The Neolithic Revolution from a price-theoretic perspective

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Abstract

The adoption of agriculture, some 10,000 years ago, triggered the first demographic explosion in human history. When fertility fell back to its original level, early farmers found themselves worse fed than the previous hunter-gatherers, and worked longer hours to make ends meet. I develop a dynamic, price-theoretic model with endogenous fertility that rationalises these events. The results are driven by the reduction in the cost of children that followed the adoption of agriculture.

Keywords: Paleoeconomics; Neolithic Revolution; hunter-gatherers; Malthus.

1 Introduction

The shift from hunting and gathering to agriculture, or the Neolithic Revolution (10,000 to 5,000 B.P.), was followed by a sharp increase in fertility (Bocquet-Appel, 2002). In the course of a few centuries, typical communities grew from about 30 individuals to 300 or more, and population densities increased from less than one hunter-gatherer per square mile to 20 or more farmers (Johnson and Earle, 2000, pp. 43, 125, 246).

This demographic explosion has been attributed to two causes. First, food was available to early farmers in unprecedented quantities (Price and Gebauer, 1995). Second, children were much cheaper for early farmers than they were for hunter-gatherers, since caring for children interfered with hunting and gathering, but not with farming. More important, children of farmers could contribute to food production (Kramer and Boone 2002).

Although early farmers produced food in larger quantities, their nutrition was poorer than that of hunter-gatherers (Armelagos et al., 1991; Cohen and Armelagos, 1984). All the extra food was used by the farmers to support... more farmers. To make matters worse, working time increased after agriculture was adopted. Ethnographical studies indicate that hunter-gatherers worked less that six hours per day, whereas primitive horticulturists worked seven hours on average, and intensive agriculturalists worked nine (Sackett, 1996, pp. 338–42).

I develop a dynamic, price-theoretic model with endogenous fertility that makes sense of these perplexing events, provided some plausible conditions hold. In my model, a tribe of hunter-gatherers discovers agriculture and adopts it because doing so increases the return to labour and the productivity of children. As a result, fertility rises above the replacement rate, and population begins to grow. The return to labor, which is negatively related to population size, progressively falls. In the long-run, the return to labor settles *below* its original level. When the population restabilises, later generations of farmers are poorer, consume less food, and work longer hours than hunter-gatherers. Yet the later generations choose to remain farmers because, at their numbers, reverting to hunting and gathering would make them even worse off.

The increase in the productivity of children, which amounts to a fall in their price, drives the results of the model. Enhancements in food production technology have only one effect in the long-run: population growth.

To the best of my knowledge, my model of agriculture adoption is the first to include three goods in the tribesman's utility function: food consumption, leisure, and fertility. This allows me to evaluate the welfare effects of the adoption of agriculture, both in the short-run and in the long-run. The model assumes the tribesman freely chooses a bundle of the three goods, given his total income and the prices he faces. The return to labour varies endogenously with the size of the population. In the long-run, population adjusts so that the return to labour converges to the value at which the tribesman's optimal decision is to reproduce at the replacement rate. In sum, the model combines two notions of equilibrium: a market equilibrium that holds at all times, and a Malthusian equilibrium that guarantees population will be stable in the long-run.

2 Related literature

Theories of the adoption of agriculture have been extensively surveyed by Weisdorf (2005). I will thus limit this review to previous explanations for the loss of welfare that followed the adoption.

According to Weisdorf (2004), early farmers gave away leisure in exchange for goods produced by an emerging class of specialists (e.g., craftsmen and bureaucrats). Marceau and Myers (2006) model the fall in consumption and leisure as a tragedy of the commons. Both Weisdorf and Marceau and Myers assume population remains constant during the transition to agriculture.

Two papers, one by Weisdorf (2008) and the other by Robson (2008), address the demographic dimension of the transition.

Weisdorf incorporates Malthusian population principles into a model with two sectors: hunting and agriculture. In his model, the higher productivity of agriculture motivates its adoption, but the subsequent population growth swallows the benefits. Weisdorf assumes people's only desire in life is to reproduce, and that they will work as many hours as it takes to maximise their fertility. He also assumes food consumption is an increasing function of the energy spent at work, but does not incorporate food into the utility function.

Robson develops a model with two goods: children and their health. In Robson's model, infectious diseases become more prevalent as population increases. This makes the health of children more expensive for farmers than for the (less populous) hunter-gatherers. Farmers respond by having more children and investing less in their health than their predecessors.

3 A model of agriculture adoption

3.1 Model setup

A tribe has $N > 0$ identical adult members or tribesmen. A tribesman chooses food consumption $c > 0$, leisure $r > 0$, and the number of his children $n > 0$ in order to maximise utility function $u(c, r, n)$, which is increasing in all its arguments.[1] The tribesman is subject to the following budget constraint:

$$w \cdot (T - r + \alpha n) \geq c + \kappa n$$

Variable $w > 0$ is the return to labour in units of food, $T > 0$ is the tribesman's disposable time, and $T - r > 0$ is his labour supply. Parameter $\alpha \geq 0$ represents child productivity measured in man-hours. The children of hunter-gatherers don't contribute to production, so $\alpha = 0$. When agriculture is adopted, α rises to a positive amount. Parameter $\kappa > 0$ measures the food requirements of a child.

The budget constraint can be rewritten as follows:

$$I \geq c + p^r r + p^n n, \tag{1}$$

where $I = wT$ is total income, $p^r = w$ is the price of leisure, and $p^n = \kappa - \alpha w > 0$ is the price of children.

The return to labour w is a function of a technology parameter A and of population N. As usual, w is increasing in A. Following Malthus, I assume w falls with N. Using subscripts to denote partial derivatives, these assumptions translate into $w_A > 0$ and $w_N < 0$.

Population dynamics is governed by the following equation:

$$N' = nN,$$

where N' is next period's adult population.

In the short-run, population N is fixed and fertility n responds to income and prices. In the long-run, N adjusts so that the return to labour w converges to the value at which the tribesman's optimal decision is to bear children at

[1] There is ample evidence that pre-modern peoples deliberately chose the number of their children. The methods they used included abstinence, celibacy, prolonged breast-feeding, abortion, and infanticide (see Douglas, 1966, and Cashdan, 1985).

the replacement rate: $n = 1$. These assumptions link the model to the family of endogenous fertility models in which decreasing returns to labour act as a Malthusian population check. These models were pioneered by Razin and Ben-Zion (1975). Other examples are Boldrin and Jones (2002), Eckstein et al. (1988), and Nerlove et al. (1986).

Without loss of generality, let the tribesman's choices be summarised by the Marshallian demands that stem from his utility function:

$$\begin{aligned} c &= c^{\mathrm{m}}(p^r, p^n, I), \\ r &= r^{\mathrm{m}}(p^r, p^n, I), \\ n &= n^{\mathrm{m}}(p^r, p^n, I). \end{aligned}$$

3.2 Effects of the adoption of agriculture

I model the adoption of agriculture as two technological changes: an increase in child productivity α and an enhancement in food production technology A. Here, I explore the effects of both changes.

The effects of an increase in child productivity

Let A be constant. Totally differentiating w and the Marshallian demands with respect to α, we obtain a linear system for the effects of an increase in child productivity:

$$\begin{aligned} \mathrm{w}_\alpha &= w_N \mathrm{N}_\alpha, && (2) \\ \mathrm{c}_\alpha &= c^{\mathrm{m}}_{p^r}\ \mathrm{w}_\alpha + c^{\mathrm{m}}_{p^n} \cdot (-w - \alpha \mathrm{w}_\alpha) + c^{\mathrm{m}}_I\ \mathrm{w}_\alpha T, && (3) \\ \mathrm{r}_\alpha &= r^{\mathrm{m}}_{p^r}\ \mathrm{w}_\alpha + r^{\mathrm{m}}_{p^n} \cdot (-w - \alpha \mathrm{w}_\alpha) + r^{\mathrm{m}}_I\ \mathrm{w}_\alpha T, && (4) \\ \mathrm{n}_\alpha &= n^{\mathrm{m}}_{p^r} \underbrace{\mathrm{w}_\alpha}_{\frac{\mathrm{d}p^r}{\mathrm{d}\alpha}} + n^{\mathrm{m}}_{p^n} \cdot \underbrace{(-w - \alpha \mathrm{w}_\alpha)}_{\frac{\mathrm{d}p^n}{\mathrm{d}\alpha}} + n^{\mathrm{m}}_I \underbrace{\mathrm{w}_\alpha T}_{\frac{\mathrm{d}I}{\mathrm{d}\alpha}}, && (5) \end{aligned}$$

where w_α, c_α, r_α, n_α, and N_α are the unknown total derivatives. The system is closed with $\mathrm{N}^{\mathrm{SR}}_\alpha = 0$ for the short-run, and with $\mathrm{n}^{\mathrm{LR}}_\alpha = 0$ for the long-run, where superscripts SR and LR distinguish short-run and long-run solutions.

We now search for conditions that suffice to reproduce the stylised facts of the Neolithic revolution: a short-run fertility rise ($\mathrm{n}^{\mathrm{SR}}_\alpha > 0$), a long-run increase in population ($\mathrm{N}^{\mathrm{LR}}_\alpha > 0$), and long-run falls in food consumption and leisure ($\mathrm{c}^{\mathrm{LR}}_\alpha < 0$ and $\mathrm{r}^{\mathrm{LR}}_\alpha < 0$).

Initially, the tribesman hunts and gathers, so $\alpha = 0$. Replacing $\alpha = 0$ in equations (3)–(5), we get:

$$\mathrm{c}_\alpha = (c^{\mathrm{m}}_{p^r} + c^{\mathrm{m}}_I T)\mathrm{w}_\alpha - wc^m_{p^n}, \tag{6}$$

$$\mathrm{r}_\alpha = (r^{\mathrm{m}}_{p^r} + r^{\mathrm{m}}_I T)\mathrm{w}_\alpha - wr^m_{p^n}, \tag{7}$$

$$\mathrm{n}_\alpha = (n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T)\mathrm{w}_\alpha - wn^m_{p^n}. \tag{8}$$

From equations (2) and (8), plus condition $\mathrm{N}^{\mathrm{SR}}_\alpha = 0$ we obtain:

$$\mathrm{w}^{\mathrm{SR}}_\alpha = 0,$$

$$\mathrm{n}^{\mathrm{SR}}_\alpha = -wn^m_{p^n}. \tag{9}$$

The return to labour w remains constant in the short-run ($\mathrm{w}^{\mathrm{SR}}_\alpha = 0$), because in the short-run population is fixed. Equation (9) tells us that fertility n will increase in the short-run if α increases and the demand for children has a negative slope: $n^m_{p^n} < 0$.

Should the tribesman adopt agriculture? Yes, and this is why. The return to labour remains constant in the short-run, and that implies total income and the price of leisure remain constant as well:

$$\left.\frac{\mathrm{d}I}{\mathrm{d}\alpha}\right|^{\mathrm{SR}} = T\mathrm{w}^{\mathrm{SR}}_\alpha = 0,$$

$$\left.\frac{\mathrm{d}p^r}{\mathrm{d}\alpha}\right|^{\mathrm{SR}} = \mathrm{w}^{\mathrm{SR}}_\alpha = 0.$$

But adopting agriculture increases α, which brings the price of children down:

$$\left.\frac{\mathrm{d}p^n}{\mathrm{d}\alpha}\right|^{\mathrm{SR}} = -w < 0,$$

The fall in p^n, while I and p^r stay unchanged, pushes the tribesman's budget constraint outwards, unambiguously increasing his utility.

From equations (2) and (6)–(8), plus condition $\mathrm{n}^{\mathrm{LR}}_\alpha = 0$ we get the long-run comparative statics:

$$\mathrm{w}^{\mathrm{LR}}_\alpha = \frac{wn^{\mathrm{m}}_{p^n}}{n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T},$$

$$\mathrm{c}^{\mathrm{LR}}_\alpha = \frac{c^{\mathrm{m}}_{p^r} + c^{\mathrm{m}}_I T}{n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T} wn^{\mathrm{m}}_{p^n} - wc^{\mathrm{m}}_{p^n}, \tag{10}$$

$$\mathrm{r}^{\mathrm{LR}}_\alpha = \frac{r^{\mathrm{m}}_{p^r} + r^{\mathrm{m}}_I T}{n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T} wn^{\mathrm{m}}_{p^n} - wr^{\mathrm{m}}_{p^n}, \tag{11}$$

$$\mathrm{N}^{\mathrm{LR}}_\alpha = \frac{wn^{\mathrm{m}}_{p^n}}{w_N \cdot (n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T)} \tag{12}$$

Equations (9)–(12) yield a set of sufficient conditions for fertility to rise in the short-run, population to increase in the long-run, and food consumption and leisure to fall in the long-run:

1. The return to labour is decreasing in population: $w_N < 0$.
2. The Marshallian demand for children has a negative slope: $n^m_{p^n} < 0$.
3. The demand for children is increasing in the return to labour: $\mathrm{n}_w = n^{\mathrm{m}}_{p^r} + Tn^{\mathrm{m}}_I > 0$. This condition can be interpreted in terms of child labour supply: the supply of child labour increases when the return to their labour increases.
4. Consumption is a normal good, and a gross substitute of leisure and children: $c^{\mathrm{m}}_I, c^{\mathrm{m}}_{p^r}, c^{\mathrm{m}}_{p^n} > 0$.
5. Leisure is a gross substitute of children: $r^m_{p^n} > 0$.
6. Leisure is decreasing in the return to labour: $\mathrm{r}_w = r^{\mathrm{m}}_{p^r} + r^{\mathrm{m}}_I T < 0$.
7. Leisure is more responsive to changes in the return to labour than to changes in the price of children: $|r^{\mathrm{m}}_{p^r} + r^{\mathrm{m}}_I T| > r^{\mathrm{m}}_{p^n}$.
8. Fertility is more responsive to changes in the price of children than to changes in the return to labour: $n^{\mathrm{m}}_{p^r} + n^{\mathrm{m}}_I T < |n^{\mathrm{m}}_{p^n}|$.

Later generations of farmers don't revert to hunting and gathering because that would increase the price of children, while total income and the price of leisure remain constant. The farmers' welfare would thus fall in the short-run. At their numbers, hunting and gathering is no longer an option... The farmers are trapped in a nasty equilibrium with lots of people, low incomes, scanty food, and too much work.

What lies behind these puzzling results?

An increase in the productivity of children promotes a present and future rise in fertility, because more productive children are cheaper:

$$\left.\frac{\mathrm{d}p^n}{\mathrm{d}\alpha}\right|^{\mathrm{SR}} = \left.\frac{\mathrm{d}p^n}{\mathrm{d}\alpha}\right|^{\mathrm{LR}} = -w < 0.$$

But equilibrium requires later generations to reproduce at the replacement rate ($n = 1$). Since children will remain cheap in the long-run, the return to labour must fall below its original level ($\mathrm{w}^{\mathrm{LR}}_\alpha < 0$) to induce future generations to limit their fertility to one child per capita. The fall in the return to labour is achieved through the increase in population ($\mathrm{N}^{\mathrm{LR}}_\alpha > 0$) that results from a temporary increase in fertility ($\mathrm{n}^{\mathrm{SR}}_\alpha > 0$).

In addition, the long-run reduction in the return to labour implies the price of leisure will fall:

$$\left.\frac{\mathrm{d}p^r}{\mathrm{d}\alpha}\right|^{\mathrm{LR}} = \mathrm{w}^{\mathrm{LR}}_\alpha < 0.$$

Because food is a normal good and a gross substitute of leisure and children, the long-run reductions in I, p^r and in p^n will all push food consumption downwards ($\mathrm{c}_\alpha^{\scriptscriptstyle\mathrm{LR}} < 0$).

Two opposing forces act upon leisure in the long-run. On the one hand, leisure will be cheaper, so the tribesmen will tend to rest more and work less. On the other hand, total income will be lower and children will be cheaper: since leisure is a normal good and a gross substitute of children, the tribesmen will want to reduce leisure and increase working hours. Conditions 7 and 8 guarantee the second effect will dominate the first, so leisure decreases in the long-run ($\mathrm{r}_\alpha^{\scriptscriptstyle\mathrm{LR}} < 0$).

The effects of enhancements in food production technology

Let α be constant. Totally differentiating w and the Marshallian demands with respect to A, we obtain a linear system for the effects of enhancements in the food production technology:

$$\begin{aligned}
\mathrm{w}_A &= w_A + w_N \mathrm{N}_A, \\
\mathrm{c}_A &= c^{\mathrm{m}}_{p^r}\ \mathrm{w}_A + c^{\mathrm{m}}_{p^n} \cdot (-\alpha \mathrm{w}_A) + c^{\mathrm{m}}_I\ \mathrm{w}_A T, \\
\mathrm{r}_A &= r^{\mathrm{m}}_{p^r}\ \mathrm{w}_A + r^{\mathrm{m}}_{p^n} \cdot (-\alpha \mathrm{w}_A) + r^{\mathrm{m}}_I\ \mathrm{w}_A T, \\
\mathrm{n}_A &= n^{\mathrm{m}}_{p^r} \underbrace{\mathrm{w}_A}_{\frac{\mathrm{d}p^r}{\mathrm{d}A}} + n^{\mathrm{m}}_{p^n} \cdot \underbrace{(-\alpha \mathrm{w}_A)}_{\frac{\mathrm{d}p^n}{\mathrm{d}A}} + n^{\mathrm{m}}_I \underbrace{\mathrm{w}_A T}_{\frac{\mathrm{d}I}{\mathrm{d}A}},
\end{aligned}$$

where w_A, c_A, r_A, n_A, and N_A are the unknown total derivatives. The system is closed with $\mathrm{N}_A^{\scriptscriptstyle\mathrm{SR}} = 0$ for the short-run, and with $\mathrm{n}_A^{\scriptscriptstyle\mathrm{LR}} = 0$ for the long-run.

Using $\alpha = 0$, the system boils down to:

$$\begin{aligned}
\mathrm{w}_A &= w_A + w_N \mathrm{N}_A, \\
\mathrm{c}_A &= c^m_{p^r}\, \mathrm{w}_A + c^m_I\, \mathrm{w}_A T, \\
\mathrm{r}_A &= r^m_{p^r}\, \mathrm{w}_A + r^m_I\, \mathrm{w}_A T, \\
\mathrm{n}_A &= n^m_{p^r} \mathrm{w}_A + n^m_I \mathrm{w}_A T
\end{aligned}$$

Under the conditions stated in the previous section, we obtain:

$$\begin{aligned}
\mathrm{w}_A^{\scriptscriptstyle\mathrm{SR}} &= w_A > 0, \\
\mathrm{n}_A^{\scriptscriptstyle\mathrm{SR}} &= n^m_{p^r} w_A + n^m_I w_A T > 0, \\
\mathrm{w}_A^{\scriptscriptstyle\mathrm{LR}} &= \mathrm{c}_A^{\scriptscriptstyle\mathrm{LR}} = \mathrm{r}_A^{\scriptscriptstyle\mathrm{LR}} = \mathrm{n}_A^{\scriptscriptstyle\mathrm{LR}} = 0, \\
\mathrm{N}_A^{\scriptscriptstyle\mathrm{LR}} &= -\frac{w_A}{w_N} > 0.
\end{aligned}$$

It follows that the return to labour rises in the short-run and so does fertility, and that the only long-run effect of a larger A is an increase in population. Consumption and leisure don't change in the long-run because neither total income nor prices change:

$$
\begin{aligned}
\left.\frac{\mathrm{d}I}{\mathrm{d}A}\right|^{\mathrm{LR}} &= T\mathrm{w}_A^{\mathrm{LR}} = 0 \\
\left.\frac{\mathrm{d}p^r}{\mathrm{d}A}\right|^{\mathrm{LR}} &= \mathrm{w}_A^{\mathrm{LR}} = 0 \\
\left.\frac{\mathrm{d}p^n}{\mathrm{d}A}\right|^{\mathrm{LR}} &= 0
\end{aligned}
$$

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