \quad (25)$$

and the adult population growth rate at time  $t$  is

$$\frac{\Delta N_t}{N_t} \equiv \frac{N_{t+1} - N_t}{N_t} = \frac{\sigma}{\beta}(x_t + y_t) - 1, \tag{26}$$

which will be simply referred to as the population growth rate. In the following subsection, we will use the information from Section 2 to derive the population dynamics.

**3.1. Stage 1: Hunting-gathering**

Given an initial level of population:

$$N_0 < \left( \frac{\theta}{\varphi\rho^{1-\alpha}} \right)^{1/(1-\gamma)} \frac{Z}{l}, \tag{27}$$

the human population engages in hunting-gathering only. Substituting (13) into (26) yields the growth rate of population as

$$\frac{\Delta N_t}{N_t} = \frac{\sigma}{\beta}\theta l^\gamma \left( \frac{Z}{N_t} \right)^{1-\gamma} - 1, \tag{28}$$

which yields the following steady-state level of population in the hunting-gathering era:

$$N_H^* = \left( \frac{\sigma}{\beta}\theta l^\gamma \right)^{1/(1-\gamma)} Z. \tag{29}$$

If the following inequality holds:

$$N_H^* < \left( \frac{\theta}{\varphi\rho^{1-\alpha}} \right)^{1/(1-\gamma)} \frac{Z}{l} \Leftrightarrow \frac{\sigma}{\beta}\varphi\rho^{1-\alpha}l < 1, \tag{30}$$

then the human population would remain as hunter-gatherers indefinitely. Substituting (29) into (13) yields  $x^* = \beta/\sigma$ , which is increasing in fertility cost  $\beta$  and decreasing in the degree  $\sigma$  of fertility preference but independent of hunting productivity  $\theta$  and land  $Z$ . In other words, the population is in a hunting-gathering Malthusian trap, in which higher hunting productivity  $\theta$  and more land  $Z$  increase the level of population  $N_H^*$  but not the level of income  $x^*$ .

Alternatively, if  $\sigma\varphi\rho^{1-\alpha}l > \beta$ , then an agricultural society would emerge. Therefore, the transition from hunting-gathering to agriculture occurs under the following conditions: a low fertility cost  $\beta$ , a strong fertility preference  $\sigma$ , a high level of agricultural productivity  $\varphi\rho^{1-\alpha}$ , and a high level of labor supply  $l$ . A strong fertility preference  $\sigma$  and a low fertility cost  $\beta$  give rise to a higher level of population and make it more likely to cross the population threshold for the emergence of agriculture in a Boserupian manner, but they also reduce income  $x^* = \beta/\sigma$  in case the population remains in a hunting-gathering Malthusian trap. Although a higher level of hunting productivity  $\theta$  and a larger amount of land  $Z$  also increase population, they increase the endogenous threshold for agriculture as well by making hunting-gathering more attractive. These opposite effects cancel each other, and hence, hunting productivity  $\theta$  and the amount of land  $Z$  do not affect the transition to agriculture, which stands in stark contrast to the case of exogenous population.

Finally, high agricultural productivity  $\varphi\rho^{1-\alpha}$  reduces the endogenous threshold by making agriculture more attractive, and hence, a higher level of agricultural productivity  $\varphi\rho^{1-\alpha}$  can trigger the Neolithic Revolution. This finding is consistent with the empirical evidence in Olsson and Hibbs (2005), who find that favorable biogeographic conditions can trigger the transition to agriculture. Olsson (2001) examines the archeological evidence in the Jordan Valley and concludes that the abundance of species suitable for agriculture was one of the key reasons for the transition to agriculture. This abundance of agricultural species corresponds to a high level of agricultural productivity in our model. Furthermore, our analysis implies that climate change that affects agricultural productivity would also affect the transition to agriculture, for example, Richerson et al.



(2001) argue that the climatic conditions during the most recent Ice Age were hostile to agriculture and made the transition to agriculture impossible at that time.

**3.2. Stage 2: From hunting-gathering to agriculture**

Suppose the population size  $N_t$  crosses the first threshold, that is,

$$\left(\frac{\theta}{\varphi\rho^{1-\alpha}}\right)^{1/(1-\gamma)} \frac{Z}{l} < N_t < \frac{Z}{\rho l}. \tag{31}$$

Then, the transition from hunting-gathering to agriculture begins. We can substitute (15) into (26) to derive the population growth rate as

$$\frac{\Delta N_t}{N_t} = \frac{\sigma}{\beta} \varphi \rho^{1-\alpha} l - 1 > 0, \tag{32}$$

which is positive if and only if the transition to agriculture occurs (i.e.,  $\sigma \varphi \rho^{1-\alpha} l > \beta$ ) and implies that population  $N_t$  increases over time during the gradual transition from hunting-gathering to agriculture.

**3.3. Stage 3: Complete transition to agriculture**

Given (32), the level of population  $N_t$  eventually crosses the second threshold, that is,

$$\frac{Z}{\rho l} < N_t < N_I, \tag{33}$$

where  $N_I$  is implicitly given in (16) and (17). At this stage, we can substitute (19) into (26) to derive the growth rate of population as

$$\frac{\Delta N_t}{N_t} = \frac{\sigma}{\beta} \varphi l^\alpha \left(\frac{Z}{N_t}\right)^{1-\alpha} - 1, \tag{34}$$

which yields a steady-state level of population in agriculture as

$$N_A^* = \left(\frac{\sigma}{\beta} \varphi l^\alpha\right)^{1/(1-\alpha)} Z. \tag{35}$$

If  $N_t$  reaches  $N_A^*$  before reaching  $N_I$ , then the economy would remain as an agricultural society indefinitely. Substituting (35) into (19) yields  $x^* = \beta/\sigma$ , which is once again increasing in fertility cost  $\beta$  and decreasing in the degree  $\sigma$  of fertility preference but independent of agricultural productivity  $\varphi$  and land  $Z$ . In other words, the population is now in an agricultural Malthusian trap, in which higher agricultural productivity  $\varphi$  and more land  $Z$  increase the level of population  $N_A^*$  but not the level of income  $x^*$ .

**3.4. Stage 4: Industrial economy**

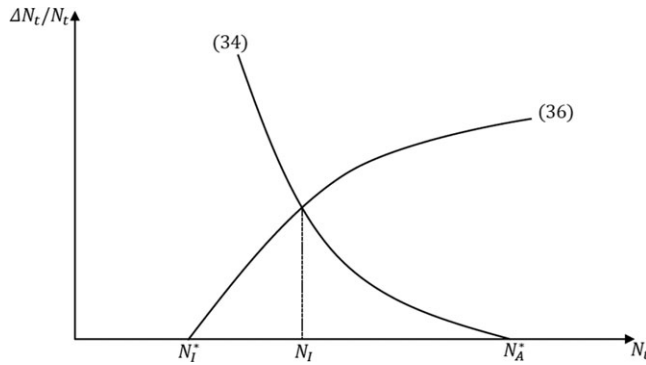
If the level of population  $N_t$  manages to cross the third threshold  $N_I$ , then an industrial economy emerges. In this case, we can substitute (20) into (26) to derive the population growth rate as

$$\frac{\Delta N_t}{N_t} = \frac{\sigma A}{\beta} \left(l - \frac{\delta}{N_t}\right) - 1, \tag{36}$$

which is increasing in  $N_t$ . Setting  $\Delta N_t/N_t = 0$  yields the following level:

$$N_I^* = \frac{\delta}{l - \beta/(\sigma A)}, \tag{37}$$

above which the population grows over time during the industrial era.



**Figure 1.** Industrial threshold. Figure plots the population growth rate in (34) and (36) and shows that the economy switches from agriculture to industrial production when population crosses the threshold  $N_I$ .<sup>17</sup>

Figure 1 shows that if and only if  $N_A^* > N_I^*$ , then  $N_t$  would reach the third threshold  $N_I$  and trigger the emergence of an industrial economy. When  $N_t > N_I$ , the output level  $x_t + y_t$  is higher under industrial production than under agricultural production. From (35) and (37), the inequality  $N_A^* > N_I^*$  is equivalent to

$$\left( l - \frac{\beta}{\sigma A} \right) \left( \frac{\sigma}{\beta} \varphi l^\alpha \right)^{1/(1-\alpha)} \frac{Z}{\delta} > 1. \tag{38}$$

Therefore, the transition from an agricultural economy to an industrial economy occurs under the following conditions: a low fertility cost  $\beta$ , a strong fertility preference  $\sigma$ , a high level of agricultural productivity  $\varphi$ , a high level of labor supply  $l$ , a large amount of land  $Z$ , a high level of industrial productivity  $A$ , and a low fixed cost  $\delta$  for operating industrial firms.

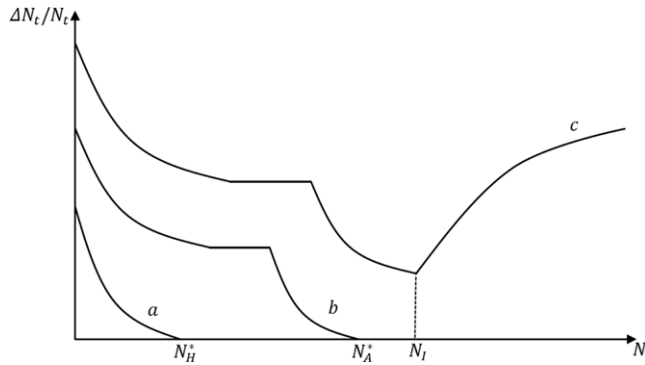
As before, a strong fertility preference  $\sigma$  and a low fertility cost  $\beta$  give rise to a higher level of population and make it more likely to cross the population threshold  $N_I$  for the emergence of an industrial economy, but they also reduce income  $x^* = \beta/\sigma$  in case the population remains in an agricultural Malthusian trap. Interestingly, unlike the case of exogenous population, a high level of agricultural productivity  $\varphi$  can now trigger industrialization by raising the level of population. This result is consistent with the early work of Nurkse (1953) and Murphy et al. (1989) and also supported by the empirical evidence in Olsson and Hibbs (2005) and Ang (2015), who find that favorable initial biogeographic conditions can contribute to the subsequent development in the industrial era and technology adoption in as late as 1500 AD, in addition to the Neolithic Revolution.

Furthermore, a high level of industrial productivity  $A$  and a low fixed cost  $\delta$  of industrial production reduce the endogenous threshold by making industrial production more attractive and can also trigger industrialization. Finally, if the population size reaches the industrial threshold, then a modern economy emerges and the population growth rate rises toward a steady-state value given by  $\Delta N/N = \frac{\sigma}{\beta} A l - 1$  in the long run.<sup>18</sup>

**3.5. Summary**

We summarize all the above results in the following proposition:

**Proposition 1.** *Under exogenous population growth, human society evolves from hunting-gathering to agriculture and then an industrial economy. Under endogenous population growth, the population may stop growing in a hunting-gathering society; in this case, the population remains as hunter-gatherers. The Neolithic Revolution occurs under a low fertility cost, strong fertility*



**Figure 2.** Dynamics of population growth.

Figure plots the following three scenarios: case (a) plots the population growth rate given by (28); case (b) plots the population growth rate given by (28), (32), and then (34); and case (c) plots the population growth rate given by (28), (32), (34), and then (36).

*preference, high agricultural productivity, and high labor supply. The population may also stop growing in an agricultural society; in this case, the economy remains in an agricultural Malthusian trap. Industrialization occurs under a low fertility cost, strong fertility preference, high agricultural productivity, high labor supply, a large amount of agricultural land, high industrial productivity, and a low fixed cost of industrial production.*

*Proof.* The population growth rate is summarized in (39). From (30), if  $\sigma\varphi\rho^{1-\alpha}l > \beta$ , then  $N_t$  reaches the agricultural threshold before the hunting-gathering steady-state  $N_H^*$ . If (38) holds, then  $N_t$  reaches the industrial threshold  $N_I$  before the agricultural steady state  $N_A^*$ . □

If the population manages to evolve from hunting-gathering to agriculture and then activate the emergence of an industrial economy, the dynamics of the population growth rate can be summarized as follows:

$$\frac{\Delta N_t}{N_t} = \frac{\sigma}{\beta}(x_t + y_t) - 1 = \begin{cases} \frac{\sigma}{\beta}\theta l^\gamma \left(\frac{Z}{N_t}\right)^{1-\gamma} - 1 & \text{for } N_t < \left(\frac{\theta}{\varphi\rho^{1-\alpha}}\right)^{1/(1-\gamma)} \frac{Z}{l} \\ \frac{\sigma}{\beta}\varphi\rho^{1-\alpha}l - 1 & \text{for } \left(\frac{\theta}{\varphi\rho^{1-\alpha}}\right)^{1/(1-\gamma)} \frac{Z}{l} < N_t < \frac{Z}{\rho l} \\ \frac{\sigma}{\beta}\varphi l^\alpha \left(\frac{Z}{N_t}\right)^{1-\alpha} - 1 & \text{for } \frac{Z}{\rho l} < N_t < N_I \\ \frac{\sigma}{\beta}A \left(l - \frac{\delta}{N_t}\right) - 1 & \text{for } sN_t > N_I \end{cases} \quad (39)$$

Figure 2 plots the population growth rate  $\Delta N_t/N_t$  for the following three scenarios: (a) the population converges to a hunting-gathering Malthusian trap as discussed in Section 3.1; (b) the population converges to an agricultural Malthusian trap as discussed in Section 3.3; and (c) the population achieves long-run growth as discussed in Section 3.4.

### 4. Empirical evidence

In this section, we use cross-country data to evaluate the effects of agricultural productivity on the transition to agriculture and the subsequent industrialization. Specifically, we follow Ashraf and Galor (2011) and Ang (2015) to employ a two-stage least squares regression:

$$\tau_j = \kappa_1\varphi_j + \Phi_j + \epsilon_{1,j} \quad (40a)$$

$$y_j = \kappa_2\widehat{\tau}_j + \Phi_j + \epsilon_{2,j} \quad (40b)$$

**Table 1.** Summary statistics

	<i>n</i>	Mean	SD	Min	Max
Non-agricultural employment share (%)	94	64.09	26.65	7.87	99.72
Timing of agricultural transition	94	4475.32	2357.30	400.00	10,500.00
Prehistoric biogeographic endowment index	94	0.08	1.40	-1.33	1.91
Terrain ruggedness index	94	1.22	1.13	0.02	6.20
Log level of land area	94	9.88	2.07	3.47	13.75
Ratio of fertile soil (%)	94	35.77	22.50	0.00	100.00
Ratio of area within 100 km of ice-free coast (%)	94	38.65	37.43	0.00	100.00

Data sources: World Bank Data for the share of non-agricultural employment; Putterman and Trainor (2006) for the timing of agricultural transition; Nunn and Puga (2012) for other variables.

where (40a) describes the first-stage regression and (40b) describes the second-stage regression.<sup>19</sup> In (40a),  $\varphi_j$  denotes the prehistoric level of agricultural productivity in present-day country  $j$ , for which we use an index of prehistoric biogeographic endowments as a proxy. We use data from Olsson and Hibbs (2005) on domesticable wild animals and plants known to exist in prehistory (in location that corresponds to present-day country  $j$ ).<sup>20</sup> Then, we follow Ang (2015) to combine the two dimensions (animals and plants) into a single index by computing their first principal component.

In (40a),  $\tau_j$  denotes the timing of agricultural transition, measured by the number of years before 2000 CE, whereas  $\widehat{\tau}_j$  in (40b) denotes the predicted value of  $\tau_j$  from the first-stage regression.  $y_j$  denotes the degree of industrialization, measured by the share of non-agricultural employment in 1991. We use data in 1991 because data on employment shares are only available from 1991 for many countries, so using earlier data would lead to a sharp reduction in the sample size. Our underlying assumption is that countries experiencing earlier industrialization should have higher shares of non-agricultural employment in the modern era.

Our theory predicts that  $\kappa_1$  and  $\kappa_2$  are significantly positive.  $\kappa_1$  being significantly positive implies that a higher level of agricultural productivity triggers an earlier transition to agriculture.  $\kappa_2$  being significantly positive implies that an earlier transition to agriculture (triggered by a higher level of agricultural productivity) also causes a higher degree of industrialization in the modern era.

$\Phi$  is a set of control variables, including the constant term. We follow Nunn and Puga (2012) to control for a terrain ruggedness index, total land area, the ratio of fertile soil to land area, and the percentage of land area that is within 100 km of the nearest ice-free coast. We also consider continent fixed effects. Finally,  $\epsilon_{1,j}$  and  $\epsilon_{2,j}$  are the error terms. Table 1 presents the summary statistics and data sources.

Table 2 presents our regression results. Columns (1)–(2) do not include control variables except for the constant term and continent fixed effects, whereas columns (3)–(4) include control variables. The odd columns show the first-stage regression, whereas the even columns show the second-stage regression. The estimation results show that  $\kappa_1$  and  $\kappa_2$  are positive and statistically significant at least at the 5% level. Using the estimates in columns (3)–(4), we find that increasing the index of prehistoric biogeographic endowments by one (recall that this index ranges from -1.3 to 1.9) causes an earlier agricultural transition by about one millennium (1040 years) and a higher degree of industrialization reflected by a larger share of non-agricultural employment of 8.3% (=  $1040 \times 0.008\%$ ) in 1991.<sup>21</sup>

To ensure the robustness of our results, we explore other proxies for industrialization in the modern era. First, we consider the non-agricultural share of GDP as a dependent variable in the second-stage regression.<sup>22</sup> In this case, we can use earlier data in 1980 and still retain a sample size of 62.<sup>23</sup> Second, we consider the log of GDP per capita as a dependent variable in the second-stage

**Table 2.** Effects of agricultural productivity on agricultural transition and industrialization

	(1)	(2)	(3)	(4)
	First stage	Second stage	First stage	Second stage
Dependent variable	<i>transition</i>	<i>industrialization</i>	<i>transition</i>	<i>industrialization</i>
<i>productivity</i>	1007.589***		1040.010***	
	(222.444)		(220.875)	
<i>transition</i>		0.009**		0.008***
		(0.004)		(0.003)
<i>rugged</i>			-3.811	-3.510
			(121.511)	(2.329)
<i>landarea</i>			21.883	-1.193
			(81.984)	(1.309)
<i>soil</i>			8.911	-0.254***
			(6.598)	(0.093)
<i>nearcoast</i>			-3.729	0.155*
			(5.386)	(0.079)
Continent fixed effects	✓	✓	✓	✓
F-stat on instrument	33.465***		33.533***	
Observations	94	94	94	94
R <sup>2</sup>	0.719	0.353	0.728	0.507

Notes: Robust standard errors in parentheses. \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ . In Table 2, productivity refers to the index of prehistoric biogeographic endowments; transition refers to the timing of agricultural transition; and industrialization refers to the non-agricultural employment share in 1991. The IV regressions employ the index of prehistoric biogeographic endowments as an instrument for the timing of agricultural transition.

regression.<sup>24</sup> In this case, we can use even earlier data in 1950 and retain a sample size of 88.<sup>25</sup> Table 3 presents the regression results. The estimated coefficients of  $\kappa_1$  and  $\kappa_2$  remain positive and statistically significant at the 1% level. These estimates imply that increasing the index of prehistoric biogeographic endowments by one causes an earlier agricultural transition by about one millennium as before and gives rise to a larger share of non-agricultural GDP of 7.2% ( $= 1031 \times 0.007\%$ ) in 1980 and also an increase in GDP per capita by 21.5% ( $= 1077 \times 0.0002 \times 100\%$ ) in 1950.<sup>26</sup>

## 5. Conclusion

In this study, we have developed a simple Malthusian model that captures the economic evolution of human society across the three stages of hunting-gathering, agriculture, and industrial production. We find that under endogenous population growth, the evolution to the next stage is not inevitable. If the population fails to reach the agricultural threshold, then the human population remains as hunter-gatherers. If the population fails to reach the industrial threshold, then the human population remains as agriculturalists. Our model identifies several potential causes for the Neolithic Revolution: a high level of agricultural productivity, a low cost of fertility, a strong preference for fertility, and a high level of labor supply. An implication is that the transitions to agriculture in different parts of the world (such as Central Mexico, China, the Middle East, and Sub-Saharan Africa) at different time periods could have been triggered by different reasons. Furthermore, the above conditions that trigger the Neolithic Revolution can also trigger the subsequent industrialization, but not necessarily vice versa because other conditions (such as a high level of industrial productivity and a low fixed cost of industrial production) may also trigger industrialization. Although our simple model is unlikely to capture all possible causes for the

Table 3. Robustness tests

	(1)	(2)	(3)	(4)
	First stage	Second stage	First stage	Second stage
Dependent variable	<i>transition</i>	<i>GDP share</i>	<i>transition</i>	<i>GDP per capita</i>
<i>productivity</i>	1030.978*** (263.145)		1077.342*** (212.819)	
<i>transition</i>		0.007*** (0.002)		0.0002** (0.0001)
Control variables	✓	✓	✓	✓
Continent fixed effects	✓	✓	✓	✓
F-stat on instrument	23.961***		39.073***	
Observations	62	62	88	88
R <sup>2</sup>	0.804	0.169	0.765	0.536

Notes: Robust standard errors in parentheses. \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ . In Table 3, productivity refers to the index of prehistoric biogeographic endowments; transition refers to the timing of agricultural transition; GDP share refers to the non-agricultural share of GDP in 1980; and GDP per capita refers to the log of GDP per capita in 1950. The IV regressions employ the index of prehistoric biogeographic endowments as an instrument for the timing of agricultural transition.

Neolithic Revolution and the subsequent industrialization, we find empirical support for agricultural productivity as a determinant for the timing of transitions to agriculture and the degree of industrialization in the modern era.

## Acknowledgements

We would like to thank Francesco Zanetti for helpful comments. Chu gratefully acknowledges financial support from the Asia-Pacific Academy of Economics and Management at the University of Macau. The usual disclaimer applies.

## Notes

- 1 See Hublin et al. (2017) and Richter et al. (2017).
- 2 See Barker (2006) for a detailed discussion of the archaeological evidence on the origins of agriculture and Larson et al. (2014) for an interdisciplinary approach to the understanding of the roles of the domestication of plants and animals on the transition to agriculture.
- 3 See Madsen et al. (2010) and Madsen and Murtin (2017) for interesting empirical studies on the Industrial Revolution in Britain.
- 4 Boserup (1965) argues that agricultural methods depend on the population size. Her idea has been extended to the case in which the transition to agriculture depends also on the population size, see Cohen (1977).
- 5 In a related literature, Horan et al. (2005) and Chu (2023) explore the transition from multiple human species to a single human species in a hunting-gathering economy.
- 6 Weisdorf (2005) also reviews the related archaeological and anthropological literature.
- 7 Olsson (2001) develops a model that allows for four potential explanations for the agricultural transition: environmental conditions, population pressure, cultural influence, and external factors. Weisdorf (2003) develops a model in which an agricultural society allows for non-food-producing specialists who supply non-food goods.
- 8 The approach in Locay (1989) and Baker (2008) implicitly assumes that the discovery of technology occurs before agents have incentives to adopt it, for example, Tudge (1999) discusses evidence that proto-farming existed much earlier than the Neolithic Revolution.
- 9 See also Chu et al. (2022) who introduce an agricultural sector to the Schumpeterian model with endogenous takeoff in Peretto (2015) and show that high agricultural productivity triggers industrialization. In a related study, Chu et al. (2020) explore how status-seeking culture affects industrialization.

- 10 In Appendix A, we present an extension of our model in which the fixed cost  $\delta$  is interpreted as a fixed cost of operation in a monopolistic industrial market. Specifically, one can think of the reduced-form production function in (7) as capturing a modern monopolistic market with firm-level production functions  $Y = \{\int_0^1 [Y(i)]^\epsilon di\}^{1/\epsilon}$  and  $Y(i) = A[l_Y(i) - \delta]$ , see Appendix A for this analysis.
- 11 Smith (1975) considers a dynamic model of replenishable common resources in which animal extinction is caused by excessive hunting.
- 12 According to Nurkse (1953), technological improvements that raised agricultural productivity helped to release labor from agriculture to industrial production and were crucial for the Industrial Revolution.
- 13 From (17), a sufficiently large  $\delta$  would suffice to ensure  $N_I > Z/(\rho l)$ .
- 14 In the case of a monopolistic market, the industrial transition may become gradual because the wage of industrial labor is less than  $A$ , see Appendix A for this analysis.
- 15 For  $I_F < Z/(\rho N)$ , the marginal product of agricultural labor is simply  $\varphi\rho^{1-\alpha} < A$ .
- 16 This is despite the availability of land  $Z_H$  for hunting-gathering. However, under a monopolistic market in Appendix A, land may still be occupied for agriculture even in the industrial era.
- 17 In Figure 1, (34) and (36) are determined by the left-hand side and right-hand side of (16), respectively.
- 18 Peretto (2021) also finds that the endogenous fertility rate rises toward a steady state in a Schumpeterian growth model with endogenous takeoff.
- 19 We have also considered the two regressions separately, and our results are robust, see Appendix B.
- 20 Domesticable plants refer to the number (33 species in total) of annual or perennial wild plants (such as wheat, rice, and millet with a mean kernel weight of more than 10 mg. Domesticable animals refer to the number (14 species in total) of prehistoric mammals (such as goat, sheep, and pig) weighing over 45 kg.
- 21 If we consider (40b) as a separate regression as  $y_j = \kappa_3\varphi_j + \Phi_j + \epsilon_{3j}$ , then the estimated  $\kappa_3$  continues to be significantly positive and has a similar value as  $\kappa_1\kappa_2$ , implying that agricultural productivity affects industrialization mainly via agricultural transition, see Table B1 in Appendix B.
- 22 Data source: World Bank Data.
- 23 Our results (available upon request) are robust if we use data in 1970 or 1990. However, considering earlier data in 1960 would drastically reduce the sample size to 29.
- 24 Data source: Maddison Project Database.
- 25 Considering earlier data in 1940 would reduce the sample size to 36.
- 26 Recall that the dependent variable in column (4) of Table 3 is the log of GDP per capita.
- 27 One can endogenize the mass of varieties as  $m \geq 1$ , in which case growth in population  $N$  would expand varieties  $m$  and increase industrial output  $Y$  as in Romer (1990), see Section 4.3 in Chu (2022) for this analysis.

## References

- Ang, J. (2015) Agricultural transition and the adoption of primitive technology. *Economic Inquiry* 53(4), 1818–1838.
- Ashraf, Q. and O. Galor (2011) Dynamics and stagnation in the Malthusian epoch. *American Economic Review* 101(5), 2003–2041.
- Baker, M. (2008) A structural model of the transition to agriculture. *Journal of Economic Growth* 13(4), 257–292.
- Barker, G. (2006) *The Agricultural Revolution in Prehistory: Why did Foragers become Farmers?*. New York: Oxford University Press.
- Boserup, E. (1965) *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. London: Allen & Unwin.
- Bowles, S. and J.-K. Choi (2019) The Neolithic agricultural revolution and the origins of private property. *Journal of Political Economy* 127(5), 2186–2228.
- Chu, A. (2022) From Neolithic Revolution to Industrialization. MPRA Paper No. 111835.
- Chu, A. (forthcoming) Natural selection and Neanderthal extinction in a Malthusian economy. *Journal of Population Economics*. <https://doi.org/10.1007/s00148-023-00939-z>
- Chu, A., H. Fan and X. Wang (2020) Status-seeking culture and development of capitalism. *Journal of Economic Behavior and Organization* 180, 275–290.
- Chu, A., P. Peretto and X. Wang (2022) Agricultural revolution and industrialization. *Journal of Development Economics* 158, 102887.
- Cohen, M. (1977) *The Food Crises in Prehistory: Overpopulation and the Origins of Agriculture*. New Haven: Yale University Press.
- Cohen, M. and G. Armelagos (1984) Paleopathology at the origins of agriculture. In: Cohen, M. and G. Armelagos. (eds.), *Paleopathology at the Origins of Agriculture*, pp. 585–602. Florida, Orlando: Academic Press.
- Diamond, J. (1997). Guns, Germs, and Steel: The Fates of Human Societies. New York: Norton.
- Dow, G. and C. Reed (2015) The origins of sedentism: Climate, population, and technology. *Journal of Economic Behavior & Organization* 119, 56–71.
- Dow, G. and C. Reed (2022) *Economic Prehistory: Six Transitions that Shaped the World*. Cambridge: Cambridge University Press.

- Dow, G., C. Reed and N. Olewiler (2009) Climate reversals and the transition to agriculture. *Journal of Economic Growth* 14(1), 27–53.
- Galor, O. (2005) From stagnation to growth: Unified growth theory. *Handbook of Economic Growth* 1, 171–293.
- Galor, O. (2011) *Unified Growth Theory*. Princeton: Princeton University Press.
- Galor, O. and D. Weil (2000) Population, technology and growth: From the Malthusian regime to the demographic transition. *American Economic Review* 110(4), 806–828.
- Horan, R., E. Bulte and J. Shogren (2005) How trade saved humanity from biological exclusion: An economic theory of Neanderthal extinction. *Journal of Economic Behavior & Organization* 58(1), 1–29.
- Hublin, J. J., A. Ben-Ncer, S. Bailey, S. Freidline, S. Neubauer, M. Skinner, I. Bergmann, A. Le Cabec, S. Benazzi, K. Harvati and P. Gunz (2017) New fossils from Jebel Irhoud, Morocco and the pan-African origin of Homo sapiens. *Nature* 546(7657), 289–292.
- Krugman, P. (1979) Increasing returns, monopolistic competition, and international trade. *Journal of International Economics* 9(4), 469–479.
- Larson, G., D. Piperno, R. Allaby, M. Purugganan, L. Andersson, M. Arroyo-Kalin, L. Barton, C. Climer Vigueira, T. Denham, K. Dobney and A. Doust (2014) Current perspectives and the future of domestication studies. *Proceedings of The National Academy of Sciences of The United States of America* 111(17), 6139–6146.
- Locay, L. (1989) From hunting and gathering to agriculture. *Economic Development and Cultural Change* 37(4), 737–756.
- Madsen, J., J. Ang and R. Banerjee (2010) Four centuries of British economic growth: The roles of technology and population. *Journal of Economic Growth* 15(4), 263–290.
- Madsen, J. and F. Murtin (2017) British economic growth since 1270: The role of education. *Journal of Economic Growth* 22(3), 229–272.
- Murphy, K., A. Shleifer and R. Vishny (1989) Income distribution, market size and industrialization. *Quarterly Journal of Economics* 104(3), 537–564.
- North, D. and R. Thomas (1977) The first economic revolution. *Economic History Review* 30(2), 229–241.
- Nunn, N. and D. Puga (2012) Ruggedness: The blessing of bad geography in Africa. *Review of Economics and Statistics* 94(1), 20–36.
- Nurkse, R. (1953) *Problems of Capital Formation in Underdeveloped Countries*. New York: Oxford University Press.
- Olsson, O. (2001) The rise of Neolithic agriculture. Working Paper in Economics No. 57, University of Goteborg.
- Olsson, O. and D. Hibbs (2005) Biogeography and long-run economic development. *European Economic Review* 49(4), 909–938.
- Peretto, P. (2015) From Smith to Schumpeter: A theory of take-off and convergence to sustained growth. *European Economic Review* 78, 1–26.
- Peretto, P. (2021) Through scarcity to prosperity: Toward a theory of sustainable growth. *Journal of Monetary Economics* 117, 243–257.
- Putterman, L. and C. A. Trainor (2006) *Agricultural Transition Year Country Data Set*. Brown University.
- Richerson, P., R. Boyd and R. Bettinger (2001) Was agriculture impossible during the Pleistocene but mandatory during the Holocene? A climate change hypothesis. *American Antiquity* 66(3), 387–411.
- Richter, D., R. Grun, R. Joannes-Boyau, T. Steele, F. Amani, M. Rué, P. Fernandes, J. Raynal, D. Geraads, A. Ben-Ncer and J. Hublin (2017) The age of the hominin fossils from Jebel Irhoud, Morocco, and the origins of the middle stone age. *Nature* 546(7657), 293–296.
- Romer, P. (1990) Endogenous technological change. *Journal of Political Economy* 98(5, Part 2), S71–S102.
- Smith, V. (1975) The primitive hunter culture, Pleistocene extinction, and the rise of agriculture. *Journal of Political Economy* 83(4), 727–756.
- Tudge, C. (1999) *Neanderthals, Bandits and Farmers: How Agriculture Really Began*. New Haven: Yale University Press.
- Weisdorf, J. (2003) Stone Age economics: The origins of agriculture and the emergence of non-food specialists. Discussion Paper 03-34, University of Copenhagen.
- Weisdorf, J. (2005) From foraging to farming: Explaining the Neolithic Revolution. *Journal of Economic Surveys* 19(4), 561–586.
- Weisdorf, J. (2011) The Neolithic Revolution from a price-theoretic perspective. *Journal of Development Economics* 96(2), 209–219.

## Appendix A: Monopolistic market in the industrial era

In this appendix, we replace the reduced-form industrial production function in (7) by a modern monopolistic market with a standard CES aggregator:<sup>27</sup>

$$Y = \left\{ \int_0^1 [Y(i)]^\varepsilon di \right\}^{1/\varepsilon}, \quad (\text{A1})$$



where  $\varepsilon \in (0, 1)$  determines the elasticity of substitution  $1/(1 - \varepsilon)$  between differentiated products  $Y(i)$  for  $i \in [0, 1]$ . Profit maximization yields the conditional demand function:

$$Y(i) = \left[ \frac{p}{p(i)} \right]^{1/(1-\varepsilon)} Y \Leftrightarrow p(i) = p \left[ \frac{Y}{Y(i)} \right]^{1-\varepsilon}, \tag{A2}$$

where  $p$  and  $p(i)$  are, respectively, the prices of  $Y$  and  $Y(i)$  for  $i \in [0, 1]$ .

As in Krugman (1979), operating an industrial firm requires a fixed cost  $\delta > 0$  under which the output of  $Y(i)$  is

$$Y(i) = A[l_Y(i) - \delta], \tag{A3}$$

where  $l_Y(i)$  is the labor devoted to the production of  $Y(i)$ . The profit function for firm  $i$  is

$$\pi(i) = p(i)Y(i) - wl_Y(i) = pY^{1-\varepsilon}[Y(i)]^\varepsilon - w \left[ \frac{Y(i)}{A} + \delta \right], \tag{A4}$$

where  $w$  is the wage rate of industrial labor. Profit maximization yields markup pricing:

$$p(i) = \frac{1}{\varepsilon} \frac{w}{A} > \frac{w}{A}, \tag{A5}$$

where  $w/A$  is the marginal cost of producing  $Y(i)$ . The amount of monopolistic profit is

$$\pi(i) = p(i)A[l_Y(i) - \delta] - wl_Y(i) = \frac{1-\varepsilon}{\varepsilon} w \left[ l_Y(i) - \frac{\delta}{1-\varepsilon} \right], \tag{A6}$$

which is positive if and only if  $l_Y(i) = \bar{l}_Y N > \delta/(1 - \varepsilon)$  for all  $i \in [0, 1]$ . As before, due to the fixed cost  $\delta$ , the industrial market would not operate unless population  $N$  is sufficiently large.

To be consistent with our baseline model, we assume that agents produce their own food output  $x$  for their own consumption and raising children. However, they need to purchase industrial output  $y$  (when available) using their industrial labor income  $wl_Y$ . Therefore, in the industrial era, each agent maximizes  $x + y = f + y$  subject to farming production in (4), labor constraint  $l_F + l_Y = l$ , and the following budget constraint:

$$py = wl_Y + \frac{1}{N} \int_0^1 \pi(i) di, \tag{A7}$$

where profits  $\pi(i) \geq 0$  are redistributed to all  $N$  agents equally. The first-order condition is

$$\frac{\partial(x+y)}{\partial l_F} = \underbrace{\alpha \varphi (l_F)^{\alpha-1} \left( \frac{Z}{N} \right)^{1-\alpha}}_{\equiv MPL_F} - \frac{w}{p}, \tag{A8}$$

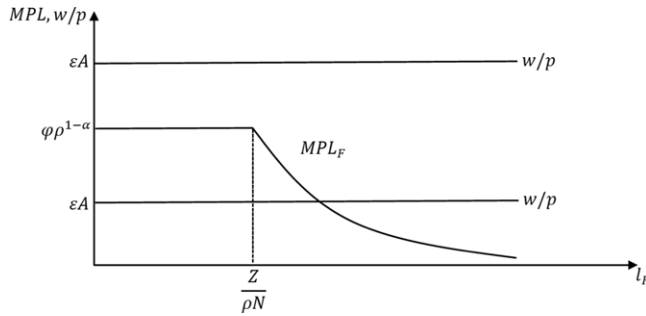
where  $w/p = w/p(i) = \varepsilon A$  from symmetry and markup pricing in (A5). Figure A1 plots (A8) and shows that there are two scenarios: (a) interior solution (i.e.,  $\varphi \rho^{1-\alpha} > \varepsilon A$ ) and (b) corner solution (i.e.,  $\varphi \rho^{1-\alpha} < \varepsilon A$ ). Recall that we have only assumed  $\varphi \rho^{1-\alpha} < A$  but  $\varepsilon < 1$ .

**Interior solution:** If  $\varphi \rho^{1-\alpha} > \varepsilon A$ , then the equilibrium level of agricultural labor  $l_F$  from (A8) is

$$l_F = \left( \frac{\alpha \varphi}{\varepsilon A} \right)^{1/(1-\alpha)} \frac{Z}{N}, \tag{A9}$$

which implies that the equilibrium level of industrial labor is

$$l_Y = l - l_F = l - \left( \frac{\alpha \varphi}{\varepsilon A} \right)^{1/(1-\alpha)} \frac{Z}{N}. \tag{A10}$$



**Figure A1.** Labor market.

Figure plots (A8) and shows that there can be a gradual transition (i.e.,  $l_F > 0$ ) or an immediate transition (i.e.,  $l_F = 0$ ) from agriculture to industrial production.

An industrial market would only emerge if  $N$  is sufficiently large to cover the fixed cost  $\delta$  such that  $l_Y N \geq \delta / (1 - \varepsilon)$ , which is required for nonnegative profit  $\pi(i) \geq 0$ . Then, (A10) yields

$$N \geq \frac{1}{l} \left[ \left( \frac{\alpha \varphi}{\varepsilon A} \right)^{1/(1-\alpha)} Z + \frac{\delta}{1-\varepsilon} \right] \equiv N_I(\varphi, Z, \delta, A, l), \tag{A11}$$

which is now given by a closed-form solution and has the same comparative statics as (17).

Before the emergence of industrial production, the population growth rate  $\Delta N_t / N_t$  and the steady-state population level  $N_A^*$  in the agricultural era are given by (34) and (35) in Section 3.3. If  $N_t$  reaches  $N_A^*$  before reaching  $N_I$ , then the economy would remain as an agricultural society indefinitely. From (35) and (A11), the inequality  $N_A^* > N_I$  is equivalent to

$$\left( \frac{\sigma l}{\beta} \right)^{1/(1-\alpha)} > \left( \frac{\alpha}{\varepsilon A} \right)^{1/(1-\alpha)} + \frac{\delta}{(1-\varepsilon)\varphi^{1/(1-\alpha)}Z}, \tag{A12}$$

which shows that the gradual transition from an agricultural economy to an industrial economy begins under the following conditions: a low fertility cost  $\beta$ , a strong fertility preference  $\sigma$ , a high level of agricultural productivity  $\varphi$ , a high level of labor supply  $l$ , a large amount of land  $Z$ , a high level of industrial productivity  $A$ , and a low fixed cost  $\delta$  for operating industrial firms. These conditions are the same as in Section 3.4, except that the transition in this case is gradual (i.e.,  $l_F > 0$ ) until  $N_t \rightarrow \infty$ .

Under the interior solution, the level of output per capita in the industrial era is given by

$$x + y = f + y = \varphi(l_F)^\alpha \left( \frac{Z}{N_t} \right)^{1-\alpha} + A \left( l_Y - \frac{\delta}{N_t} \right) = \varphi(l_F)^\alpha \left( \frac{Z}{N_t} \right)^{1-\alpha} - A l_F + A \left( l - \frac{\delta}{N_t} \right), \tag{A13}$$

which is decreasing in  $l_F$  because  $\alpha \varphi(l_F)^{\alpha-1} (Z/N)^{1-\alpha} = w/p = \varepsilon A < A$ . Then, (A9) shows that  $l_F$  is decreasing in  $N$ . Substituting (A9) and (A13) into (26) yields the population growth rate, which as before converges toward the same steady state  $\Delta N/N = \frac{\sigma}{\beta} A l - 1$  as  $N_t \rightarrow \infty$ .

**Corner solution:** If  $\varphi \rho^{1-\alpha} < \varepsilon A$ , then the level of industrial labor  $l_Y$  increases sharply from 0 to  $l$  when  $N_t$  crosses the threshold  $N_I \equiv \delta / [(1 - \varepsilon)l]$ . In this case, the inequality  $N_A^* > N_I$  is equivalent to

$$(1 - \varepsilon) \left( \frac{\sigma}{\beta} \varphi l \right)^{1/(1-\alpha)} \frac{Z}{\delta} > 1, \tag{A14}$$

which uses (35) and has the same comparative statics for  $\{\beta, \sigma, \varphi, l, Z, \delta\}$  as in Section 3.4. The only exception is industrial productivity  $A$ ; however, a larger  $A$  makes the corner solution more

likely to apply in which case industrialization could be triggered as a result because the threshold  $N_I$  decreases from (A11) to  $N_I \equiv \delta/[(1 - \varepsilon)l]$ .

It is useful to note that although the industrial transition is immediate in this case,  $N_I \equiv \delta/[(1 - \varepsilon)l]$  is not the same as  $N_I$  in (16)–(17) and that there exists a unique interior value of  $\varepsilon \in (0, 1)$  above which  $\delta/[(1 - \varepsilon)l]$  is greater than  $N_I$  in (16)–(17) in which case industrialization occurs later because the markup ratio  $1/\varepsilon$  is too small to cover the fixed cost  $\delta$ . Finally, under the corner solution, the level of output per capita and the population growth rate in the industrial era are the same as (20) and (36), respectively. In the long run, the population growth rate rises toward the same steady state  $\Delta N/N = \frac{\sigma}{\beta}Al - 1$  as  $N_t \rightarrow \infty$ .

## Appendix B: Robustness check

**Table B1.** Separate regression  $y_j = \kappa_3 \varphi_j + \Phi_j + \epsilon_{3j}$

	<i>industrialization</i>	<i>GDP share</i>	<i>GDP per capita</i>
	(1)	(2)	(3)
<i>productivity</i>	8.490*** (1.925)	6.813*** (1.951)	0.170** (0.071)
<i>rugged</i>	−3.541* (1.796)	−1.454 (2.024)	−0.073 (0.058)
<i>landarea</i>	−1.014 (0.980)	0.138 (1.010)	−0.005 (0.044)
<i>soil</i>	−0.181*** (0.068)	−0.055 (0.092)	−0.008* (0.004)
<i>nearcoast</i>	0.125** (0.058)	0.119 (0.076)	0.005** (0.002)
Continent fixed effects	✓	✓	✓
Observations	94	62	88
$R^2$	0.679	0.446	0.604

Notes: Robust standard errors in parentheses. \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ . Here, we estimate the effects of agricultural productivity on the share of non-agricultural employment in 1991 in column 1, the non-agricultural share of GDP in 1980 in column 2, and the log of GDP per capita in 1950 in column 3.