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Abstract

Time-budget studies done among contemporary primitive people suggest that the first farmers worked harder to attain subsistence than their foraging predecessors. This makes the adoption of agriculture in the Stone Age one of the major curiosities in human cultural history. Theories offered by economists and economic historians largely fail to capture work-intensification among early farmers. Attributing a key role to human metabolism, this study provides a simple framework for analysing the adoption of agriculture. It demonstrates how the additional output that farming offered could have lured people into agriculture, but that subsequent population increase would eventually have swallowed up its benefits, forcing early farmers into an irreversible trap, where they had to do more work to attain subsistence compared to their foraging ancestors. The framework draws attention to the fact that, if agriculture arose out of need, as some scholars have suggested, then this was because pre-historic foragers turned down agriculture in the first place. Estimates of population growth before and after farming, however, in light of the present framework seem to suggest that hunters were pulled rather than pushed into agriculture.

JEL Codes: J22, Q56, O10

Keywords: Agriculture, Hunting-Gathering, Malthus, Metabolism, Neolithic Revolution

1 Introduction

This paper addresses a one of the major curiosities in human cultural history: why hunting and gathering was eventually replaced by agriculture. The work is inspired by a long-standing debate in the anthropological science about how much work pre-historic foragers had to do to achieve subsistence. The earlier anthropological tradition assumed that hunter and gatherers lead hard lives of constant struggle to make a living. It was believed that the advent of agriculture had reduced the labour input necessary to attain subsistence and thus would have afforded people the extra time required to develop advanced societies.

Systematic time-budget studies done in the 1960's among contemporaneous primitive people, however, completely turned the conventional story on its head, as labour inputs in foraging communities proved to be amazingly small. A seminal time-study done by renounced anthropologist Richard B. Lee among the Dobe Bushmen, a group of hunters and gatherers located in southern Africa, showed that an average adult, despite a harsh environment, devoted only between 12 and 19 hours to work per week (Lee 1968). Later studies done among other groups of foragers have confirmed Lee's observation: contemporary primitive people rarely put in more than six hours of labour per day, or about two-thirds of the labour input of people living in more advanced societies (Voth 2001).

Lee and fellow anthropologists (Lee and Devore 1968; Sahlins 1972) became spokesmen of the view that pre-historic foragers were effectively the most leisured people in history. By contrast to the earlier view, the first agriculturalists are now believed to have put in more rather than less labour to attain subsistence. The current standpoint accordingly holds that Palaeolithic foragers possessed all the knowledge necessary to take up agriculture, but that they would not embark upon time-costly methods of food production unless there was good reason to do so. Jack R. Harlan, one of the great pioneers of historical ecology, summarises the contemporary view as follows:

"Why farm? Why give up the 20-hour work week and the fun of hunting in order to toil in the sun? Why work harder, for food less nutritious and a supply more capricious? Why invite famine, plague, pestilence and crowded living conditions?" (Harlan, *Crops and Man*, 1992)

Why indeed, under these circumstances, would any society decide to adopt agriculture? A few attempts have been made in the fields of economics and economic history to try to provide a framework suitable for discussing the factors that eventually led to the emergence of agriculture (North and Thomas 1977, Smith 1975, Locay 1989, Marceau and Meyers 2006 and Seabright 2008).[1]

Remarkable, these studies generally fail to explain the fact that farming entailed a process of work-intensification, a key element to the puzzle about agricultural adoption. Marceau and Meyers (2006) and Seabright (2008) are exceptions. According to Marceau and Meyers, however, it needs extraordinary circumstances—conflict and excessive hunting—to justify farming in the face of hard work, circumstances that are not normally observed to have appeared at the onset of agriculture (Fernandez-Armesto 2001).

In Seabright's view, more work results, not (as the evidence suggest) from more time spent in food-procurement activities, but from more hours allocated to defence.[2] Seabright's study, which is more about the spread of agriculture than its origin, would nicely complement ideas presented in the current study, if one wanted to explore a combination of agricultural adoption and its subsequent dispersal.

The present study offers a simple framework for analysing the adoption of agriculture. The framework serves a dual purpose. First, it provides insight into the puzzle why early farmers would toil more to obtain subsistence compared to their foraging predecessors. A key explanatory factor in this context, the current study argues that human metabolism—the fact that physical work not only generates calories but also demands them—plays a crucial role for understanding a potential lack of enthusiasm towards farming and

[1] In addition, several studies in economics highlights the importance of the Neolithic Revolution for subsequent growth and development (Ashraf and Galor 2007, 2008; Galor and Moav 2002, 2007; Hibbs and Olsson 2005).

[2] This makes Seabright's theory consistent with earlier beliefs (Oppenheimer 1914) that placed emphasis on the idea that armed foragers would consist of a threat to early farmers.

why its adoption would eventually lead to work-intensification. As will be established further below, agriculture, once it became economically viable, would lure people into an irreversible trap, where the higher population densities that agriculture permitted forced early farmers into working more hours and prevented them from a return to the leisured lifestyle of foragers once farming was introduced. In this sense, agricultural adoption resembles the *prisoner's dilemma*: individually rational decisions, i.e. an attempt to expand the size of one's family whenever possible, produce a sub-optimal outcome, where all individuals end up working harder to attain subsistence.

The second purpose of the framework is to see if some headway can be made with regards to a long-standing dispute among archaeologists and anthropologists about whether farming arose from necessity or opportunity. The main conclusion drawn from the analysis below is that, if agriculture arose out of need, then this was because pre-historic foragers refused the opportunity to take up farming in the first place. This, in turn, would implicitly give insight into the evaluation of work versus leisure among pre-historic hunters. The current study discusses the origins of agricultural reluctance and the types of pressures that would ultimately have triggered the emergence of farming. It ends up giving favour, however, to idea that agriculture emerged from opportunity rather than need.

The paper continues as follows. Section 2 provides a simple framework for analysing agricultural adoption. Section 3 analyses the transition to agriculture and explores the effects of agricultural adoption on demography, productivity and hours worked. The framework's predictions are then used to see if some of the existing theories about agricultural adoption should be favoured over others. Finally, section 4 concludes.

2 A Simple Framework for analysing the Transition to Agriculture

Consider an egalitarian society in which a single good (food or calories) is produced. By egalitarian is meant that every member of the society puts in the same amount of work and that the total output is shared equally between the members. There are two potential sectors for production: foraging and farming. The differences between the two are discussed further below. In period t, the society consists of L_t identical individuals. The gross rate of growth of population (the number of surviving children per adult) is denoted n_t and is determined endogenously below. Hence, change in the size of the labour force between two consecutive periods is given by $L_{t+1}=n_tL_t$. Unless explicitly stated, all variables are considered in period t.

As might have been the case for all pre-industrial societies (Clark 2007), the economy under consideration is assumed to be subject to so-called *Malthusian* population dynamics. Such dynamics involve the combination of two elements. The first element is the law of diminishing returns. In the presence of a fixed factor of production, such as land, the application of this law implies that any improvement in productive potential is ultimately swallowed up by a larger population. The second element, which links directly to Malthus (1798), is a positive relationship between the resources of parents and their reproductive success. The combination of these elements means that the economy over the long run is kept in a homeostatic, so-called *Malthusian* equilibrium, where the population level is constant and where incomes are maintained at the level of subsistence.

By contrast to the stylised version of the Malthusian model, subsistence in the present context is not tied to a specific income level. Here, instead, subsistence refers to the *caloric surplus*—defined as an individual's income (its caloric output) net of its own-consumption (its caloric requirements)—that permits an individual exactly one surviving offspring. In this sense, the current framework provides an alternative way of thinking about subsistence in a Malthusian economy.

Malthusian population dynamics in the present framework, therefore, appear through the use of three basic relationships. The first is a positive link between an individual's labour input (hours worked) and its potential earnings (caloric output). The second is a positive relationship between an individual's labour input (hours worked) and its caloric requirements (its metabolism). The third is a positive correlation between an individual's caloric surplus (caloric output minus caloric requirements) and its reproductive success (surviving children).

In the following, the three relationships described above are explained in detail. Next, the individual's preferences are discussed and its optimisation problem analysed. Finally, the framework is used to examine society's choice of food procurement methods.

Labour Input and Earnings

The first relationship—that between labour input and income earned—is captured in the following way. There are two potential sectors of production: hunting (sector *H*) and agriculture (sector *A*). Depending on its prospective earnings and its metabolism (specified below), an individual may decide to work in both sectors (mixed activities) or in either of the two (specialisation).

Suppose that the production of output is characterised by constant returns to land and labour, and that land is in fixed supply. Hence, the production function for sector $i \in [H,A]$ is given by $Y_i = B_i(l_i L)^{\alpha}$, where $0<\alpha<1$ implies that there is diminishing returns to labour.[3] The variable l_i, which is found endogenously below, measures the labour input (hours worked) of an individual employed in sector *i*, and B_i measures sector *i*'s total factor productivity (which increase with the stock of knowledge about how to transform input into output and with better climatic conditions). Because of the equalitarian nature of the society, income per worker in each sector is equal to the average product, meaning that $w_i = Y_i/L = B_i l_i^{\alpha}/L^{1-\alpha}$ for $i \in [H,A]$.

Foraging and farming are distinguishable from several perspectives (see Pryor 2005). Here, we focus on one particular aspect, namely that farming—unlike foraging—needs a fixed labour investment before food goods can be reaped. Using plant production, farming involves numerous distinct tasks, such as land preparation and planting, nurturing activities, fertilising, irrigating, weeding and selecting seeds to store for next year. For the case of meat production, there is breeding and feeding involved before the meat is ready

[3] Obviously, the size of α need not be the same in both sectors. However, sector-specific α values would severely complicate matters without affecting the qualitative nature of the results obtained further below.

for butchering. In either case, time spend defending ones agricultural produce, as extensively discussed by Seabright (2005, 2008), comes in addition.

To capture these aspects in the model, suppose that it requires a fixed labour input of $\lambda>0$ hours per worker to operate the agricultural sector. This assumption, which is similarly, in principle, to assumptions made in related studies, also serves the purpose of permitting the possibility of specialising in hunting.

Labour Input and Caloric Requirements

The second relationship—that between labour input and caloric requirements—rests on the biological fact that an individual's caloric needs above the so-called *resting metabolic rate* (*RMR*) increase with the individual's physical activities.[4] To capture this relationship in a non-complicated manner, suppose that the total caloric requirements of an individual, who puts in l identical (physically equally demanding) hours of work, can be written as $v=v(l)$. The function v is assumed to be continuous and monotonic, with $v(0)=RMR>0$. For tractability of the analysis below, it is assumed that $v(l)=\beta l+RMR$, where $\beta>0$ is a positive constant.

Caloric Surplus and Reproductive Success

The third and finally relationship—that between an individual's caloric surplus and its reproductive success—is captured as follows. Suppose that the reproductive success of an individual is 'checked' (in a Malthusian sense) by the size of its caloric surplus (its caloric output minus its caloric requirements). Symbolically, an individual's reproductive success—its number of surviving children—is given by the function $n=n(s)$, where $s=w-v$ is the individual's caloric surplus, and where the function n is assumed to be continues and monotonic, with $n(0)=0$ and $n(\infty)>1$. Together, these assumptions imply that a so-called *subsistence caloric surplus* exists, defined as the caloric surplus at which an individual is able to raise exactly one surviving offspring.

[4] A similar approach is found in Dalgaard and Strulik (2007,2008).

Preferences, Optimisation and the Choice of Food Procurement Methods

As will become apparent below, the combination of caloric needs and diminishing returns to labour in production will create an inherent upper limit with respect to how many hours an individual decides to work. For simplicity, therefore, it will be assumed throughout each individual has available as many units of labour as it wishes to supply.

As for preferences, suppose, as a starting point, that, above all, an individual wants to maximise its number of surviving offspring (the size of its family). This amounts to saying an individual acts so as to maximise its caloric surplus. Once this is done, then utility is derived from time spent in leisurely activities. Later on, the assumption that individuals primarily wish to maximise the size of their families is relaxed.

According to the current preferences, each individual, faced with information about its earning schedules in the two potential sectors (captured by the w_i functions) and its metabolism (captured by the v function), allocates a number of hours to work in each sector, so that the marginal revenue of its labour input equals the marginal costs. Then, the individual chooses a combination of sectors (i.e. uses one or both) so as to maximise its caloric surplus.

In the following, the framework presented above is used to examine the individual's (and thus society's) choice of food procurement methods. More specifically, starting from a Malthusian equilibrium before the origins of agriculture, the purpose of the following is to analyse the conditions under which agriculture will emerge, and to explore its effects on demography, productivity, and labour input needed to obtain subsistence, in the short run as well as in the long run.

3 Analysis

Although there is still much debate about what factors that led to the emergence of farming, there nevertheless seems to agreement on the following stylised facts about agricultural origins (see Harlan 1992; Smith 1995). First, in all the places where agriculture emerged, population densities, as well as rates of population growth, were reported as being significantly higher (in some cases more than 60 times) compared to those of foragers. Second, higher population growth and densities are taken as unmistakable evidence that output per capita, as well as output per unit of land, were considerably higher among the first farmers than among their foraging predecessors. Finally, as was mentioned in the introduction section, it is generally agreed that pre-historic hunters had to do less labour to achieve subsistence compared to people living in more advanced societies.[5] How well does the framework presented above capture these stylised facts?

Figure 1 shows a Malthusian equilibrium before the rise of agriculture. A Malthusian equilibrium is a situation where the caloric surplus of each individual is at the level of subsistence, i.e. where each person is capable of supplying exactly as many calories as it needs to provide for one surviving offspring. Note that diminishing returns to labour in the production of output and the positive relationship between caloric surplus and population growth together implies that a Malthusian equilibrium is globally stable.

[Figure 1 about here]

Figure 1 shows that farming, for sufficiently low levels of agricultural productivity, is economically unviable. In other words, the use of agriculture demands more calories than it generates. Graphically, this implies that the earning schedule for farming (the w_A-curve) lies below the metabolism schedule (the *v*-curve) regardless of the level of individual labour input. Meanwhile, as is demonstrated in Figure 2, a sufficiently large increase in, or shock to, agricultural productivity will make farming worthwhile. Specifically, the level of agricultural productivity above which farming is economically viable (see Appendix A1) is $(\lambda/(\delta + RMR))^{1-\alpha} B_H$.

[Figure 2 about here]

[5] There is one more important point, which is often broad up in relation to the transition to agriculture, namely that the health of early farmers appear to have been significantly poorer than that of the last foragers (Cohen and Armelagos 1984). This drawback of farming, however, is mainly attributed to the occurrence of the crowd-related diseases, the monotonous work, and the poorer diet that seem to characterise primitive agriculturalist (Harlan 1995).

Note that, as long as agriculture is economically unviable, demographic and climatic pressures—two factors commonly believed to have triggered the shift to farming—could not have lead to agricultural adoption. Departing from a Malthusian equilibrium before the origins of agriculture (Figure 1), an increase in population, or a climatic downturn, both shift down the two earning schedules, making agricultural adoption even more unlikely (less economically viable).

Starting from the situation depicted in Figure 1, suppose, for one reason or another, that an increase in agricultural productivity appears that makes farming economically viable. Provided that people wish to maximise the number of their surviving offspring, which has been assumed so far, agriculture is then immediately adopted (Figure 2).

In the short run, the extra surplus that farming permits translates into more surviving offspring, thus leading to growth in the size of the population. In the long run, however, population increase, because of diminishing returns to labour, shifts down both earning schedules, gradually eating up the caloric surplus generated in each of the two sectors. This process continues until the total caloric surplus of each individual reaches the level of subsistence, and the economy is back in a Malthusian equilibrium. This is capture by Figure 3.

[Figure 3 about here]

Compared to the Malthusian equilibrium before the origins of agriculture (Figure 1), the new Malthusian equilibrium (Figure 3) is one of mixed activities. That is, a share of the individual's caloric surplus is now obtained using farming. If the variable *r* measures the ratio of productivity in the two sectors, so that $r=B_A/B_H$, then it follows that the higher is *r* (the more productive is farming compared to foraging) the smaller is the share of labour allocated to hunting activities, and the smaller is the fraction of income generated in the hunting sector (see Appendix A2).

Moreover, as long as there are fixed labour costs ($\lambda>0$) associated with the use of farming, members of agricultural societies (societies where farming has been introduced) work harder (for more hours) to attain subsistence than their foraging counterparts. Since they work more hours—thus consuming more calories—farming societies also have higher levels of income per capita and population density compared to societies that rely exclusively on hunting (see Appendix A3).

Note how the transition to agriculture cannot be reversed. Once the population has increased, the 'ratchet effect' makes a return to the leisured lifestyle of hunters impossible. Thus, having reached a Malthusian equilibrium after agricultural adoption (Figure 3), a society of mixed activities is caught in an irreversible trap, where its members toil more for subsistence compared to their foraging ancestors.

Consistent with the stylised facts presented above, therefore, farming societies have higher population densities (and, periodically, higher population growth); they have higher output per worker and, therefore, higher output per unit land; and they put in more hours of work to attain subsistence compared to their foraging counterparts.

Agriculture Origins—Necessity or Opportunity?

Anthropologists and archaeologists have long debated what factors led to the adoption of agriculture. The leading explanations roughly divide into two competing school (Smith 1995), one maintaining that farming arose from opportunity (mainly due to growth in the knowledge about how to cultivate and domesticate wild plants and animals), the other that it resulted from need (primarily provoked by demographic or climatic pressures). Can the present framework take us further as to whether one school should be favoured over the other?

The first observation to take away from the analysis carried out above is that farming could not have occurred unless it was already economically viable. This tautology is important, because it rejects the idea that agricultural adoption was *initially* forced by demographic or climatic pressures. In other words, if agricultural arose out of need, then this was because pre-historic foragers refused the opportunity to take up farming in the first place. But, then, what would be the origins of such reluctance towards agriculture? And what would eventually have led to its adoption?

In the analysis above, farming was adopted immediately after it became economically viable, suggesting that agriculture emerged out of opportunity. The underlying reason for this, of course, has to do with people's preferences. If family extension was the prime objective of pre-historic hunters, then agriculture would have been adopted once it was capable of generating a caloric surplus. A reluctance to take up agriculture when possible would then reflect the fact that family increase was not a top-priority. If this is true, then it would imply that contemporary hunters attribute a higher value to leisure relative to family size compared to people of farming societies.

Some scholars have reasoned that pre-history hunters would rather live in equilibrium with carrying capacity using foraging than to embark upon time-costly methods of agriculture (Binford 1968). And that the additional output that primitive farming techniques offered would lead to a reduction in rates of labour productivity (measured as output per unit of labour input), a feature believed to be a major barrier to agricultural intensification (Boserup 1965). In either case, unwillingness to take up agriculture would make Figure 2 instead of Figure 1 a relevant starting point for discussing the factors that led to agricultural adoption. In such circumstances, therefore, it would need some sort of imbalance, or pressure, to induce people to shift to farming.

What would be the source of such pressure? A recent theory ascribes the transition to agriculture to an unusual climatic episode taking place after the ending of the last Ice Age. As the ice sheets ceded to warmer and moister conditions, pre-historic hunters would have been able to exploit an increasing number of wild plants, which enabled them to increase their populations while still remaining in equilibrium with carrying capacity. However, between 10,800 and 10,300 years ago a global climatic downturn, known as the 'Younger Dryas', brought colder and drier environmental conditions. This climatic episode dramatically decreased the yield of wild cereals, which is believed to have motivated cultivation (Bar-Yosef and Belfer-Cohen 1991). In terms of the framework presented above, a gradual improvement in climatic conditions would little by little shift up the earnings schedule for hunting (and potentially for farming), causing growth of caloric surpluses and thus a steady increase in the size of hunting populations. A sudden climatic downturn, rapidly forcing down the earning schedules, would then leave the hunting societies with no choice but to resort to agriculture to save their population from demise.

An alternative view involves the pressure of an increasing population. Departing from Africa, evidence indicates that by some 15,000 years ago the human species had colonised all the inhabitable areas of Europe, Asia and the New World. Cohen (1977) speculates that this global over-population could indeed have triggered agricultural adoption. In the context of the present framework, emigration from one region, causing immigration and population pressure in another, would shift down both earning schedules (Figure 3), creating a reduction in the caloric surplus that can be generated using foraging. In turn, this provides a motive for taking up agriculture in order to supply enough calories to avoid population decline.

[Figure 4 about here]

The question of whether agriculture arose from opportunity or need seems to boil down to whether substantial population growth occurred before or after agriculture first appeared. What does the data say? Estimates of annual average rates of growth of population before and after farming, based on data provided by Kremer (1993), are shown in Figure 4. Although population growth does seem to gain momentum in the run up to the Neolithic Revolution, the Figure clearly indicates that rates of growth were far higher after farming had emerged, which tends then to favour the idea that pre-historic hunters were pulled rather than pushed into taking up agriculture.

4 Conclusion

Early agriculturalists seem to have worked harder to attain subsistence than their foraging predecessors. This makes the origins of agricultural one of the major curiosities in human cultural history. Existing studies in the fields of economics and economic history largely fail to capture the issue of work-intensification, or they argue that it needs extraordinary circumstances—wars and excessive hunting—to motive the shift, conditions that were rarely present at the onset of agriculture.

Attributing a key role to human metabolism, this study demonstrates how the extra output that agriculture offered could have lured people into taking up farming. However, faced with diminishing returns to labour in the production of output, subsequent population growth would eventually swallow up any benefits from embarking upon agriculture, forcing early farmers into an irreversible trap, where they had put in more hours of work to attain subsistence than did their foraging ancestors.

If agricultural arose out of need, which some scholars have suggested, then this was because pre-historic hunters refused the opportunity to take it up once it became economically viable. Such reluctance may have been rooted in a partiality towards leisure over larger families. In the end, outside factors, such as a climatic worsening and demographic pressure stemming from immigration, would have provided an incentive to embark upon agriculture in order to avoid depleted resources and ultimately demographic tragedy. Still, estimates show that population increase was considerably more pronounced after agricultural had emerged, leaving the overall impression that people were lured rather than forced into farming.

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1 Appendix

1.1 A1

In order to find the level of (total factor) productivity in agricultural required to make farming economically viable, we first need to calculate the number of hours worked per individual in a Malthusian equilibrium. Then, we need to compute the population level that can be supported in a Malthusian equilibrium before the origins of agriculture. Once we have this information, we then can determine the level of agricultural productivity needed to generate a non-negative caloric surplus from using farming.

How much work do people do in a Malthusian equilibrium? Each invidual allocates a number of hours to work, so that the marginal benefits of working equals the marginal costs hereof, i.e. until $\partial w_i/\partial l = \partial v/\partial l$ for $i \in \{H, A\}$. Calculating the derivatives, it follows that the optimal labour input per individual in sector $i \in \{H, A\}$ is given by

$$l_i = \left(\frac{\alpha}{\beta} B_i\right)^{\frac{1}{1-\alpha}} \frac{1}{L}. \tag{1}$$

Suppose that the number of calories require to ensure the survival of exactly one offspring is $\delta > 0$. In a Malthusian equilibruim, therefore, the caloric surplus of each individual is $s = \delta$, meaning that, before the origins of agriculture,

$$s_H = w_H\left(l_H, L_H, B_H\right) - \beta l_H - RMR = \delta.$$

Inserting income from hunting, as well as equation (1), and solving for L_H , we find that the population level in a Malthusian equilibrium before the rise of agriculture is given by

$$L_H = \frac{(1-\alpha)\left(\left(\frac{\alpha}{\beta}\right)^{\alpha} B_H\right)^{\frac{1}{1-\alpha}}}{RMR + \delta}. \tag{2}$$

Hence, starting from a Malthusian equilibrium before agricultural adoption, farming is economically viable if it yields a non-negative caloric surplus, i.e. if

$$s_A = w_A\left(l_A, L_H, B_A\right) - \beta l_A - \lambda \geqslant 0$$

Inserting agricultural income, as well as equations (1) and (2), and solving for B_A, the level of agricutural productivity required to make farming economically viable is

$$B_A \geqslant \left(\frac{\lambda}{RMR+\delta}\right)^{1-\alpha} B_H. \tag{3}$$

1.2 A2

In order to calculate the share of labour and income coming from hunting activities, we need to know the level of population in a Malthusian equilibrium after agriculture has emerged (subscript $H+A$). This can be calculated using the information that the total caloric surplus of each individual is given by

$$s = s_H + s_A = w_A\left(l_H, L_{H+A}, B_H\right) + w_A\left(l_A, L_{H+A}, B_A\right) - \beta\left(l_H + l_A\right) - \lambda - RMR = \delta.$$

Inserting incomes from the two sectors, as well as equations (1) and (2), and solving for L_{H+A}, it follows that the size of the population in a Malthusian equilibrium after the origins of agriculture is

$$L_{H+A} = \frac{(1-\alpha)\left(1 + r^{\frac{1}{1-\alpha}}\right)\left(\left(\frac{\alpha}{\beta}\right)^{\alpha} B_H\right)^{\frac{1}{1-\alpha}}}{\lambda + RMR + \delta} \tag{4}$$

where the variable r defines the ratio of productivity in the two sectors, i.e. $r \equiv B_A/B_H$.

Next, using equations (1), (2) and (4), we can now calcutlate the share of total invididual labour input allocated to hunting, which is

$$\frac{l_H\left(l_H, L_{H+A}, B_H\right)}{l_H\left(l_H, L_{H+A}, B_H\right) + l_A\left(l_A, L_{H+A}, B_A\right) + \lambda} = \begin{cases} 1 & \text{if} \quad r \leqslant \left(\frac{\lambda}{RMR+\delta}\right)^{1-\alpha} \\ \frac{1}{1+r^{\frac{1}{1-\alpha}}} \frac{\lambda+RMR+\delta}{\lambda+RMR+\delta+\frac{\beta(1-\alpha)}{\alpha}\lambda} & \text{if} \quad r > \left(\frac{\lambda}{RMR+\delta}\right)^{1-\alpha} \end{cases},$$

Similarly, the share of total individual income coming from hunting activities is simply

$$\frac{w_H\left(l_H, L_{H+A}, B_H\right)}{w_H\left(l_H, L_{H+A}, B_H\right) + w_A\left(l_A, L_{H+A}, B_A\right)} = \begin{cases} 1 & \text{if} \quad r \leqslant \left(\frac{\lambda}{RMR+\delta}\right)^{1-\alpha} \\ \frac{1}{1+r^{\frac{1}{1-\alpha}}} & \text{if} \quad r > \left(\frac{\lambda}{RMR+\delta}\right)^{1-\alpha} \end{cases}.$$

It follows that the fraction of income coming from hunting, as well as the share of labour allocated to hunting activities, decrease in r once agriculture is adopted.

1.3 A3

In order to compare the labour input of a forager (someone who uses hunting exclusively) to that of a farmer (someone who uses mixed activities), we need to know the respective labour input per individual in a Malthusian equilibrium. Inserting equation (2) into (1), it follows that the labour input of a forager in a Malthusian equilibrium is

$$l_H\left(l_H, L_H, B_H\right) = \frac{\alpha\left(RMR+\delta\right)}{\beta\left(1-\alpha\right)}.$$

By comparison, using the same calculation procedure, the labour input of a farmer is

$$l_H\left(l_H, L_{H+A}, B_H\right) + l_A\left(l_A, L_{H+A}, B_A\right) + \lambda = \frac{\alpha\left(\lambda+RMR+\delta\right)}{\beta\left(1-\alpha\right)} + \lambda.$$

It thus follows that farmers, in a Malthusian equilibrium, work more hours than foragers provided that $\lambda > 0$, i.e. that there are fixed costs associated with the use of agriculture. Similarly, it can be variefied that agriculturalists have higher incomes then hunters, i.e. that

$$w_H\left(l_H, L_{H+A}, B_H\right) + w_A\left(l_A, L_{H+A}, B_A\right) > w_H\left(l_H, L_H, B_H\right),$$

as long as $\lambda > 0$.

Finally, comparing equations (2) and (4), it follows that a society of farmers have higher population densities than those of foragers, given that equation (3) is fulfilled and farming is adopted.

Figure 1: Malthusian Equilibrium before Agriculture

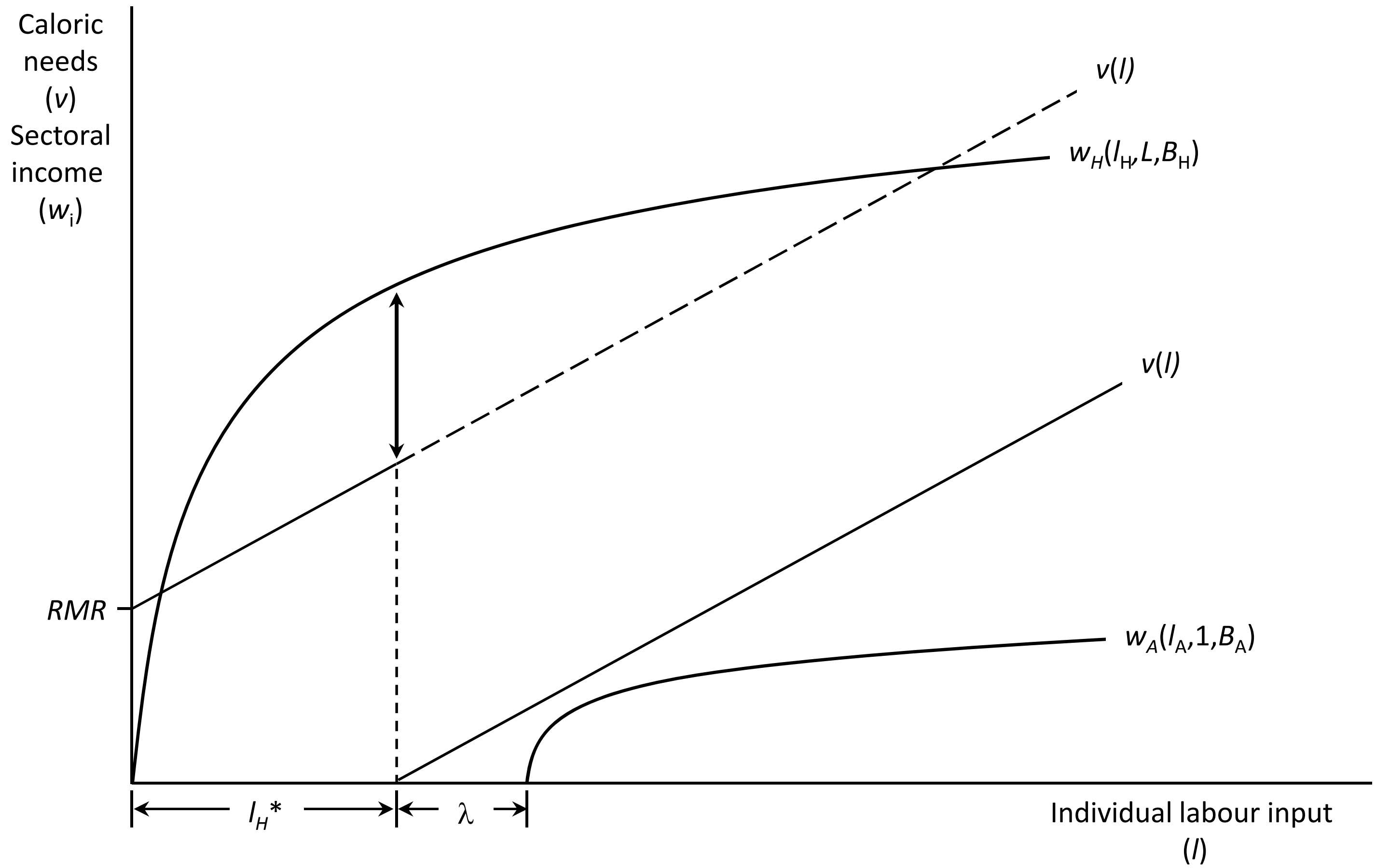


Figure 2: Agricultural Adoption

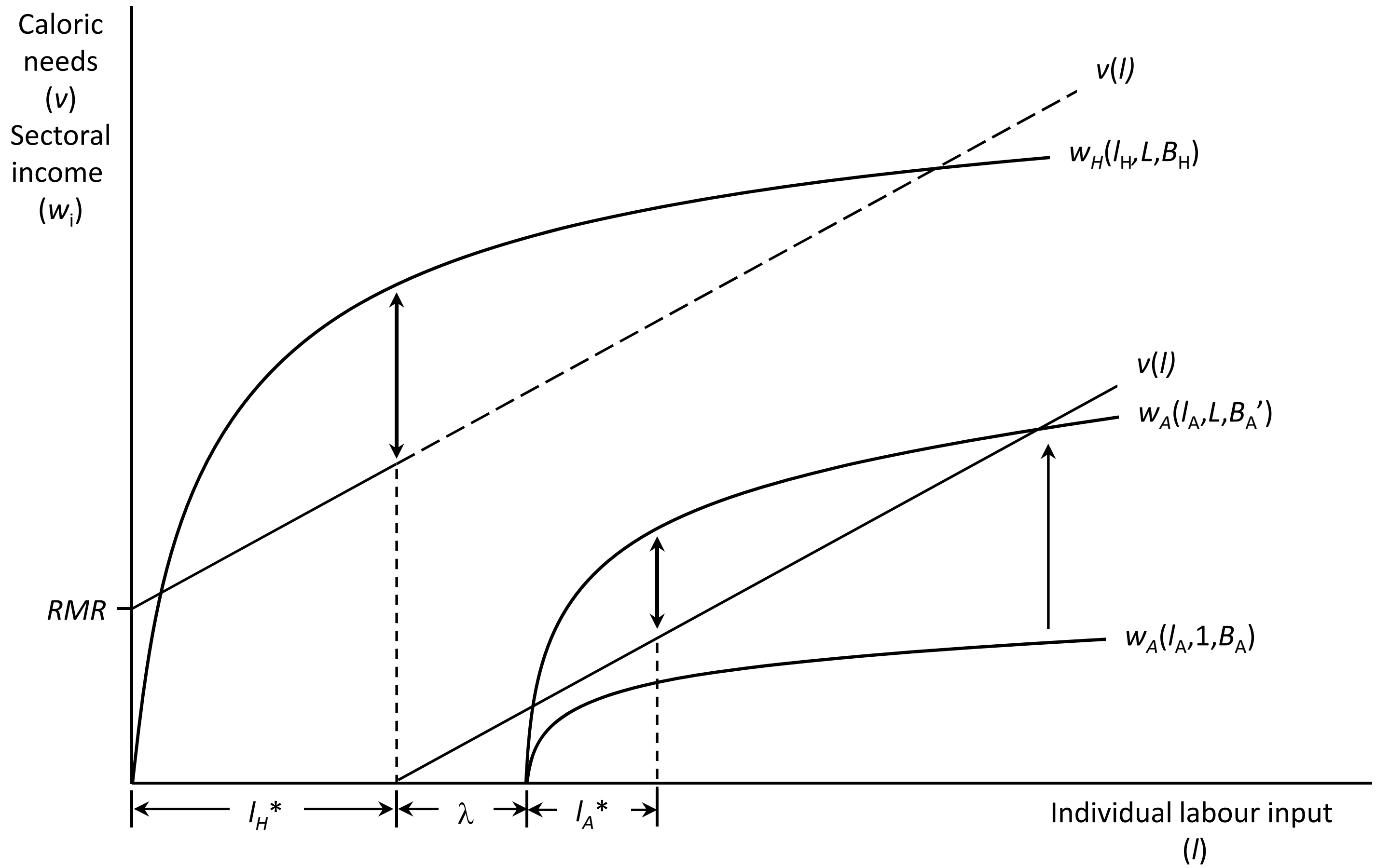


Figure 3: Malthusian Equilibrium after Agriculture

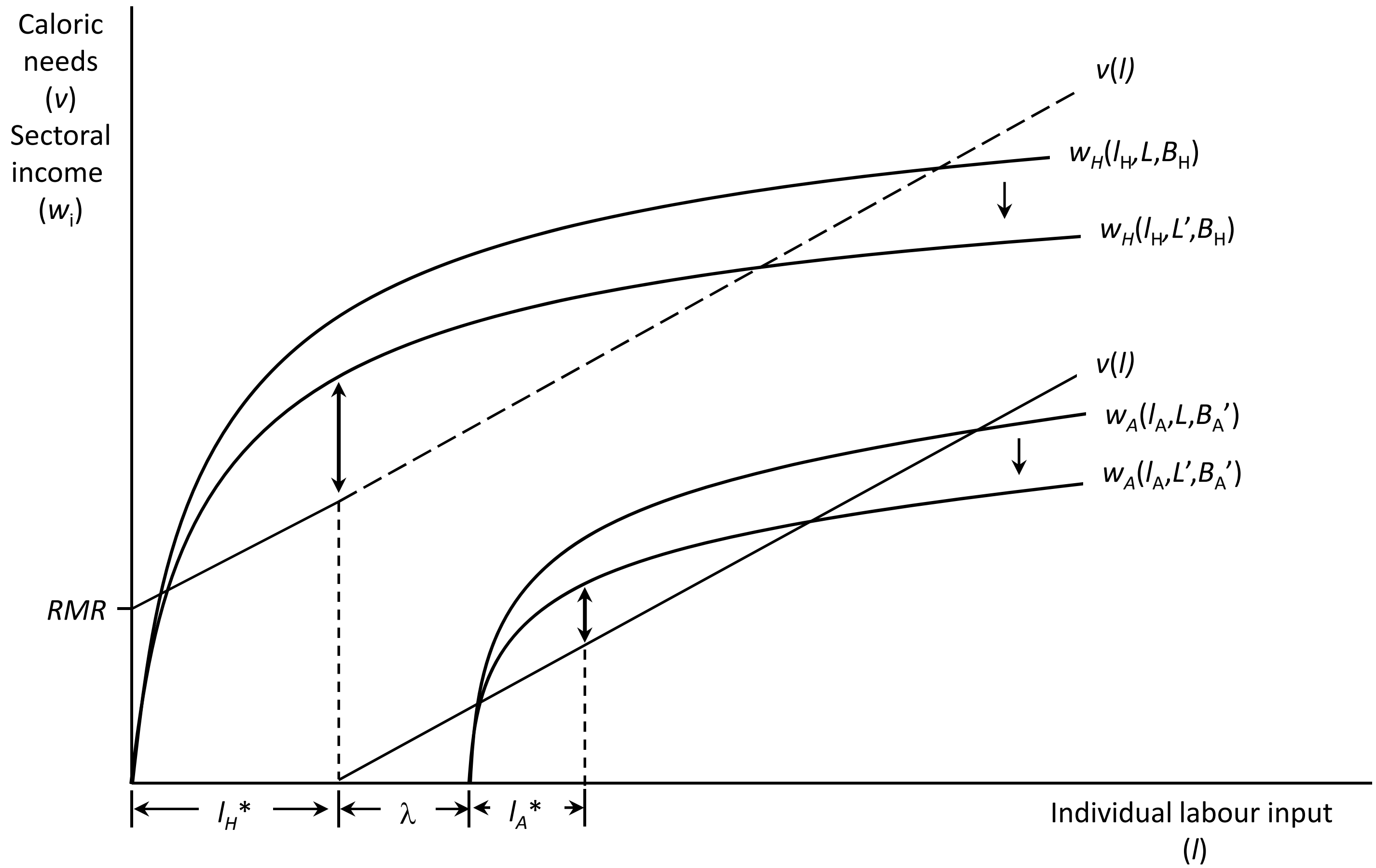
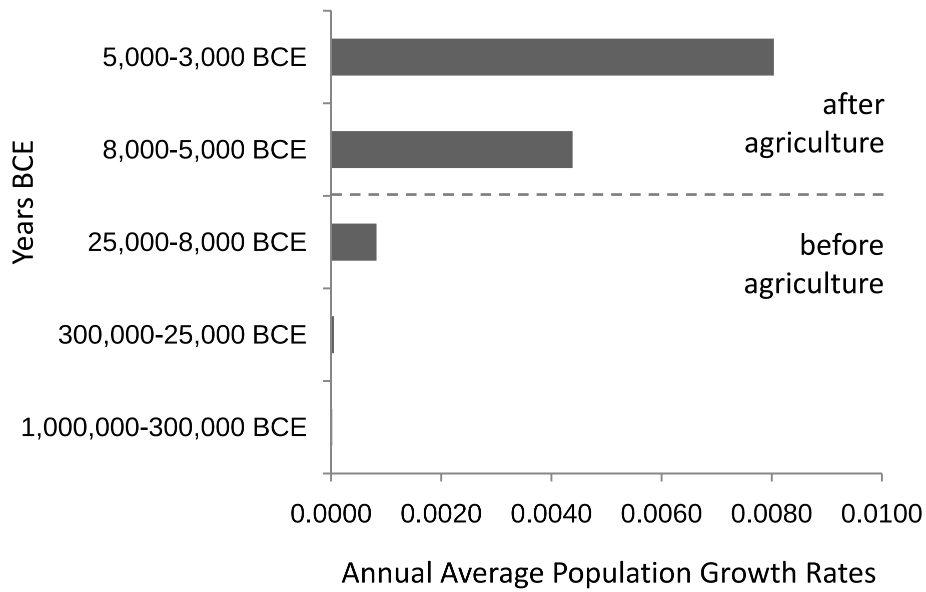


Figure 4: Population Growth before and after Agriculture



Source: Kremer (1993)