

# A “BIOECONOMIC” VIEW OF THE NEOLITHIC AND RECENT DEMOGRAPHIC TRANSITIONS\*

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## ABSTRACT

The demographic transitions here are associated with: 1) The shift from hunting and gathering to agriculture. 2) The industrial revolution. There are puzzles associated with both of these. In the neolithic transition to agriculture, humans became less well-fed, smaller, more prone to disease and lived shorter lives. Why then was this new system chosen? During the second, or “recent,” transition, fertility fell markedly, despite an overall rise in income. Why did individuals not use the extra income to produce more offspring? The present paper develops a simple biological model, with two age classes, that reproduces the key phenomena in these two transitions.

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## I. INTRODUCTION

The underlying aim of the present paper is to reverse, at least partially, the usual implicit causal relationship between economics and biology. That is, instead of taking biology as the effectively exogenous and usually unexamined background for modern economic behavior, the economics of hunting and gathering societies is taken as the setting in which biological evolution formed human characteristics. In particular, the huge intergenerational resource flows in human societies shaped preferences towards the quantity and quality of children that help to relate and explain two remarkable episodes in human history.

The first of these episodes was the displacement of hunting and gathering (foraging) by agriculture. Agriculture began perhaps ten thousand years ago in the fertile crescent in the Middle East, and not long after that in China and in the Western Hemisphere. There was not an immediate unambiguous improvement in the human condition following this shift. Apparently, instead, malnutrition became more common, humans became smaller, infectious diseases became more prevalent, and mean age at death decreased. How can these effects be reconciled with the relentless spread of agriculture across Europe? Why does this not violate any reasonable account of rational individual choice?

The second episode is more recent and better documented. During the industrial revolution in 19th century Europe, mortality rates first fell markedly, but then, a little later, birth rates also declined. Overall population growth rose, but then declined back to a moderate level, with lower mortality rates and birth rates than before. Incomes rose on average during this recent transition. How can such rising incomes be reconciled with lower fertility?

What economic preferences would be consistent with these observations? Is this not a clear violation of the biological imperative to maximize the number of offspring?

The present paper shows that these phenomena in the two demographic transitions are generated by variants of the same simple model. In this model, there are two overlapping age classes—young and adult. Young individuals are subject to mortality, so not all of them survive to be adult. A key assumption is that the adults determine both the quantity of their offspring and the capital invested in each of them. The approach here is biological in the basic sense that individuals maximize the long-run number of descendants. However, this goal is accomplished by maximizing the total output of all of one's immediate descendants, or the product of the number of offspring and the quality of each of them (as is also economically plausible). A further biological aspect is that there are feedback effects from the size of the population that eventually choke off growth. One such feedback effect reduces individual output, reflecting limited natural resources such as land.

To model the neolithic transition, in particular, the capital invested in offspring is interpreted as somatic capital, that is, as the energy used to build the body of each individual. In this setting, the probability of individual survival incorporates another negative feedback effect from increased population, that arising from increased infectious disease. The instigating factor in the neolithic transition is a technology shift to agriculture that raises productivity. This implies that individuals would prefer agriculture over foraging if both economic systems were available. The model then predicts that the transition will raise mortality, because it raises population, in the long run. Fertility rises but somatic capital

falls, also in this long run. Thus individuals put greater emphasis on the quantity of children at the expense of their somatic capital endowment. Intuitively, quality relates to the potential number of grandchildren, so that quality is affected twice as much as is quantity by the increase in mortality. Finally, detailed dynamic properties of the transition are derived, with short-run effects that exaggerate those arising in the long run.

To capture the more recent transition, an interpretation of capital as human capital, such as education, is favored. Now mortality is taken to be a basic instigating factor for the transition. It is subjected to an exogenous decrease, reflecting the advent of cheap but effective public health measures. As a complementary factor, productivity rises due to industrialization. In the long run, the combined effects of better health and industrialization raise population, human capital, and income. Fertility, on the other hand, is predicted to fall. Intuitively, again, quality is affected more than is quantity by the decrease in mortality. Finally, detailed dynamic properties of the model are derived. Fertility is predicted to rise in the short run, as is characteristic of the actual transition in many countries. Similarly, income may fall in the short run, and there is evidence consistent with this prediction also.

The model then dispels the paradoxical flavor of the data on the neolithic transition. Although this model is fundamentally Darwinian, the induced preferences over quantity and quality of offspring are economically reasonable. In terms of these, individuals would prefer agriculture to foraging, despite the litany of ill-effects ultimately brought about. The model also resolves the key puzzle of the recent 19th century demographic transition. That is, in terms of the same preferences, individuals would choose lower fertility despite higher incomes.

Altogether, the success of the model in accounting for two phenomena that occurred in very different historical settings encourages faith in this approach. From a practical point of view, understanding the recent demographic transition is obviously very important. The present analysis increases confidence in the prediction that birth rates will fall in societies currently in the early stages of such a transition.

## II. THE NEOLITHIC TRANSITION TO AGRICULTURE

### *II.A. Facts and Issues*

#### *II.A.1. The Spread of Agriculture in Europe, Population Growth*

The large scale adoption of agriculture and a settled way of life at the expense of hunting and gathering occurred a remarkably short time ago. Agriculture seems to have arisen in the fertile crescent in the Middle East roughly 10,000 years ago. It started spreading about 9,000 years ago, taking about 4,000 years to spread to the northern and western fringes of Europe—Scandinavia, England and Spain—moving at about 1 kilometer a year. This transition was associated with a sharp rise in population. Cavalli-Sforza and Cavalli-Sforza [1995, Chapter 6] discuss the traces that this left in the modern European gene pool. (See also Ammerman and Cavalli-Sforza [1984], and Cavalli-Sforza, Menozzi and Piazza [1994, Chapter 5.11].)

Indeed the first principal component of the present genetic geographic distribution generates a map that matches well the map of the arrival date of agriculture as estimated from radiocarbon dating of the earliest associated remains. Cavalli-Sforza and Cavalli-Sforza

[1995] hypothesize that the genotype of the hunter-gatherers originally in the fertile crescent differed noticeably from those in Europe. As the population of farmers rose, there was a wave of emigration into neighboring lands. The genotype of these emigrants was then diluted by that of the original hunter-gatherer inhabitants so, as this wave progressed further away from the Middle East, the resulting dilution increased. Cavalli-Sforza and Cavalli-Sforza emphasize that the spread of agriculture was not purely the spread of an idea, but involved the movement of people themselves. (Corroborating evidence is provided by Gray and Atkinson [2003], who use statistical linguistic analysis to infer that the English language, for example, originated about 9,000 years ago in what is now Turkey.)

More direct evidence concerning the sharp rise in population following the transition to agriculture is provided by Bocquet-Appel [2002], who studies the age distribution of skeletons found in neolithic graveyards. Other things equal, that is, the higher the proportion of skeletons of the young, the more rapidly growing the population is deduced to have been. He finds such evidence of a wave of population growth spreading across Europe that is consistent with the genetic and radiocarbon evidence.

#### *II.A.2 Evidence on Health, Nutrition, Stature and Life Expectancy.*

Inevitably enough this transition was once considered a necessary first step towards modern industrial society—part of the triumphant march of human progress. Recently, however, a much more interesting possibility has been emerging. (Diamond [1997, Chapters 4-10], and Tudge [1998], provide informal accounts of this new view. The basic reference for all the following precise evidence is Cohen and Armelagos [1984]. This is a symposium of work

on the effect of this transformation world-wide, as summarized in Chapter 23. Steckel and Rose [2002] is a more recent symposium, concentrating on the Western Hemisphere, but coming to generally similar conclusions.)

In the first place, the greater incidence of skeletal lesions suggest that the adoption of agriculture was associated with a rise in infectious disease. Such diseases may have been less prevalent among hunter-gatherers because of their low population densities, but have become more prevalent with the greater densities implied by agriculture.

In the second place, and verging on the paradoxical, the advent of agriculture was apparently associated with a higher incidence of chronic malnutrition. Evidence for this can be found in the porosity of the skull associated with anemia, since the likely cause of this latter disorder is inadequate nutrition. Indeed, agriculture seems not even to have reduced the variability in the food supply from that under foraging. The occasional famine caused by crop failure may have been more severe than the shortfalls in food obtained from foraging. This is suggested by evidence of physiological stress, such as irregular growth patterns of bones and, particularly, dental enamel. As a result of this worsening in the food supply, there may have also been a concomitant decrease in physical stature.

On the other hand, it may be that hunting and gathering was more physically demanding than was agriculture, although this might be a matter of peak effort rather than the total work load. This is suggested by a possible reduction in arthritis, for example, after the advent of agriculture.

Finally, estimates of the age at death for the skeletons that are available, combined

with estimates of the steady state growth rate of the population, suggest a decrease in life expectancy occurred with agriculture.

### *II.A.3. Issues*

The conclusions drawn here have not escaped criticism, notably from Wood *et al* [1992], who suggest, for example, that the data are equally consistent with an improvement in health in the transition from foraging to agriculture. That is, the presence of bone lesions in a particular skeleton might mean that this individual was actually more resistant to the associated diseases than was another individual who succumbed before forming any such lesions. If there were a decrease in disease with the transition, the adoption of agriculture would be less puzzling from a rational choice perspective. On the other hand, the increase in population density makes an increase in infectious disease otherwise among the least surprising of the conclusions drawn above.

The best way to address such issues is consider additional evidence. For example, recent populations in which infectious diseases were largely untreated could illuminate whether there is a positive or negative correlation between bone lesions in skeletons and the incidence of disease among the living. Further, such populations could demonstrate the correlation between population density and the incidence of disease. Indeed, the perhaps surprising affluence and health of present day hunter-gatherers helps to reinforce the original conclusions. Sahlins [1988] indeed coined the phrase “the original affluent society” to reflect the apparent high productivity of the !Kung, for example, in acquiring plant and animal food. (Sahlins argues, however, that this affluence of the !Kung is achieved in part by lowered

expectations.) Robson and Kaplan [2003] also summarize data from a number of sources showing that hunter-gatherers have surprisingly low mortality rates and high life expectancy.

Suppose the original interpretations then withstand further scrutiny. This raises the awkward question: Why would individuals have chosen to participate in agriculture at the expense of foraging? Why did agriculture spread? The present paper shows that the original “naive” interpretations do not, in any case, conflict with a straightforward biological explanation.

### *II.B Model A.*

The model here shows that a rise in population results if agriculture raises per capita productivity or output. The above evidence concerning a reduction in life expectancy is compatible with that on the increase in disease. The model incorporates these as effects arising from the increased population density due to agriculture. The increase in mortality now tends to reduce somatic capital, or stature, as is also consistent with the evidence. At the same time, fertility is predicted to rise, so individuals make a different trade-off between the quality and quantity of offspring.

The emphasis in the present paper is thus on why the transition to agriculture had the effects that it apparently did. The important question of why the transition occurred when it did is given less emphasis. (But see Section II. C for discussion of some explanations that have been put forward.)

In detail then, consider a population in which there are just two overlapping age classes— young and adult. For simplicity, individuals reproduce asexually. Subject to her income,

each adult chooses the quantity of her offspring and the amount of capital,  $K$ , say, invested in each of these. In this neolithic setting, capital is interpreted as somatic or embodied capital, reflecting stature and strength. Undoubtedly, this is subject to genetic influence, which might entail only slow modification. However, somatic capital is also subject to rapid discretionary change, since it is greatly affected by nutrition, especially during growth.

Adult output is then a function of somatic capital,  $K > 0$ . Additional arguments of output are the total number of adults,  $N \geq 0$ , and a parameter,  $\alpha$ , to reflect greater reliance on agriculture. The following restrictions are then imposed on the production function,  $F$  :

Assumption 1. i) As a function of  $K$ , the production function for adult output is similar to that used in the theory of perfect competition. More precisely, for some  $\bar{K} > 0$  and each  $N \geq 0$  and  $\alpha$ , there exists  $\bar{K}(N, \alpha) \geq \bar{K}$ , such that  $F(K, N, \alpha) = 0$ , for  $K \in [0, \bar{K}(N, \alpha)]$ ;  $F_K(K, N, \alpha) > 0$  and  $F_{KK}(K, N, \alpha) < 0$ , for all  $K > \bar{K}(N, \alpha)$ ; and  $F_K(K, N, \alpha) \rightarrow 0$ , as  $K \rightarrow \infty$ .

ii) The shift to agriculture is advantageous, in that  $F_\alpha(K, N, \alpha) > 0$ . On the other hand, an increase in the number of adults,  $N$ , decreases output, since there are fixed factors such as land. That is,  $F_N(K, N, \alpha) < 0$ . The transition to agriculture does not increase the marginal productivity of somatic capital, so that  $F_{K\alpha}(K, N, \alpha) \leq 0$ . Similarly, neither does a larger population increase the marginal product of capital, so that  $F_{KN}(K, N, \alpha) \leq 0$ .

The assumptions concerning the dependence of output on capital are represented in

Figure 1. There is then a unique capital stock that maximizes the average product of capital. The parameter  $\bar{K}$  is a lower bound on the amount of capital that can be invested in each offspring.

The greater energy productivity of agriculture assumed here would be reinforced, in the present Model A, by the presumably lower net energy cost of raising each child under agriculture than under foraging. With respect to the assumption that  $F_{K\alpha}(K, N, \alpha) \leq 0$ , it is plausible that, although primitive agriculture was physically demanding, primitive hunting was even more so, requiring substantial strength, agility and endurance. In the same spirit,  $F_{KN}(K, N, \alpha) \leq 0$ . Although many of the results below follow if  $F_{KN}(K, N, \alpha)$  is sufficiently small in absolute terms, the present assumption is for simplicity.

Note that  $K$  might also be interpreted as human capital, as learning by doing, for example. The cognitive demands of foraging are indeed likely to be at least comparable to those of agriculture, so that the above restrictions on the production function would still hold. (Robson and Kaplan [2003] present evidence on the demands of hunting.) More generally, there might be two distinct capital stocks—somatic and human. There is no reason to suspect that this more complex model would yield qualitatively different results, however.

The transition from young to adult is governed as follows:

Assumption 2. The probability of survival from young to adult is  $p(N) \in (0, 1)$ , where  $p'(N) < 0$ , for all  $N \geq 0$ .

That is, perhaps the key feedback effect of population  $N$  is on survival, reflecting the in-

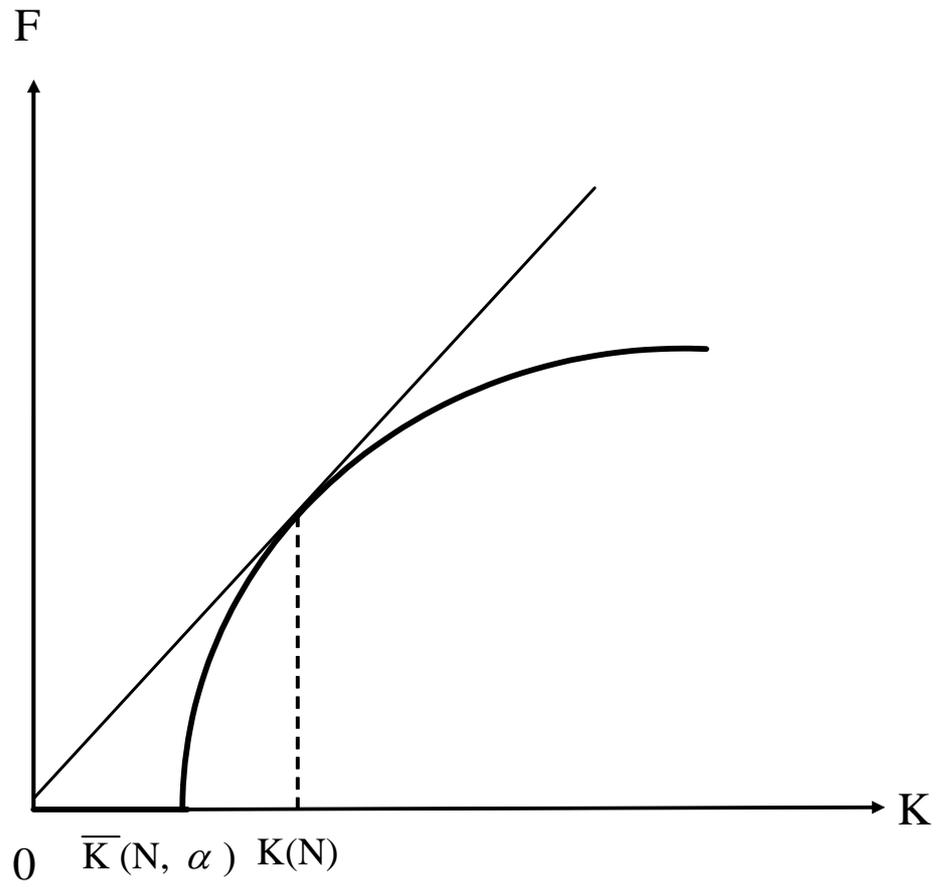


Figure 1: Adult Energy Output

creased prevalence of infectious diseases in a denser population.

An important generalization of the model here would be to allow mortality to be influenced by individual choice. For example, if an individual dedicated more energy to immune function, by increasing the range and depth of antigens, this could increase survival. Perhaps the simplest way to make individual choices matter like this would be for somatic capital to be an additional argument of survival probability, so that this became  $p(K, N)$ , where  $p_K(K, N) > 0$ . Thus greater investment in somatic capital would increase survival as well as adult output. Similar results to those here can then be obtained if the function  $p(K, N)F(K, N, \alpha)$  satisfies restrictions analogous to those imposed on  $F(K, N, \alpha)$  alone in Assumption 1.

### *II.B.1 The Equilibrium Steady State*

In any steady state such that  $N$  is constant, the ratio of adults to the young is  $p$ , so economic feasibility yields the following characterization:  $p(N)F(K, N, \alpha) = K$ . This model then gives a prominent role to intergenerational transfers from adults to the young. (See Robson and Kaplan [2003] for data from hunter-gatherer societies concerning the magnitude of these transfers.) Consider further an “equilibrium steady state” where, in addition to this steady state condition,  $K$  solves  $\max_{K \geq \bar{K}} \frac{F(K, N, \alpha)}{K}$  :

Lemma 1. From Assumption 1, it follows that, for each  $N \geq 0$ , there exists a unique optimal  $K \geq \bar{K} > 0$ ,  $K(N)$ , say, maximizing  $\frac{F(K, N, \alpha)}{K}$ . If, as additional hypotheses,  $\frac{p(0)F(K(0), 0, \alpha)}{K(0)} > 1$ , but  $\frac{p(N)F(K(N), N, \alpha)}{K(N)} < 1$ , when  $N$  is large enough,

there exists a unique equilibrium steady state,  $(N, K(N)) \gg 0$ . This is the only solution for  $N \geq 0$  and  $K \geq \bar{K}$  of

$$p(N)F_K(K, N, \alpha) = 1 \text{ and } p(N)F(K, N, \alpha) = K. \quad (1)$$

*Proof.* Assumption 1 implies that, for each  $N \geq 0$ , there exists a unique optimal  $K(N) \geq \bar{K}$  maximizing  $\frac{F(K, N, \alpha)}{K}$ . Further, if  $V(N) = \frac{p(N)F(K(N), N, \alpha)}{K(N)}$ , then  $V'(N) = \frac{p'F + pF_N}{K} < 0$ . Given that  $V(0) > 1$ , and  $V(N) < 1$ , for large  $N$ , existence of the unique equilibrium steady state follows. Finally,  $K(N)$  is the only solution for  $K > \bar{K}(N, \alpha)$ , of the first-order condition  $F_K(K, N, \alpha)K = F(K, N, \alpha)$ . It follows that the equilibrium steady state is the only solution for  $N \geq 0$  and  $K \geq \bar{K}$  of  $p(N)F(K, N, \alpha) = K$  and  $p(N)F_K(K, N, \alpha) = 1$ . ■

This equilibrium steady state has the property that any alternative type that enters in small numbers will do worse in terms of ultimate descendants, so this state is the long run prediction of the model. (This result can be extended to a population that is not in a steady state. See Section II.B.4.) To see that this property holds, note that, if a given adult has income  $F(K_0, N, \alpha)$ , the number of her adult descendants at date  $t + 1$  is

$$\begin{aligned} \frac{F(K_0, N, \alpha)}{K_1} p(N) \frac{F(K_1, N, \alpha)}{K_2} p(N) \dots \frac{F(K_t, N, \alpha)}{K_{t+1}} p(N) = \\ \frac{F(K_0, N, \alpha)}{K_{t+1}} p(N)^{t+1} \prod_{\tau=1}^t \frac{F(K_\tau, N, \alpha)}{K_\tau}. \end{aligned} \quad (2)$$

Indeed, this follows since the fertility of the adult descendant at any date  $\tau$  is  $\frac{F(K_\tau, N, \alpha)}{K_{\tau+1}} \equiv f_\tau$ , say. Although maximizing the number of offspring at any given date  $t + 1$  involves choosing  $K_{t+1} = \bar{K}$ , it nevertheless follows that any type that does not maximize  $\frac{F(K_t, N, \alpha)}{K_t}$  at every date  $t$  is *eventually* dominated by the type that does this:

Lemma 2. Consider an equilibrium steady state for a continuum population composed of one type that chooses  $K_t = K(N)$ , say,  $t = 1, 2, \dots$ , where  $K_0 = K(N)$  also. (Each individual here is “infinitesimally small,” but also divisible.) An adult of the original type at  $t = 0$  has one adult descendant at each date  $t > 0$ . Suppose  $\tilde{N}_t$  is the similar stream of adult descendants for an adult at date  $t = 0$  of any alternative type choosing  $K_t \geq \bar{K}$  that do not maximize  $\frac{F(K_t, N, \alpha)}{K_t}$  at every  $t = 1, 2, \dots$ . It follows that there exists a time  $T$  and  $\delta > 0$  such that

$$\tilde{N}_t < 1 - \delta, \text{ for all } t \geq T. \quad (3)$$

*Proof.* Note first that the introduction of a single new individual has no effect on the population,  $N$ . If there is a finite number of deviations from  $K(N)$ , (3) is immediate from (2), for any  $T$  after the last deviation. Suppose then that there are infinite number of deviations, but (3) does not hold. Thus, for all  $\delta > 0$ , there exists a sequence  $\{t_i\}_{i=1}^{\infty}$  such that  $\tilde{N}_{t_i} \geq 1 - \delta$ , for all  $t_i$ . It is without loss to suppose  $t_1$  is strictly after the first deviation. However, assuming  $\delta$  is small enough, the only way to obtain  $\tilde{N}_{t_i} \geq 1 - \delta$ , despite this fixed first deviation, is to choose  $\tilde{K}_{t_i} \leq K(N) - \varepsilon$ , for some  $\varepsilon > 0$ . Thus every date in the sequence  $\{t_i\}_{i=1}^{\infty}$  involves such a deviation. Further, since these deviations are all at least  $\varepsilon > 0$ , the only way to overcome their cumulative effect is to choose  $\tilde{K}_{t_i} \rightarrow \bar{K}$ . Assumption 1 then implies that  $F(\tilde{K}_{t_i}, N, \alpha) = 0$ , for large enough  $t_i$ , so that  $\tilde{N}_{t_i+1} = 0$  and the deviating line becomes extinct, yielding the desired contradiction. ■

Maximization of  $\frac{F(K_t, N, \alpha)}{K_t}$  at every date  $t$  is equivalent to the maximization of  $\frac{F(K_{t-1}, N, \alpha)}{K_t} F(K_t, N, \alpha)$  at every  $t$ , since  $F(K_{t-1}, N, \alpha)$  is given. This criterion is proportional

to the total output of all the immediate surviving descendants of a given adult at date  $t - 1$ . Alternatively, it can be interpreted as the product of the number of offspring,  $f_t = \frac{F(K_{t-1}, N, \alpha)}{K_t}$ , and the “quality,”  $F(K_t, N, \alpha)$ , of each of them. Lemma 2 shows that these preferences over quantity and the particular functional form of quality would be favored by natural selection.

The hypothesis is then that humans were selected to have these preferences by 2 million years of hunting and gathering. It is not simply that humans were selected to make a particular numerical choice of both quantity and quality. Rather they are assumed to recognize the impact that investment in offspring has on the adult income of these offspring, regardless of the functional form involved. Such flexibility would be needed for humans in foraging societies to make the right decisions in the wide spectrum of circumstances that presumably arose during this period. It is not then required that natural selection occur during the relatively brief transition to agriculture itself; rather the characteristics of this transition just express these preferences. (Neither will natural selection be required to actually operate during the recent demographic transition.) Once these preferences are in place, that is, there is no need to rely further on the notoriously slow process of biological evolution.

### *II.B.2 Population Maximized*

Given the inclusion of population,  $N$ , in the production and survival functions, it is of interest that there is no “biological externality” here. That is, the equilibrium steady state yields the maximum population that could be obtained, even in principle, in any steady state. Maximizing descendants as if  $N$  were fixed is appropriate because  $N$  is itself maximized.

Lemma 3. Suppose that, in addition to the assumptions used in Lemma 1,  $p(0)F(K, 0, \alpha) > K$ , but  $p(N)F(K, N, \alpha) < K$ , if  $N$  is large enough, for all  $K \geq \bar{K}$ . Then the unique equilibrium steady state is also the unique solution to  $\max_{K \geq \bar{K}} N$  s.t.  $p(N)F(K, N, \alpha) = K$ .

*Proof.* Under the stated conditions, the constraint  $p(N)F(K, N, \alpha) = K$  yields  $N > 0$  as a function of  $K \geq \bar{K}$ . It then follows that  $(p'F + pF_N)\frac{dN}{dK} + pF_K = 1$ , so that  $\frac{dN}{dK} = 0$  if and only if  $pF_K = 1$ . Further,  $\frac{d^2N}{dK^2} = \frac{-pF_{KK}}{p'F + pF_N} < 0$ , whenever  $\frac{dN}{dK} = 0$ , so that the equilibrium steady state is the unique maximizer of  $N$ . ■

The above argument shows that maximization of  $N$  entails maximization of “profit,”  $p(N)F(K, N, \alpha) - K$ , for that value of  $N$ . The individual interest in maximizing “average product,”  $\frac{p(N)F(K, N, \alpha)}{K}$ , is then consistent with the social efficiency condition on the “marginal product,”  $p(N)F_K(K, N, \alpha) = 1$ , given that “profit” is zero. This is reminiscent of the theory of perfect competition, although the incentives of the individual and society here are not precisely analogous to those that apply there.

It follows that this equilibrium steady state also maximizes the total population of young and adults,  $\frac{N(1+p(N))}{p(N)}$ , since this is an increasing function of  $N$ . On the other hand, this steady state does not maximize GNP,  $G$ , say, where  $G = NF(K, N, \alpha)$ , since  $\frac{dG}{dK} = NF_K > 0$ , if  $\frac{dN}{dK} = 0$ . By the same token, neither does it maximize per capita income,  $F(K, N, \alpha)$ .

### II.B.3. Comparative Statics of the Equilibrium Steady State

Consider now the effect of a sudden increase in  $\alpha$ , representing a shift towards agriculture.

Note first that an individual right at the boundary between agriculture and foraging would have a private incentive to adopt agriculture, or to continue with it, because agriculture improves each child's income, given  $F_\alpha(K, N, \alpha) > 0$ . Agriculture would then spread at the expense of hunting and gathering.

Indeed, any individual engaged in agriculture after the transition would also see foraging as an unambiguously worse alternative. This argument does not rely on the network externalities that imply it would be difficult to be the only forager in an agricultural population, despite the likely importance of these.

Consider then the effect that a higher  $\alpha$  throughout the population has on the resulting equilibrium steady state, characterized as in (1). (The "additional hypotheses" of Lemma 1 remain true for small changes in  $\alpha$ .) Hence, differentiating the second equation in (1) with respect to  $\alpha$  and using the first equation yields

$$\frac{dN}{d\alpha} = \frac{-pF_\alpha}{p'F + pF_N} > 0. \quad (4)$$

Hence the shift to agriculture raises the long run level of the population, as a direct consequence of the greater productivity of agriculture. In addition,  $\frac{dp}{d\alpha} = p' \frac{dN}{d\alpha} < 0$ , so that mortality rises, due to this increased crowding.

Differentiating the first equation in (1) now yields

$$\frac{dK}{d\alpha} = \frac{-pF_{K\alpha} - (p'F_K + pF_{KN}) \frac{dN}{d\alpha}}{pF_{KK}} < 0, \quad (5)$$

so stature declines as a consequence of the shift to agriculture. That this key comparative static result is implied by (1) can be seen as follows. A key effect of this shift is that

the expected marginal product of capital,  $p(N)F_K(K, N, \alpha)$ , falls because the increase in population increases mortality, as reflected in the term  $p'F_K < 0$  in (5), thus helping reduce the demand for capital. The assumptions that  $F_{K\alpha} \leq 0$  and  $F_{KN} \leq 0$  serve to reinforce this reduction.

Fertility,  $f = \frac{F(K, N, \alpha)}{K} = \frac{1}{p(N)}$ , say, on the other hand, must rise with the shift,  $\frac{df}{d\alpha} > 0$ , since  $N$  rises. From the point of view of the entire population, it is inevitable that fertility rises if mortality rises, as a consequence of a steady state. From the point of view of an individual, however, the rise in fertility reflects a shift in favor of the quantity of offspring at the expense of the capital endowment,  $K$ .

An intuition for this shift is as follows. An increase in mortality decreases the marginal benefit of the quantity of offspring, simply because this quantity is deflated by the probability of survival. However, quality is related to the potential number of grandchildren, and this number is then doubly subject to the increase in mortality. Thus, an increase in mortality reduces the marginal benefit of quality by more than it reduces the marginal benefit of quantity.

The rise in the quantity of offspring is regardless of the effect of the transition on income,  $F(K, N, \alpha) = \frac{K}{p(N)}$ . This effect can be found as follows:

$$\begin{aligned} \frac{\frac{dF}{d\alpha}}{F} &= \frac{\frac{dK}{d\alpha}}{K} - \frac{\frac{dp}{dN} \frac{dN}{d\alpha}}{p} = \\ &= -\frac{F_{K\alpha}}{KF_{KK}} - \left( \frac{p'F_K}{pKF_{KK}} + \frac{F_{KN}}{KF_{KK}} + \frac{p'}{p} \right) \frac{dN}{d\alpha}. \end{aligned} \quad (6)$$

It is then sufficient for  $\frac{dF}{d\alpha} < 0$  that  $\frac{F_K}{KF_{KK}} < -1$ . (This condition is that the factor demand for  $K$  is elastic.) This condition and Assumption 1 can be satisfied, for example, if  $F(K, N, \alpha) =$

$K^\beta \Psi(N) + \alpha$ , for all  $\beta \in (0, 1)$ , where  $\alpha < 0$ , for all  $K \geq \bar{K}(N, \alpha) > 0$ . It is plausible then that income falls with the advent of agriculture. Income must, however, fall by a smaller percentage than somatic capital, given that fertility rises.

To sum up these comparative static results:

Theorem 1. Given Assumptions 1 and 2 and the additional hypotheses of Lemma 1, it follows that  $\frac{dN}{d\alpha} > 0$  and that  $\frac{df}{d\alpha} > 0$ , so that population and fertility rise with the advent of agriculture. It also follows that  $\frac{dK}{d\alpha} < 0$ , so that physical stature decreases. Given that, in addition,  $\frac{F_K}{KF_{KK}} < -1$ , then  $\frac{dF}{d\alpha} < 0$ , so income falls.

Although no information is available on the impact of the neolithic transition on income, these predictions are otherwise consistent with the observations discussed in Section II.A.

#### *II.B.4. Dynamics*

Consider now a population in an equilibrium steady state, which is subjected to an increase in  $\alpha$ . The short run dynamics by which the new equilibrium steady state is reached are now explored. For the sake of simplicity, the increase in  $\alpha$  is instantaneous here, but qualitatively similar results would hold if this increase were instead continuous but sufficiently rapid.

First consider how the population evolves in general, without the steady state requirement. If there is a single type choosing an arbitrary somatic stock  $K_t$ , the total population,

$N_t$ , is governed by the difference equation:

$$N_{t+1} = N_t p(N_t) F(K_t, N_t, \alpha) / K_{t+1}. \quad (7)$$

It simplifies matters to consider the differential equation associated with this difference equation. Where  $N(t)$  is population, this is:

$$\frac{1}{N(t)} \frac{dN(t)}{dt} = \frac{p(N(t)) F(\tilde{K}(t), N(t), \alpha)}{\tilde{K}(t)} - 1, \quad (8)$$

where  $\tilde{K}(t)$  is the arbitrary continuous-time counterpart of  $K_t$ . Suppose now that  $\tilde{K}(t) \equiv K(N(t)) \equiv \arg \max_{K \geq \bar{K}} \frac{F(K, N(t), \alpha)}{K}$ . Any equilibrium of (8), defined now as  $N^*$ , say, is the unique solution for  $N$  of  $\frac{p(N) F(K(N), N, \alpha)}{K(N)} = 1$ , yielding the unique equilibrium steady state, as in (1).

Use of such an associated differential equation is appropriate in general if the length of each generation is small relative to the time for the transition. This seems reasonable here with an intergenerational time of perhaps 20 years and a time for the transition of several thousand years. In any case, the differential equation (8) focuses on the salient features of the difference equation (7).

As an example of how matters are simplified, note that it is possible (but non-trivial) to formulate and prove a generalization of Lemma 2 for (7). However, in continuous time, as in (8), it is immediate that any type that deviates from  $K = K(N(t))$  on a set of times of positive measure will fall permanently behind. That is, individuals who choose the optimal  $K$  in terms of the the given preferences over the quality and quantity of children cannot be biologically outperformed by any alternative choice, even in this general dynamic setting.

The differential equation has the following properties, where  $\alpha$  is constant:

Theorem 2A. Suppose that Assumptions 1 and 2 hold, as do the additional hypotheses of Lemma 1. If  $N(0) < N^*$ , then (8) implies that population  $N(t) \uparrow N^*$ . Fertility  $f(t) = \frac{F(K(N), N, \alpha)}{K(N)} \downarrow f^* = \frac{F(K(N^*), N^*, \alpha)}{K(N^*)}$ . If, in addition,  $F_{KN} > F_N/K$ , somatic capital  $K(t) \uparrow K^* = K(N^*)$ . Income,  $F$ , may increase or decrease in general. If, in addition,  $\frac{F_K}{KF_{KK}} < -1$  and  $F_{KN}$  is close enough to zero, then  $F(t) \uparrow F(K^*, N^*, \alpha)$ . If income increases, then so must somatic capital.

*Proof.* Since  $\frac{p(N)F(K(N), N, \alpha)}{K(N)}$  is a strictly decreasing function of  $N$ , an increasing path for  $N$  is immediate from (8). Fertility,  $f$ , falls since  $\frac{df}{dN} = \frac{F_N(K(N), N, \alpha)}{K(N)} < 0$ , by the envelope theorem. Since  $\frac{dK}{dN} = \frac{F_N - KF_{KN}}{KF_{KK}} > 0$ ,  $K$  is increasing. Income,  $F$ , rises since  $\frac{dF}{dN} = F_K \frac{dK}{dN} + F_N = F_N \left(1 + \frac{F_K}{KF_{KK}}\right) - \frac{F_K F_{KN}}{F_{KK}} > 0$ , given that  $\frac{F_K}{KF_{KK}} < -1$  and  $F_{KN} \leq 0$  is sufficiently close to zero. The last assertion is obvious, but also follows since  $\frac{dF}{dt} > 0$  implies  $F_{KN} > F_N/K$ . ■

The description of the short run dynamics is then completed by deriving the immediate implications of the initial jump in  $\alpha$  :

Theorem 2B. Suppose that Assumptions 1 and 2 hold and that the additional hypotheses of Lemma 1 hold throughout the range of  $\alpha$ . If  $\alpha$  jumps up there can be no jump in  $N$ . There is a jump up in fertility,  $f$ , but a jump down in somatic capital,  $K$ . Income,  $F$ , jumps down given that  $\frac{F_K}{KF_{KK}} < -1$ .

*Proof.* Fertility jumps up since  $\frac{df}{d\alpha} |_{N=\bar{N}} = \frac{F_\alpha(K(N),N,\alpha)}{K(N)} > 0$ , by the envelope theorem, holding  $N$  constant. Capital jumps down, however, since  $\frac{dK}{d\alpha} |_{N=\bar{N}} = \frac{F_\alpha - KF_{K\alpha}}{KF_{KK}} < 0$ . Income jumps down since  $\frac{dF}{d\alpha} |_{N=\bar{N}} = F_K \frac{dK}{d\alpha} |_{N=\bar{N}} + F_\alpha = F_\alpha \left( 1 + \frac{F_K}{KF_{KK}} \right) - \frac{F_K F_{K\alpha}}{F_{KK}} < 0$ , assuming  $\frac{F_K}{KF_{KK}} < -1$ . ■

The implications of Theorems 1, 2A and 2B for population,  $N$ , fertility,  $f$ , somatic capital,  $K$ , and income,  $F$ , are sketched in Figure 2. The assumptions underlying the detailed short run effects on somatic capital and income, as in Theorems 2A and 2B, are stronger than those needed to obtain the long run effects, as in Theorem 1. Under these assumptions, however, the initial jumps in fertility, somatic capital, and income, as in Theorem 2B, are exaggerations of the long run effects, as in Theorem 1. The exaggerated effects on fertility and somatic capital would have made these shifts easier to identify empirically.

### *II.C. Related Theoretical Literature*

There is relatively little theoretical literature explicitly on the topic of the contribution here. The present paper is implicitly related to work in biology considering the optimal “clutch size.” (See Lack [1968], and Smith and Fretwell [1974].) That is: What is the optimal number and size of eggs for a bird to lay and incubate in a nest? It is plausible that a larger number of eggs laid, for example, would reduce the probability of survival of each egg. There might then be an interior optimum for the number of eggs laid that maximizes the expected number surviving. This is basically a trade-off between quantity and quality of offspring. In the present model, this trade-off does not involve the probability of survival

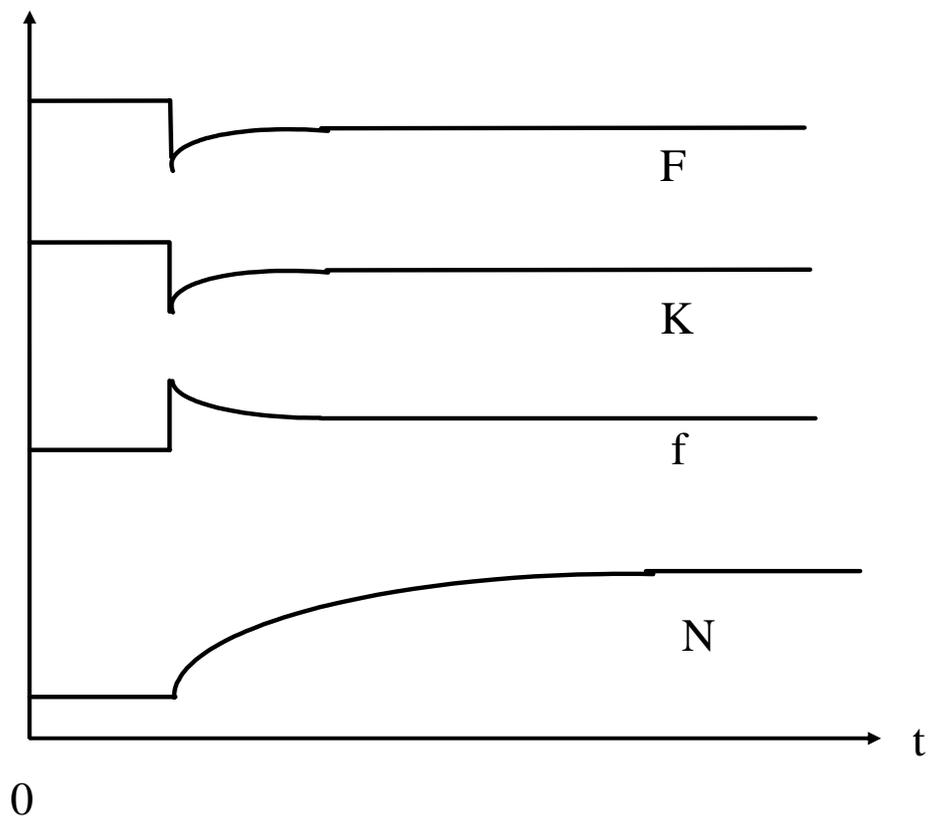


Figure 2: Model A Dynamics

itself, but rather the productivity of the next generation, so an optimal level of somatic capital must be chosen.

The present analysis is also related to the well-known notion of  $r - K$  selection due to MacArthur and Wilson [1967]. That is, some of the key *results* of  $r - K$  selection hold in a suitably simplified version of the present model, although for somewhat different reasons. If, for example, one species was subjected here to greater exogenous mortality than was another related species, then the first species would produce a larger quantity of smaller offspring. Although such correlations can be found in the data, lack of evidence for the *basis* of  $r - K$  selection—adaptation to varying growth rates—has helped to reduce its appeal within biology. (See Stearns [1992, p. 105 and pp. 206-207].)

Buttressing the incorporation of “carrying capacity” in the present model, Lee [1987] provides cogent arguments for the relevance of these biological considerations to demography. If humans have institutions that prevent the absolute biologically maximal population being reached, but that anticipate the same limits, a density-dependent model would still be appropriate. Improvements in technology might enable the carrying capacity of an economy to be stretched, although not finally removed altogether. The present model considers a technological shock in the form of a one-time improvement in productivity. More realistically, there should be continuing technological change, allowing continuing population growth after the neolithic demographic transition, as presumably occurred.

An alternative, or complementary, hypothesis for the origin of agriculture is that it was precipitated by increasing scarcity of game. Vernon Smith proposed that the common

property nature of large prey, in particular, led to their overexploitation by humans and eventual extinction. (This is an alternative to an older theory that the end of the last ice age led to dessication of plant food and hence a reduction in these prey animals. See Vernon Smith [1975].) More detailed data like that collected by Cohen and Armelagos [1984], would help here, but are not currently available. If the declines in health, stature, and life expectancy started well before the advent of agriculture, this might suggest that extinction of large game was a contributing factor. In the first place, however, further declines at or just after the transition to agriculture would still warrant an explanation as in the current paper. Secondly, it should be noted that a decline in availability of animal food might only cause a reduction in stature, for example, in the short run. In the long run, it might be expected to instead cause a reduction in the size of the human population. If a particular stature was adapted to a foraging lifestyle, that is, the long run might restore this to its previous level.

An intriguing theoretical hypothesis is offered by Marceau and Myers [2000]. Based on a theory of coalition formation, they argue that the advent of agriculture might have been precipitated by technological change. Before this transition, there was a grand coalition that somehow avoided overexploitation of the environment. At the transition, the grand coalition splintered, resulting in a loss of efficiency that might have resulted in lower output at first. Marceau and Myers essentially reverse the pattern of overexploitation of a common property resource found in Smith.

The main contribution of the present paper to understanding the effects of the transition

to agriculture is to offer a new explanation to the small number of models of this phenomenon; an explanation indeed whose basic form applies to a more recent demographic transition, as is shown next.

### III. THE RECENT DEMOGRAPHIC TRANSITION DURING THE INDUSTRIAL REVOLUTION

#### *III.A. Facts and Issues*

The basic facts relevant here were not recently uncovered, as for the neolithic transition, but are well-known. Most of the theoretical papers mentioned in Section III.D.2 below include a sketch of these facts; a more detailed reference is Chesnais [1992]. The defining features of the demographic transition during industrialization are: 1) There is first a fall in the mortality rate, perhaps due to simple and cheap, but effective, measures to improve public health and medicine. This induces a growth spurt in the population. 2) The fertility rate eventually falls, reestablishing a rough balance between the birth and death rates. Additional typical features include: 1) Income rises on average during the transition. 2) Migration from the country to the city takes place. 3) The educational system expands.

The basic puzzle this raises is: Why did fertility fall sharply following a sharp fall in mortality? That is, given that incomes rose, why would individuals not use the extra resources to produce more offspring?

### *III.B. Model B.*

Again, the emphasis here is on why the recent transition had the effects that it did, and the important question of why the transition occurred when it did is not addressed.

The model to be developed here is a variant of Model A. There are still two age classes— young and adult. The output of each adult is still  $F(K, N, \alpha)$ , where  $N$  is number of adults, but  $\alpha$  now represents the shift to urbanization and industrialization. The main distinction is that capital,  $K$ , is now reinterpreted as human capital—such as education or on-the-job training. Thus the cross-partial derivatives  $F_{KN}(K, N, \alpha)$  and  $F_{K\alpha}(K, N, \alpha)$  now plausibly have the opposite sign to that in Model A. Of course, the functions described here should incorporate a great deal of technological change, as compared to those used in Model A. Altogether:

Assumption 3. i) The dependence of  $F$  on  $K$  alone is as in i) of Assumption 1. ii) Further,  $F_{\alpha}(K, N, \alpha) > 0$ , so that the direct effect of industrialization is to raise income, and  $F_N(K, N, \alpha) < 0$ , so that crowding reduces productivity, due to the presence of finite resources such as land. However, the shift to industrial output at the expense of agriculture, or a larger population, does not lower the marginal product of human capital, so that  $F_{KN}(K, N, \alpha) \geq 0$  and  $F_{K\alpha}(K, N, \alpha) \geq 0$ .

A defining characteristic of the recent demographic transition was the cheap but effective suppression of infectious disease, for example. In Model B, then, it is reasonable to take mortality as exogenous:

Assumption 4. Improved public health is incorporated in the survival probability from young to adult,  $p(\alpha) \in (0, 1)$ , say, where  $p'(\alpha) > 0$ .

Lemma 1 becomes:

Lemma 5. From Assumption 3, it follows that there exists a unique optimal  $K \geq \bar{K}$ ,  $K(N) = \arg \max_{K \geq \bar{K}} \frac{p(\alpha)F(K, N, \alpha)}{K}$ . As additional hypotheses, suppose that  $\frac{p(\alpha)F(K(0), 0, \alpha)}{K(0)} > 1$  and  $\frac{p(\alpha)F(K(N), N, \alpha)}{K(N)} < 1$ , if  $N$  is large enough. Then there exists a unique equilibrium steady state,  $(N, K(N)) \gg 0$ , the only solution for  $N \geq 0$  and  $K \geq \bar{K}$  of

$$p(\alpha)F_K(K, N, \alpha) = 1 \text{ and } p(\alpha)F(K, N, \alpha) = K. \quad (9)$$

Lemma 2 holds here as stated, despite the reformulation of the model. That is, if there is a type that chooses  $K \geq \bar{K}$  to maximize  $\frac{F(K, N, \alpha)}{K}$ , in a steady state such that  $p(\alpha)F(K, N, \alpha) = K$ , then this type cannot be outdone by any alternative behavior. The criterion can be interpreted as the product of the quantity and quality of offspring, as before. Again, there is no “biological externality” so no steady-state population can exceed that in the equilibrium steady state, and a version of Lemma 3 and the following remarks hold here.

### *III.B.1. Comparative Statics of the Equilibrium Steady State*

Consider now the effect of an increase in  $\alpha$ , representing the effect of better public health and of industrialization. (The “additional hypotheses” of Lemma 5 hold for small changes in

$\alpha$ .) Differentiating the second condition in (9) with respect to  $\alpha$  and using the first condition also, it follows that

$$\frac{dN}{d\alpha} = -\frac{p'F + pF_\alpha}{pF_N} > 0, \quad (10)$$

so that population rises, as a consequence of the lower mortality and greater productivity arising in the industrial revolution.

Differentiating the second equation in (9) yields

$$\frac{dK}{d\alpha} = -\frac{p'F_K + pF_{K\alpha} + pF_{KN}\frac{dN}{d\alpha}}{pF_{KK}} > 0, \quad (11)$$

so that human capital rises also. In these circumstances, that is, lower mortality increases the expected marginal product of capital,  $p(\alpha)F_K(K, N, \alpha)$ , as reflected in the term  $p'F_K > 0$  in (11), so tending to increase the demand for capital,  $K$ . The assumptions that  $F_{K\alpha} \geq 0$  and  $F_{KN} \geq 0$  reinforce this effect.

On the other hand, fertility  $f = \frac{F}{K} = \frac{1}{p(\alpha)}$  must fall since  $p'(\alpha) > 0$ . From the point of view of the entire population, fertility must fall if mortality falls, as a consequence of the definition of a steady state. From the point of view of an individual, however, fertility falls because individuals choose to favor the human capital endowment of each offspring,  $K$ , over the quantity of these offspring.

Again, an intuition for this shift is that a decrease in mortality increases the marginal benefit of quality by more than it increases the marginal benefit of the quantity of children. This is because quality is related to the potential number of grandchildren, and so is doubly subject to this decrease in mortality.

This reduction in the quantity of offspring arises regardless of the direction of the change

in income,  $F = \frac{K}{p(\alpha)}$ . This can be found as follows.

$$\begin{aligned} \frac{\frac{dF}{d\alpha}}{F} &= \frac{\frac{dK}{d\alpha}}{K} - \frac{\frac{dp}{d\alpha}}{p} = \\ &= -\frac{p'F_K}{pKF_{KK}} - \frac{p'}{p} - \frac{F_{K\alpha}}{KF_{KK}} - \frac{F_{KN}}{KF_{KK}} \frac{dN}{d\alpha}. \end{aligned} \quad (12)$$

Hence it is sufficient for  $\frac{dF}{d\alpha} > 0$  that  $\frac{F_K}{KF_{KK}} < -1$ , so income rises in the long run. Since fertility falls, however, income must rise by a smaller percentage than does human capital.

To sum up all these comparative statics results for Model B:

**Theorem 3.** Suppose Assumptions 3 and 4 hold, as do the additional hypotheses of Lemma 5. It follows that  $\frac{dN}{d\alpha} > 0$ , so that population rises as a result of industrialization and better public health. It also follows that  $\frac{df}{d\alpha} < 0$ , so that fertility falls, but that  $\frac{dK}{d\alpha} > 0$ , so that human capital rises. Given that, in addition,  $\frac{F_K}{KF_{KK}} < -1$ , then  $\frac{dF}{d\alpha} > 0$ , and income also rises.

These predictions are all consistent with the observations sketched in Section III.A.

It is worth noting that the capital stock here might instead be interpreted as stature, as in Model A. It is not immediately obvious what the sign of the cross-partials of  $K$  with  $N$  and  $\alpha$  should then be, but they seem likely to be small, in any case. Suppose they are zero, for simplicity. An appropriate version of Model B then implies that the recent demographic transition would ultimately increase stature, since the reduction in mortality increases the marginal product of this capital. Such an increase in stature is ongoing, in fact, but has so far merely roughly restored the stature humans had during hunting and gathering. (See

Angel [1975, Table 1], for example.) A general model might incorporate both these stocks, but this seems unlikely to add much to understanding the issues.

### III.B.2. Dynamics

Consider now a sharp once-and-for-all increase in  $\alpha$ . The resulting dynamics are analogous to Model A. Without requiring a steady state, if there is a single type choosing an arbitrary human capital level  $K_t$ , the total population,  $N_t$ , now evolves according to

$$N_{t+1} = N_t p(\alpha) F(K_t, N_t, \alpha) / K_{t+1}. \quad (13)$$

For simplicity, consider again the associated differential equation for population  $N(t)$ :

$$\frac{1}{N(t)} \frac{dN(t)}{dt} = \frac{p(\alpha) F(K(N), N, \alpha)}{K(N)} - 1, \quad (14)$$

where  $K(N) = \arg \max_{K \geq \bar{K}} \frac{F(K, N, \alpha)}{K}$ . This differential equation again focuses on the salient properties of the difference equation. Any steady state of (14),  $N^*$ , say, is the unique solution of  $\frac{p(N) F(K(N), N, \alpha)}{K(N)} = 1$ , the unique equilibrium steady state, as in (9). Again, it is immediate that any type that deviates from  $K = K(N)$  on a positive measure of times will fall permanently behind. Again, that is, individuals who choose the optimal  $K$  in terms of the current preferences over the quality and quantity of children cannot be biologically outperformed by any alternative choice, even in this general dynamic setting. This differential equation has the following properties, where  $\alpha$  is constant:

Theorem 4A. Suppose Assumptions 3 and 4 hold, as do the additional hypotheses of Lemma 5. If  $N(0) < N^*$ , then (14) implies that population  $N(t) \uparrow N^*$ , whereas

fertility,  $f(t) = \frac{F(K(N), N, \alpha)}{K(N)} \downarrow f^* = \frac{F(K(N^*), N^*, \alpha)}{K(N^*)}$ . Human capital,  $K(t) \uparrow K^* = K(N^*)$ . Finally, given that  $\frac{F_K}{KF_{KK}} < -1$ , income  $F(t) \uparrow F(K^*, N^*, \alpha)$ .

*Proof.* The assertion concerning  $N$  is immediate from (14). The time path of fertility  $f$  follows since  $\frac{df}{dN} = \frac{F_N(K(N), N, \alpha)}{K(N)} < 0$ , by the envelope theorem. That  $K$  increases follows from  $\frac{dK}{dN} = \frac{F_N - KF_{KN}}{KF_{KK}} > 0$ . Finally,  $\frac{dF}{dt} = F_K \frac{dK}{dN} + F_N = F_N \left(1 + \frac{F_K}{KF_{KK}}\right) - \frac{F_K F_{KN}}{F_{KK}} > 0$ , given that  $\frac{F_K}{KF_{KK}} < -1$ . ■

The description of the short run dynamics is then completed by considering the immediate effects of the jump up in  $\alpha$ .

Theorem 4B. Suppose Assumptions 3 and 4 hold and the additional hypotheses of Lemma 5 hold throughout the range of  $\alpha$ . If  $\alpha$  jumps up, there can be no jump in the population,  $N$ . However, fertility jumps up. Human capital,  $K$ , may jump down, which occurs if  $F_\alpha > KF_{K\alpha}$ . Income,  $F$ , may also jump down, which occurs if  $\frac{F_K}{KF_{KK}} < -1$  and  $F_{K\alpha}$  is small enough. If income jumps down, despite the rise in  $\alpha$ , so must human capital.

*Proof.* Fertility jumps up since  $\frac{df}{d\alpha} \big|_{N=\bar{N}} = \frac{F_\alpha(K, N, \alpha)}{K} > 0$ , by the envelope theorem. Capital is affected by  $\alpha$  via  $\frac{dK}{d\alpha} \big|_{N=\bar{N}} = \frac{F_\alpha - KF_{K\alpha}}{KF_{KK}}$ . Hence  $\frac{dK}{d\alpha} \big|_{N=\bar{N}} < 0$  if  $F_\alpha > KF_{K\alpha}$ . Income jumps down since  $\frac{dF}{d\alpha} \big|_{N=\bar{N}} = F_\alpha \left(1 + \frac{F_K}{KF_{KK}}\right) - \frac{F_K F_{K\alpha}}{F_{KK}} < 0$ , given that  $\frac{F_K}{KF_{KK}} < -1$  and  $F_{K\alpha} \geq 0$  is small enough. The final assertion is obvious, but also follows since  $\frac{dF}{d\alpha} \big|_{N=\bar{N}} < 0$  implies  $F_\alpha > KF_{K\alpha}$ .

The combined implications of Theorems 3, 4A, and 4B for population,  $N$ , fertility,  $f$ , human capital,  $K$ , and income,  $F$ , are sketched in Figure 3. Note that the assumptions underlying the detailed short run effects on human capital and income, as in Theorems 4A and 4B, are stronger than those needed for the long run effects, as in Theorem 3. Under these assumptions, however, the initial jumps in fertility,  $f$ , human capital,  $K$ , and income,  $F$ , are all in the *opposite* direction to the long run changes, as is discussed next.

More generally, if the increase in the parameter  $\alpha$  were to occur over a period of time, rather than all at once, the direction of the change in fertility,  $f$ , human capital,  $K$ , and income,  $F$ , would be ambiguous, in the short run. Thus, if this increase in  $\alpha$  were slow enough, fertility, for example, would fall in the short run as well as in the long run. Indeed, although atypical, such a pattern was observed in France during the industrial revolution. (See Chesnais [1992].)

### *III.C. The Accuracy of the Dynamic Predictions*

Model B predicts that, during the demographic transition, fertility will first rise, as in Theorem 4B, then decline, as in Theorem 4A, and end up at a new lower level, as in Theorem 3. (See Figure 3.) Indeed, Dyson and Murphy [1985] marshal substantial evidence that such a pattern was typical during the European demographic transition and during many subsequent transitions. It is worth noting that, if Model B were simplified so that the parameter  $\alpha$  affected only mortality, there would be no immediate effect of a jump in  $\alpha$  on fertility, despite the fall in fertility that would still arise in the long run. Only when there

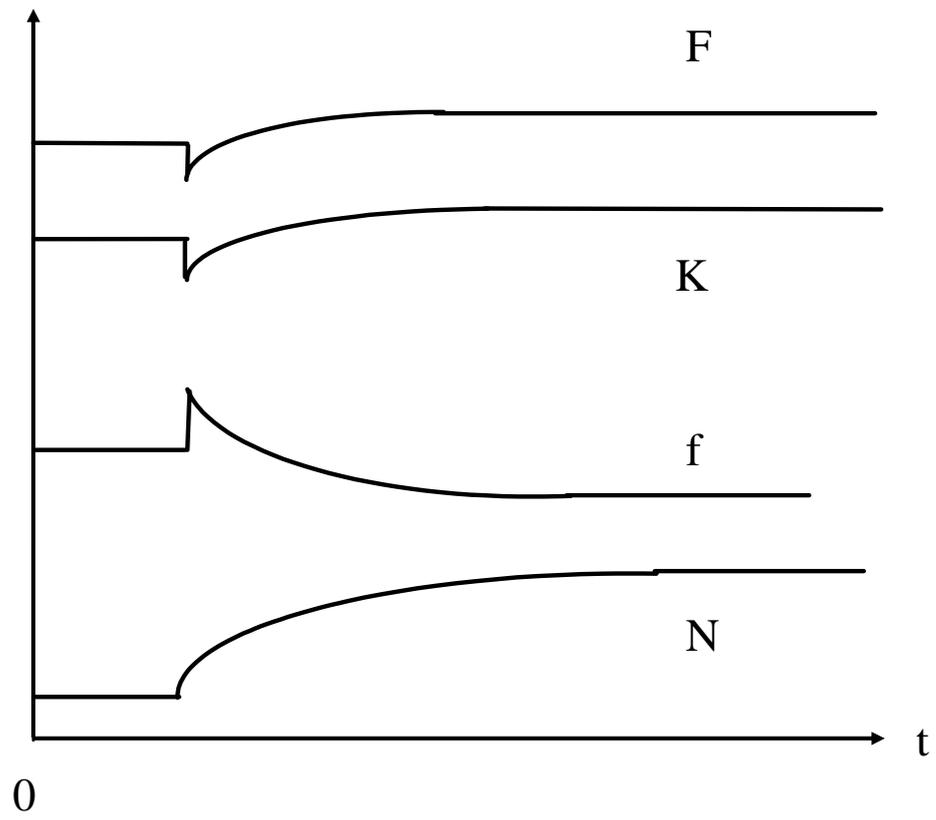


Figure 3: Model B Dynamics

is a one-time increase in productivity as well as a decline in mortality, is the demographic transition inaugurated in this way by a sharp rise in fertility.

Similarly, Model B predicts that income and human capital both first jump down, as in Theorem 4B, then rise steadily, as in Theorem 4A, and end up at a higher level, as in Theorem 3. (Again, see Figure 3.) Indeed, a popular, but not universal, view among economic historians is that, at the start of the industrial transition, real wages rose on average only rather slowly, and sometimes declined. Interestingly, stature also sometimes declined, as would be predicted by the version of Model B sketched following Assumption 3 in Section III.B. (See Feinstein [1998] for British data and Margo [2000] for the US.) Ultimately, of course, real wages rose substantially. Goldin and Katz [1996] suggest that physical capital and human capital were originally substitutes, so that skilled labor was at first displaced by machines. More recently, however, physical capital and human capital became complements, so that continued investment drove up the real wage. The present explanation is related in that lower human capital is also responsible here for the drop in income. However, there is no physical capital here.

### *III.D. Related Literature*

#### *III.D.1. Biology, Anthropology, etc.*

The recent demographic transition has attracted a great deal of applied theoretical work, both outside economics and inside. Only some of the relevant highlights are then covered here. First, the recent demographic transition has been used to motivate the need to augment the theory of biological evolution with cultural evolution. Cavalli-Sforza and Feldman

[1981, especially Chapter 3.9] use such a theory to show that the culturally determined choice of a smaller family might spread if the tendency to imitate is sufficiently strong relative to the natural selection against such a choice. Although it is plausible that a tendency to imitate might have an evolutionary basis, this basis is weakened to the extent that it is used to explain phenomena contrary to natural selection. Moreover, the present model shows that biologically appropriate behavior can explain the stylized facts.

There are also a number of papers that consider the cross-sectional link between fertility and income. That is, a biological perspective apparently implies that richer individuals would have more offspring than poorer individuals. Evidence on the actual relationship of fertility to wealth in modern societies is mixed. Daly and Wilson [1983, Figure 12-5, p. 334], for example, present data from the US census implying a positive relationship, controlling for the wife's age. Vining [1986], on the other hand, as part of a substantial critique of sociobiology, presents evidence of a negative relationship.

Such a negative relationship is not fatal in itself to a biological view. Rogers [1990], for example, reports some success in obtaining a non-monotonic relationship between current fertility and wealth. In his model, long-run reproductive success is only partially determined by current fertility since offspring generate some of their own income.

The present analysis implies that differential mortality could also help explain a negative relationship between wealth and fertility. The wealthy are healthier than the poor and have longer lives, so it is optimal for them to invest more in their offspring's human capital. As in Model B, this would reduce their fertility but increase the income of the offspring of the

wealthy and thus produce more descendants in the long run.

### *III.D.2. Economics*

A landmark paper in the economic treatment of fertility is Becker and Barro [1988]. They assume that each parent's utility depends on the parent's consumption, the number of offspring and the utility of each of them. This yields a dynastic utility that depends on the consumption and number of descendants throughout the entire family line. Parents inherit capital, earn additional income, consume, and use the remainder to reproduce and to bequeath capital to each child. Becker and Barro derive a number of implications of this—for example, that fertility is increased by a rise in the interest rate. In particular, they show that a one-time decline in mortality produces a one-time increase in fertility, followed by a fall in later generations, as consistent with the evidence in Section III.C.

Becker, Glaeser and Murphy [1999] sketch a model in which the growth of population may spur an increase in per capita income due to increasing returns from specialization. (Such a thesis is similar to that of Kremer [1993], who invokes it to explain a broader sweep of human history.) Since Becker, Glaeser, and Murphy assume that the time devoted to raising children is proportional to their number, such a rise in the wage rate may militate against quantity, so fertility falls. It is relevant that they argue for some such hypothesis going beyond a Malthusian perspective: “However, much of what has happened since the beginning of the 19th century is clearly inconsistent with crucial tenets of the Malthusian analysis. As per capita incomes of many nations grew, fertility did not increase, as predicted by Malthus, but eventually began to fall sharply.” (Becker, Glaeser and Murphy [1999, p.

145].) On the contrary, the present analysis shows that such stylized facts do not, in themselves, contradict an essentially Malthusian view.

Galor and Moav [2002] model the effects of demographic transition itself, but also explain how human society might be mired for a long time in a Malthusian regime, then suddenly undergo an industrial and demographic growth spurt, and next enter a phase of sustained growth. (See also Galor and Weil [2000].) Galor and Moav's model is biological in that preferences over quality and quantity of children differ and are subject to pressure from the economic environment. During the Malthusian era, there is slow but persistent natural selection in favor of preferences emphasizing quality. (An issue this raises is: Was there sufficient time for such selection to have a substantial effect?) Eventually, the number of individuals with such preferences is enough that the resulting technological progress pushes the economy into a virtuous cycle of growth. To produce the fall in fertility during the transition itself, they also assume that each offspring requires an input of time from their parents.

Recently, Soares [2002] developed an economic model of the recent demographic transition key aspects of which reinforce the present biological approach. Thus, he treats mortality as the primary determinant of human capital and fertility. This contrasts with the usual economic assumption that the primary determinant of fertility is income. He presents supporting evidence that mortality has varied substantially, independently of income, and verifies that this approach has empirical validity, considering changes also in post-transition economies. To incorporate mortality, Soares modifies the utility function of adults to include

life expectancy of children as an additional argument. An increase in life expectancy then increases the marginal product of human capital and tilts the balance between the quantity and quality of children in favor of quality. However, he maintains the assumption concerning the time input required for each offspring.

Indeed, this assumption is typical in the economics literature on the recent demographic transition. (It is also made by Greenwood and Sheshadri [2002], for example.) From an economic viewpoint, a higher wage rate then implies that children have a higher opportunity cost in terms of other forms of consumption, perhaps then reducing the quantity of offspring chosen, as required. This assumption certainly seems to go beyond a biological viewpoint. From such a viewpoint, other forms of consumption have no independent value—the only biological final good is offspring. It then seems inevitable that a relaxation of the income constraint could not decrease the value of the objective criterion—the number of these offspring.

A key issue then with respect to all the above economic models concerns the formulation of preferences: It seems these preferences are inconsistent with biology. But, if so, why the divergence? Were the required preferences optimal under some plausible set of previous circumstances?

The contribution of the present paper is to finesse this issue entirely by deriving the key properties of the recent demographic transition from a simple biological model that also entails reasonable economic preferences.

## IV. CONCLUSIONS

The present paper develops a model that replicates the somewhat puzzling shifts observed during two widely separated demographic transitions. This suggests these two episodes can be usefully viewed together and reinforces the validity of the basically biological approach here. A key feature of the model here is to introduce capital—somatic or human—in the simplest possible way.

The simplicity of the model serves to illuminate the basic issues. However, it cannot be taken literally. One desirable direction for generalization would be to include more than two age classes, where individuals at various ages allocate scarce resources among existing offspring of various vintages and to current reproduction. A second desirable extension would be to allow consumption. A form of consumption that is consistent with the present biological perspective is expenditure to maintain health and hence to reduce mortality. A final desirable extension of Model B, in particular, would be to allow for investment in physical capital as well as human capital. Such generalized models, however, should remain capable of producing the effects found here.

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## REFERENCES

Ammerman, Albert J. and Luigi L. Cavalli-Sforza, *The Neolithic Transition and the Genetics of Populations in Europe*. Princeton, NJ: Princeton University Press, 1984

Angel, J. Lawrence. "Paleoecology, Paleodemography, and Health." In *Population, Ecology, and Social Evolution*, edited by Steven Polgar. Mouton: The Hague, 1975.

Becker, Gary S. and Robert J. Barro, "A Reformulation of the Economic Theory of Fertility," *Quarterly Journal of Economics* 103, no. 1 (February 1988), 1-25.

Becker, Gary S., Edward L. Glaeser and Kevin M. Murphy, "Population and Economic Growth," *American Economic Review* 89, no. 2 (May 1999), 145-149.

Bocquet-Appel, Jean-Pierre. "Paleoanthropological Traces of a Neolithic Transition," *Current Anthropology* 43, no. 4 (August-October 2002): 637-50.

Cavalli-Sforza, Luigi L. and Francesco Cavalli-Sforza, *The Great Human Diasporas: The History of Diversity and Evolution*. Cambridge, MA: Perseus Books, 1995.

Cavalli-Sforza, Luigi L., and Marcus W. Feldman, *Cultural Transmission and Evolution*. Princeton: Princeton University Press, 1981.

Cavalli-Sforza, Luigi L., Paolo Menozzi and Alberto Piazza, *The History and Geography of Human Genes*. Princeton, NJ: Princeton University Press, 1994.

Chesnais, Jean-Claude. "The Demographic Transition: Stages, Patterns, and Economic Implications," Oxford: Oxford University Press, 1992.

Cohen, Mark and George Armelagos, eds., *Paleopathology at the Origin of Agriculture*. New York: Academic Press, 1984.

Daly, Martin and Margo Wilson, *Sex, Evolution, and Behavior*. Belmont, CA: Wadsworth, 1978.

Diamond, Jared. *Guns, Germs and Steel*. New York: Norton, 1997.

Dyson, Tim and Mike Murphy, "The Onset of Fertility Transition," *Population and Development Review* 11, no. 3 (September 1985), 399-440.

Feinstein, Charles H. "Pessimism Perpetuated: Real Wages and the Standard of Living in Britain during and after the Industrial Revolution," *Journal of Economic History* 58, no 3 (September 1998), 625-658.

Galor, Oded and Omer Moav, "Natural Selection and the Origin of Economic Growth". *Quarterly Journal of Economics* 117 (November 2002), 1133-1192.

Galor, Oded and David N. Weil, "Population, Technology, and Growth: From Malthusian Stagnation to the Demographic Transition and Beyond." *American Economic Review* 90 (2000), 806-828.

Goldin, Claudia and Lawrence F. Katz, "Technology, Skill, and the Wage Structure: Insights from the Past," *American Economic Review* 86, no. 2 (May, 1996), 252-257.

Gray, Russell and Quentin D. Atkinson, "Language-Tree Divergence Times Support the Anatolian Theory of Indo-European Origin," *Nature* 426, no. 6965 (November, 2003), 435-438.

Greenwood, Jeremy and Ananth Seshadri, "The US Demographic Transition," *American Economic Review* 92, no. 2, (May 2002), 153-9.

Kremer, Michael. "Population Growth and Technological Change: One Million B.C. to 1990," *Quarterly Journal of Economics* 108, no. 3 (August 1993), 681-716.

Lack, D. *Ecological Adaptations for Breeding in Birds*. London: Methuen, 1968.

Lee, Ronald D. "Population Dynamics of Humans and Other Animals," *Demography* 24, no. 4 (November 1987), 443-465.

MacArthur Robert H. and Edward O. Wilson, *Island Biogeography*. Princeton: Princeton University Press, 1967.

Marceau, Nicolas and Gordon Myers, "From Foraging to Agriculture," Simon Fraser University Department of Economics Discussion Paper #00-7, 2000.

Margo, Robert A. *Wages and Labor Markets in the United States 1820-1860*. Chicago: University of Chicago Press, 2000.

Robson, Arthur J. and Hillard S. Kaplan, "The Evolution of Human Longevity and Intelligence in Hunter-Gatherer Economies," *American Economic Review* (2003) forthcoming.

Rogers, Alan R. "Evolutionary Economics of Human Reproduction," *Ethology and Sociobiology* 11 (1990), 479-496.

Sahlins, Marshall. "Notes on the Original Affluent Society." In *Man the Hunter*, edited by Richard B. Lee and Irven DeVore. Chicago: Aldine, 1968.

Smith, Christopher C. and Stephen D. Fretwell, "The Optimal Balance between Size and Number of Offspring," *American Naturalist* 108, no. 962 (July-August 1974), 499-506.

Smith, Vernon L. "The Primitive Hunter Culture, Pleistocene Extinction, and the Rise of Agriculture," *Journal of Political Economy* 83. no. 4 (August 1975), 727-756.

Soares, Rodrigo. "Mortality Reduction, Educational Attainment, and Fertility Choice," working paper, University of Maryland, 2002.

Stearns, Stephen C. *The Evolution of Life Histories*. Oxford: Oxford University Press, 1992.

Steckel, Richard H. and Jerome C. Rose, *The Backbone of History: Health and Nutrition in the Western Hemisphere*. Cambridge: Cambridge University Press, 2002.

Tudge, Colin. *Neanderthals, Bandits and Farmers: How Agriculture Really Began*. New Haven: Yale University Press, 1998.

Vining, D.R. "Social versus Reproductive Success—The Central Theoretical Problem of Human Sociobiology," *Behavior and Brain Sciences* 9 (1986), 167-260.

Wood, James W., George R. Milner, Henry C. Harpending and Kenneth M. Weiss, "The Osteological Paradox: Problems of Inferring Health from Skeletal Samples," *Current Anthropology* 33 (1992), 343-370.