Economics Bulletin

Volume 32, Issue 1

The Emergence of Agriculture: Trickle-Down Growth and Climate Change

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Abstract

This paper analyzes a model of the transition to agriculture by allowing heterogeneous agents to make the decision on whether to engage in farming or foraging. The threshold level, which divides foragers from farmers, depends on both agricultural productivity and foraging efficiency. As agricultural productivity improves, farming becomes possible to low-skilled agents, which leads to further improvement in agricultural productivity. Due to this trickle-down mechanism, the allocation of labor to agriculture magnifies the persistence of growth dynamics. The model also explains that a temporary climate deterioration can initiate the transition to agriculture by lowering foraging efficiency.

Citation: Shinji Teraji, (2012) "The Emergence of Agriculture: Trickle-Down Growth and Climate Change", *Economics Bulletin*, Vol. 32 No. 1 pp. 913-922.
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Submitted: February 26, 2012. **Published:** March 19, 2012.

1. Introduction

The transition from hunting-gathering to agriculture was one of the major turning points in the history of mankind. The difference between the Paleolithic and the Neolithic is the mode of acquiring food: foraging in the former and agriculture in the latter. The transition to agriculture is frequently referred to as the Neolithic Revolution (Weisdorf, 2005). There has been the so-called Mesolithic between the end of the Paleolithic and the beginning of the Neolithic. Based on geological epochs, the Pleistocene–Holocene transition encompassed the Mesolithic. The Mesolithic is characterized as a "transitional and rather unstable period of broad spectrum foraging and the earliest agriculture" (Marceau and Myers, 2006).

The relationship between climate and the development of agriculture has been widely discussed (Henry, 1989). The "Younger Dryas" was a period of cold, dry climate conditions that temporarily reversed global warming during the Pleistocene-Holocene transition (Alley, 2000). Rapid reduction in the yields of natural plants forced humans to change their strategies. The emergence of agriculture can be seen as a response to the stresses of the Younger Dryas (Bar-Yosef, 1998).

Various theories have been advanced to explain the emergence of agriculture. Smith (1975) links the rise of agriculture to the extinction of large herding animals by Paleolithic hunters. According to his analysis, increased hunting efficiency eventually promoted the adoption of farming by lowering the growth rate of hunted biomass. Baker (2008) describes endogenous growth effects, in which population density and technological sophistication are likely to cause a switch to agriculture. Marceau and Myers (2006) allow individuals to form co-operative communities. At a critical state of technology, the grand coalition breaks down, resulting in a loss of efficiency. Dow et al. (2009) and Dow and Reed (2011) provide a climate-based explanation of the origin of agriculture, in which population and technology respond endogenously to climate.

This paper attempts to take another step forward in understanding the relationship between individual labor allocation and the emergence of agriculture. The model builds upon ideas from Lucas (1978) and Murphy et al. (1991), in which a distribution of skills across individuals is postulated. The relatively high-skilled agents become farmers, while the relatively low-skilled agents become foragers. Productivity is assumed to follow a learning-by-doing process over many generations, inspired by the work on this idea by Arrow (1962), Krugman (1987) and Matsuyama (1992, 2002). However, these authors do not consider the rise of agriculture, focusing only on endogenous growth in manufacturing.

On the basis of endogenous technological changes, this paper explains that a temporary climate deterioration was needed to initiate the shift to agriculture. Dow et al. (2009) is most closely related to our study. However, differently from their model, we focus on the role of heterogeneity (individuals vary in their skills). In the presence of heterogeneity, we can analyze an important mechanism through which agricultural production may trickle down from the high-skilled agents to the low-skilled agents. Cooler conditions lower foraging efficiency, which makes agricultural production attractive to the low-skilled agents. The trickle-down mechanism induces more people to become farmers, which enables agricultural productivity to grow further. Knowledge of food production accumulates more rapidly in societies with a greater number of farmers. A rapid accumulation of knowledge in agriculture pulls individuals out of hunter-gatherer societies.

The remainder of this paper proceeds as follows. Section 2 sets up the framework. Section 3 characterizes different scenarios of the dynamical system on the emergence of agriculture. Section 4 analyzes the effects of climate change on the development of agriculture. Section 5 concludes.

2. The framework

2.1 Individual decisions

Consider a society populated by a continuum of overlapping agents at each period t (time is continuous). The population size is constant over time and normalized to 1. The risk of death is individualistic, and every agent faces a constant instantaneous probability of death δ. The constant population implies that a new cohort whose size is δ is born at each moment of time. Thus, at each period t, a new cohort of size δ enters and a measure δ of agents dies.

There are two fundamental technologies for food production: agriculture and foraging. Hunter-gatherer societies take resources directly from nature, so foraging is more susceptible to climate change than agriculture. Foragers are taken to be equally productive. In contrast, individuals are differently productive in agriculture.

The model characterizes the labor force participation to agriculture or foraging. Every newly born agent needs to decide whether to engage in agriculture or foraging. Once the participation decision is made, the agent will be stuck to agriculture or foraging. Each agent born at time t decides the participation rate to agriculture, e_t, which may take a value between 0 and 1.

The agent may produce output per capita from foraging activity, q, proportional to his participation rate to foraging. With the participation rate to foraging, $1-e_t$, at time t, he receives:

$$q_t = (1-e_t)\,\theta c, \qquad (1)$$

where θ, which represents the degree of environmental impact on natural resources *compared with* agricultural production, is treated as an exogenous parameter. θ decreases (or increases) in response to a negative (or positive) climate shock. The technology in foraging transforms one unit of labor into c units of the output. Foraging offers little opportunity for technical advances, so c is constant over time. We impose the following condition: $\theta c < 1$. If this condition does not hold, every agent chooses to engage in foraging.

Agricultural productivity, A_t, reflects knowledge capital as of time t. Furthermore, it is assumed that agricultural productivity is ultimately constrained by the land endowment. Let $A = 1$ be the maximum level that the land is able to support. With the participation rate to agriculture, e_t, at time t, the agent produces output per capita from agricultural production, $e_t A_t$.

Agricultural production entails the incurrence of costs. The only possible source of heterogeneity across individuals is their cost of production in agriculture. An agent is labeled by his constant marginal cost of agriculture z. The agent, who devotes the rate e_t to agriculture, incurs $e_t z$ in food production. It might also capture differences in skills (to obtain a same output, some agents need to spend more inputs). At the beginning of his life, every agent *inherits* the skill from his predecessor who retires due to death. If an agent dies, he is replaced by a newborn of the same skill. The distribution of skills over newly entering agents can be represented by a cumulative distribution function $G(z)$, $0 \leq z$. Thus, $G(z)$ is the number of individuals with marginal cost less than or equal to z, inherited by newly born agents. A lower (or higher) z is associated with a higher (or lower) skill. By the law of large numbers, the distribution function $G(.)$ is time invariant. It is assumed that, over a large interval of z, $G(.)$ is continuously differentiable and $G'(.) > 0$.

When devoting e_t to agriculture at period t, the agent with marginal cost z receives:

$$p^z{}_t = e_t (A_t - z), \tag{2}$$

from agricultural production.

Total output per capita, π^z, has two components: individual output from foraging, q, and individual output from agriculture, p^z. From (1) and (2), total output per capita for the agent with marginal cost z is given by:

$$\pi^z{}_t = e_t (A_t - z) + (1 - e_t)\, \theta c. \tag{3}$$

The agent's only control variable is the allocation of labor between agriculture and foraging. An agent born at time t selects a level of e_t, where $0 \leq e_t \leq 1$, responding to differences in output. He takes A_t as given, though later we show how A_t changes endogenously.

Differentiating (3) with respect to e_t gives:

$$\frac{d\pi^z{}_t}{de_t} = A_t - z - \theta c.$$

If $A_t - z - \theta c > 0$, the agent with z wishes to engage in agriculture ($e_t = 1$). There is a threshold level of the cost, $A_t - \theta c$ (> 0), below which he devotes his labor to agriculture, and above which he devotes his labor to foraging. Thus, if $A_t > \theta c$, all agents with z lower than $A_t - \theta c$ prefer being farmers to being foragers. For $z = A_t - \theta c$, they are indifferent. Agents whose marginal cost is higher than $A_t - \theta c$ are better off being foragers instead of being farmers. On the other hand, if $A_t < \theta c$, $A_t - z - \theta c < 0$ holds for every z. Then, all agents prefer being foragers to being farmers. To summarize:

Lemma.

(a) *If $A_t > \theta c$, the participation rate to agriculture satisfies*

$$e_t \begin{cases} = 1 & \text{if } A_t - \theta c > z, \\ \in [0,1] & \text{if } A_t - \theta c = z, \\ = 0 & \text{if } A_t - \theta c < z, \end{cases}$$

for the agent with marginal cost of agriculture z.

(b) *If $A_t < \theta c$, the participation rate to agriculture satisfies $e_t = 0$ for all agents*.

If the level of agricultural productivity is above θc, the proportion of $G(A_t - \theta c)$ of the new cohort specializes in agriculture, and the remaining proportion, $\delta - G(A_t - \theta c)$, specializes in foraging.

2.2 Agricultural productivity

We consider two kinds of knowledge: "primitive" knowledge and "derivative" knowledge. Even though farming is inactive, agricultural productivity maintains a primitive level of knowledge, a, where $0 < a < 1$. Agricultural productivity is bounded below by a. If farming is active, derivative knowledge is gained through learning-by-doing. Learning-by-doing (with respect to planting, weeding, irrigation, and harvesting) refers to the capability to improve productivity through practice. Knowledge accumulates as a by-product of production experience in agriculture. As more agents specialize in agriculture, production experience will increase, allowing for a faster exchange of ideas. Hence, a larger farmer's share $G(A_t - \theta c)$ improves agricultural productivity.

A_t is the discounted cumulative experience of food production, given by:

$$A_t = \delta \int_{-\infty}^{t} \{a + G(A_s - \theta c)\} e^{-\delta(t-s)} ds \leq 1, \tag{4}$$

where $G(A_s - \theta c)$ is the farmer's share at period s. Because there is depreciation, A_t is bounded above by one. Differentiating (4) with respect to t yields:

$$\frac{dA_t}{dt} = \delta[\{a + G(A_t - \theta c)\} - A_t]. \tag{5}$$

The right-hand side captures innovations and erosion of technology. All newly entering agents learn production knowledge, and knowledge erodes due to death. It is multiplied by δ, since δ is both the size of the new cohort and the probability of death. Here, the parameter δ can be also interpreted as both the speed of learning in production and the rate of depreciation of learning experience in production. A steady-state situation is characterized by $dA_t/dt = 0$, in which the farmer's share in the new cohort is given by $G(A^* - \theta c) = A^* - a$.

3. The dynamical system

This section analyzes the steady states in the accumulation process of agricultural productivity. We consider two different scenarios for $\theta c > a$. In the first case, agricultural productivity as of time t satisfies $A_t > \theta c$. In the second case, $A_t < \theta c$. **Fig. 1** provides steady states in both hunter-gatherer and agricultural societies. Suppose that $G(.)$ is differentiable over the interval $(\theta c, 1)$. We impose the following sufficient condition for stability: $G'(A^* - \theta c) < 1$, for a steady state, $A^* > 0$. This condition requires that, at the steady state, the effect of an increase in the level of agricultural productivity on the proportion who chooses to engage in agriculture is not too large. This could be because the distribution function is relatively flat at this state.

Consider the first case: $A_t > \theta c$. The proportion of $G(A_t - \theta c)$ of the new cohort specializes in agriculture, and $G(A_t - \theta c)$ increases with A_t (**Fig. 1**). As long as the $a + G$ curve is above A, there is a learning-by-doing dynamic because $dA_t/dt > 0$ in (5). In a steady state of (5), the population mass engaged in agriculture is given by $G(A^* - \theta c) = A^* - a$. The society converges to A^* if A_t is above θc. Agents are more likely to be farmers if the level of agricultural productivity is higher. This, in turn, supports an equilibrium where even the low-skilled agents can engage in agriculture.

Next consider the second case: $A_t < \theta c$. The farmer's share is then zero, $G(A_t - \theta c) = 0$. In this case, as depicted in **Fig. 1**, the $a + G$ curve is constant at a. Equation (5) is now given by $dA_t/dt = \delta(a - A_t)$. For every ($\theta c >$) $A_t > a$, we have $dA_t/dt < 0$. The society will gradually lose its level of technology with the erosion of knowledge. Agricultural productivity converges to a if it is below θc ($> a$). Thus, the evolution of agricultural productivity is characterized by two distinct regimes:

Proposition 1. *Let* $\theta c > a$.
(a) *If* $A_t > \theta c$*, then* A_t *converges to* $A^* = G(A^* - \theta c) + a$ *in the long run.*
(b) *If* $A_t < \theta c$*, then* A_t *converges to* a *in the long run.*

Proposition 1 shows that a large proportion of farmers magnifies the persistence of growth dynamics. A higher level of agricultural productivity induces more people to become farmers, which provides additional knowledge to food production. Agricultural production trickles down from the high-skilled agents to the low-skilled agents. Through this trickle-down process, productivity gains expand the number of agents who specialize in agriculture.

4. Climate change

The last deglaciation terminated with an abrupt shift to cooler conditions throughout the entire northern hemisphere. The Younger Dryas was a brief climate event that interrupted the warm conditions during the late-glacial period. Whether or not this climate change impacted late Pleistocene hunter-gatherer populations is an important topic in the archaeology (Ballenger et al., 2011). If yields in natural plants decreased during the Younger Dryas, the motivation for intentional cultivation could have increased. Initiating cultivation was a response to the environmental stress during the Younger Dryas. Foragers possessed the knowledge necessary to take up agriculture, but they would not embark on costly methods of food production unless there was good reason to do so.

Now consider an abrupt climate change in our model. Foraging activity is directly affected by the environmental damage caused by climate change. A climate deterioration would decrease per capita food from foraging activity by lowering the parameter θ. Suppose a temporary climate deterioration from θ_H to θ_L, where $\theta_H > \theta_L$. This effect ($\theta_H \rightarrow \theta_L$) is depicted in **Fig. 2**.

Consider the society with $A_t > \theta_H c$ ($> a$). To the climate deterioration from θ_H to θ_L, the farmer's share increases: $G(A_t - \theta_H c) < G(A_t - \theta_L c)$. This suggests the possibility that climate change triggers agricultural production for the low-skilled agents. Some foragers are forced into agriculture by a temporary climate deterioration.

Another effect is illustrated above $\theta_H c$ in **Fig. 2**. A decline in θ shifts the $a + G$ curve upward because it makes a large proportion of agents to become farmers. Since the $a + G$ curve is above A, agricultural productivity grows, $dA_t/dt > 0$. Even the low-skilled agents are lured into agriculture by its productivity improvement. Irrespective of the climate recovery from θ_L to θ_H, agricultural productivity converges to a higher level, A^{**}. This process of a trickle-down from the high-skilled agents to the low-skilled agents can go a long way. In summary:

Proposition 2. *Consider the society with* $A_t > \theta_H c$ ($> a$). *To the climate deterioration from* θ_H *to* θ_L, *the proportion of* $G(A_t - \theta_L c) - G(A_t - \theta_H c)$ *joins in agricultural production, and agricultural productivity converges to a higher level,* A^{**}*, in the long run.*

Next, consider the economy with $A_t < \theta_H c$ and $\theta_H c > a > \theta_L c$. Farming is inactive if the climate condition is θ_H. When the climate deteriorates from θ_H to θ_L,, the farmer's share increases from 0 to $G(a - \theta_L c)$. Since the $a + G$ curve is above A (**Fig. 2**), agricultural productivity grows.

Furthermore, suppose the climate recovers from θ_L to θ_H. If learning-by-doing is relatively fast, agricultural productivity grows above $\theta_H c$. A decline in θ shifts the $a + G$ curve upward. Agricultural productivity converges to a higher level, A^{**} (**Fig. 2**). On the other hand, if learning-by-doing is not fast, agricultural productivity is below $\theta_H c$. Then A_t converges to a. In summary:

Proposition 3. *Consider the society with* $A_t < \theta_H c$ *and* $\theta_H c > a > \theta_L c$.

(a) *Suppose that a climate deteriorates from* θ_H *to* θ_L *temporarily. The farmer's share increases from* 0 *to* $G(a - \theta_L c)$, *and agricultural productivity grows.*

(b) *Suppose that the climate recovers from* θ_L *to* θ_H. *If agricultural productivity is above* $\theta_H c$*, it converges to a higher level, A**, in the long run. On the other hand, if agricultural productivity is below* $\theta_H c$*, it converges to a in the long run.*

Proposition 2 shows that a negative climate shock can stimulate progress in agricultural productivity because it induces more people to embark on agricultural production. Proposition 3 (a) also shows that a negative climate shock can stimulate permanent progress if learning-by-doing is relatively fast. Proposition 3 (b) shows that, without fast learning-by-doing, the improved climate would revert to hunter-gatherer societies. As a result, the effects of climate change on the emergence of agriculture depend on the growth rate of knowledge capital, which are not equal across societies.

5. Conclusion

This paper has analyzed a model of the transition from foraging to agriculture. The only possible source of heterogeneity across individuals is their cost of production. It might capture differences in skills. As agricultural productivity grows, farming becomes possible to relatively low-skilled agents, which leads to further improvement in agricultural productivity. Furthermore, we have investigated the effects of climate change on long-run development of agriculture. A negative climate shock can stimulate progress in agricultural productivity because it induces more people to join in agricultural production.

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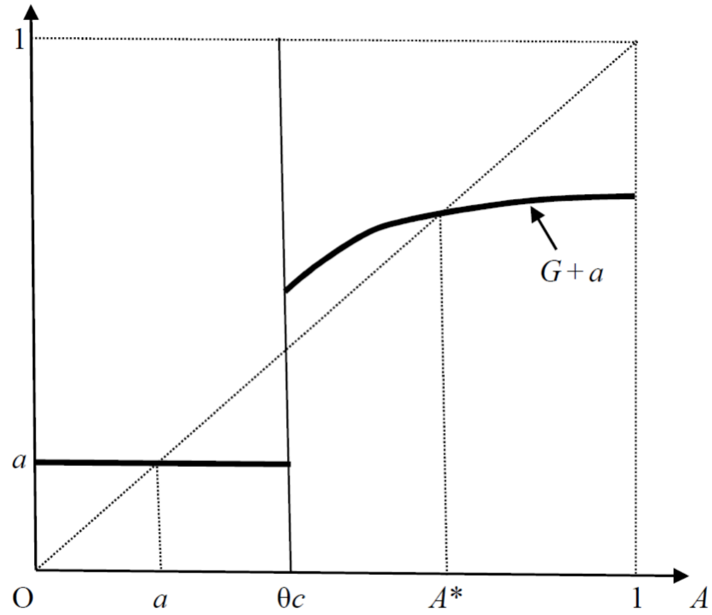

Fig. 1

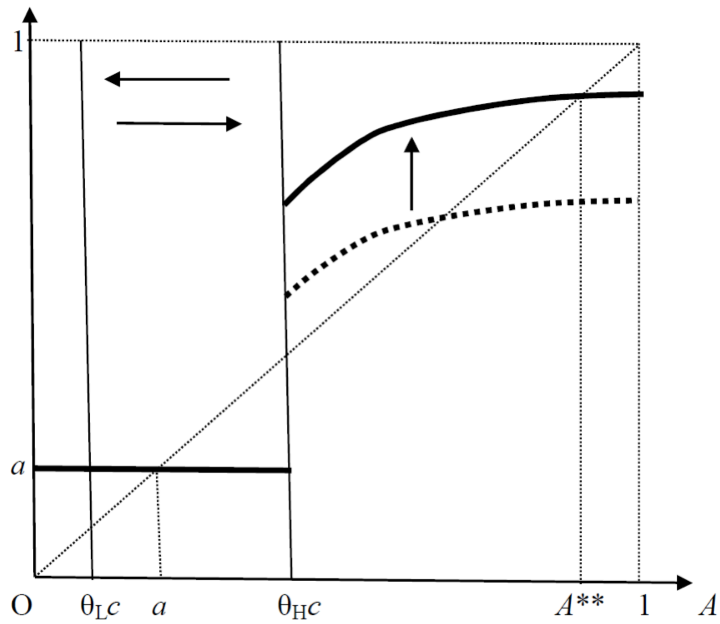

Fig. 2