Sex, Equality, and Growth (in that order)

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August 8, 2002

*I am grateful for comments on an earlier version from Lena Edlund, Paul Klein, Toshihiko Mukoyama, Johan Lagerlöf, participants at sessions at the Canadian Economic Association Meetings 2001 at McGill University, the SED Meetings 2001 at the Stockholm School of Economics, seminar participants at UQAM, Montreal, and the lunch crowd at the IUI, Stockholm.

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Abstract: We set up a unified growth model capturing the transition of a primitive and egalitarian hunter-gatherer society, into an advanced and despotic early civilization, and finally into a more egalitarian industrial society. Agents are either landowners or landless; both earn income from human capital, but only landowners earn income from land. The central assumption is that the accumulation of human capital increases with the number of people engaged in intellectual activities, "thinking." For an agent to be a thinker he must be sufficiently rich. At early stages of development, when human capital is scarce, only landowners can afford to think. Human capital thus grows with the size of the landowning class. With polygynous mating, rich landowners attract more women than landless, and thus have more offspring. This leads to a slow expansion in the size of the landowning class and thus a gradual increase in the levels of human capital. At some stage human capital may reach a critical level beyond which also landless agents become thinkers. The set a thinkers then suddenly expands, raising human capital productivity and pushing the economy to sustained growth: an industrial revolution. Allowing also for a quantity-quality trade-off in children a demographic transition sets in. But the economy may also follow a path leading to the downfall of the civilization, and a slow transition back into an egalitarian hunter-gatherer state. Which path the economy follows depends on the level of land productivity. An agricultural revolution is thus a necessary precondition for a later industrial revolution.

1. Introduction

For most part of human history we have seen very slow improvements in living standards. It was only a couple of hundred years ago that Western Europe entered an era of sustained growth in per-capita incomes, known as the industrial revolution. This was associated with equally dramatic demographic changes: first declining mortality, later falling birth rates, and in between a phase of rapid population expansion – a process known as the demographic transition. The transition into sustained growth in living standards seems to have a lot to do with an expansion of knowledge, or human capital, as indicated by the simultaneous increase in schooling (Matthews et al. 1982, Ch. 4; Galor and Moav 2002b).

The process through which knowledge is created involves research, intellectual exploration, etc. – for short, call it *thinking*. For most part of human history thinking has been the privilege of a small upper class; the poor masses have rarely had time or energy for intellectual explorations. Not until the introduction of public schooling did larger sections of society get that opportunity.

We construct a unified long-run growth model which can explain the industrial revolution and the demographic transition, and where this class-aspect of human capital accumulation plays a central role. We let human capital be a public good, accessible to all. The accumulation of human capital depends on the number of people engaged in thinking. There is no cost of thinking, but for an agent to be a thinker he must be sufficiently rich. There are many ways to model this in more detail; we could e.g. let thinking be a normal-good activity which agents consume more of when earning more. But to keep things as simple as possible, we just postulate that an agent is a thinker if his income exceeds some exogenously given threshold.

Agents belong to either one of two classes: landowners, or landless. Both earn income from human capital, but only landowners earn income from land. At early stages of development, when human capital is low, only landowners (if anyone) can afford to think. Thus the number of thinkers is given by the size of the landowning class, and therefore the productivity in human capital accumulation depends on how many agents belong to the landowning class. A slowly expanding class of landowners generates gradual increases in the levels of human capital. At some stage human capital reaches a critical level beyond which also landless agents earn above the threshold. The set a thinkers then suddenly comes to include all agents in the economy. This raises human capital productivity, which in our model generates sustained growth in human capital: an industrial revolution.

The other crucial ingredient in this story is the force which generates the expansion in the landowning class. In our model this comes from *differential reproductive success*, meaning that landowners have more offspring than landless. Again, there are many ways to model this; our approach is to let landowners' reproductive advantage originate from polygynous mating.[1] Consistent with vast anthropological evidence, in our model rich men attract more women than do poor men, and thus have more offspring.

Since landowners have more offspring – more sons – this tends to dilute landholdings over time, given that not only one son inherits. This is a crucial point in our story: we know that many historic societies have practiced so-called primogeniture, i.e., only one son has been allowed to inherit, typically the oldest. We argue, however, that this is all a matter of degree: there is always some diluting effect on landholdings, however small, if the remaining sons are not left without spoils altogether. We refer to this as *imperfect primogeniture*, for which we make both a theoretical and empirical case.[2] And, in our model, imperfect primogeniture is precisely the force which slowly but steadily expands the number of thinking landowners over time. We let this "leakage" be a constant fraction of the otherwise non-inheriting sons, but we could also let the split-up of an estate happen randomly, capturing occasional struggles between rivalling sons.

As the landowning class grows, and more agents become thinkers, the process leading toward higher levels of human capital sets in, as described above. Since human capital is identical across classes, this raises the non-land earnings of both the landless and the landowners. At the same time, however, the income earned from land by each landowner falls (since each landowner owns less land). If

[1]Polygyny means that a man can take more than one wife. The more common term polygamy formally includes polyandry, meaning that also a woman can take more than one husband – something which is rarely practiced in human societies.

[2]The theoretical case is made in Appendix A.1, and goes like this: consider a father who wants to maximize his number of grandchildren, and can split up his estate freely among sons; in our model he would in fact be indifferent between giving all land to one son, or dividing the estate equally among his sons – or any combination of the two. His number of grandchildren would be the same, only born by different sons.

landowners' incomes (from land and human capital) fall below the threshold for thinking, all thinkers vanish, and human capital falls to an exogenous minimum level. This captures the demise of a civilization. The economy thereafter slowly converges back to an egalitarian hunter-gatherer state. Our model is thus able to replicate not only a path where the expansion of the landowning class leads up to an industrial revolution, but also a path where the same process leads to the downfall of the civilization. More interesting still, which path the economy follows depends on the level of land productivity; an agricultural revolution is thus a necessary precondition for a later industrial revolution. This is consistent with Burkett, Humblet and Putterman (1999), who find that the level of pre-industrial development has a positive impact on an economy's ability to generate an industrial revolution.

The model we have described so far contains endogenous fertility, but would not generate any demographic transition. With children being a normal good, rising income would lead to rising fertility, and continually accelerating population growth. To allow for a demographic transition we introduce one more ingredient into the model: a quantity-quality trade-off. To model this, we simply assume that parents put higher weight on quality if their own human capital stock is high. Thus, as human capital growth shoots off parents choose to have fewer children. Since they invest more in each child survival rates go up as well. This generates a short spike in population growth rates, in between the fall in mortality and the fall in fertility.

Our paper adds to a recent and growing literature on the forces in long-run development. Some replicate an industrial revolution without any demographics (e.g. Goodfriend and McDermott 1995 and Hansen and Prescott 2002). Others emphasize the interaction between the industrial revolution and the demographic transition (see Lucas 2002, Ch. 5; Galor and Weil 2000; Galor and Moav 2002a; Lagerlöf 2002; Tamura 2001a). In most of these papers, as in ours, endogenous human capital investments and fertility drive the dynamics.[3] However, none of them analyze the long-run growth implications of differential reproductive success. Moreover, different from most of these long-run growth papers, we allow

[3]These papers in turn build on earlier work by Becker and Barro (1988), Barro and Becker (1989), and Becker, Murphy and Tamura (1990), who were (among) the first to model a quality-quantity trade-off in children into an endogenous growth framework.

for endogenous mortality, following e.g. Jones (2001), Kalemli-Ozcan, Ryder, and Weil (2000), Kalemli-Ozcan (2000), Morand (2000), Lagerlöf (2002), and Tamura (2001b).

Our paper also adds to a literature on polygyny [see e.g. Becker (1976), Bergstrom (1994a,b), and Guner (1999, Section 5.2)], but none of these studies growth or tries to explain why polygyny died out. Recent work by Edlund and Lagerlöf (2002) discusses growth and polygyny, but without class differences, or differences in reproductive success.

Lastly, our paper adds to a set of long-run growth models with income inequality (e.g. Galor and Moav 2002c). However, no one has yet taken seriously the long-run growth implications of the fact that intellectual activity was long the privilege of a small elite.

The rest of this paper is organized as follows. Next, Section 2 outlines a number of stylized facts we try to explain. Section 3 starts setting up the model, describing the structure of landholdings and population, budget constraints and preferences, the concept of thinkers, and the gender dimension of the model. Section 4 illustrates the dynamics in a phase diagram, and gives some numerical examples to illustrate the workings of the model. Section 5 ends with a concluding discussion which goes back to the stylized facts outlined in Section 2.

2. The stylized facts

Our model is able to explain a multitude of empirical regularities. For ease of exposition, we shall sum these up as seven distinct sets of stylized facts (despite a certain amount of overlap between them):

Stylized Fact # 1: The Three Regimes. The economic and demographic history of Western Europe has been described by Galor and Weil (1999, 2000) as passing through three distinct phases, or regimes. These can be identified in the diagram in Figure 2.1, which shows the annual growth rates of population and per-capita income in Western Europe the last millennium. The economy is first situated in a so-called *Malthusian Regime*, in which population and per-capita incomes are almost constant, or grow very slowly. Moreover, the relationship between per-capita income and population growth is positive: small increases in income lead to increased population growth.

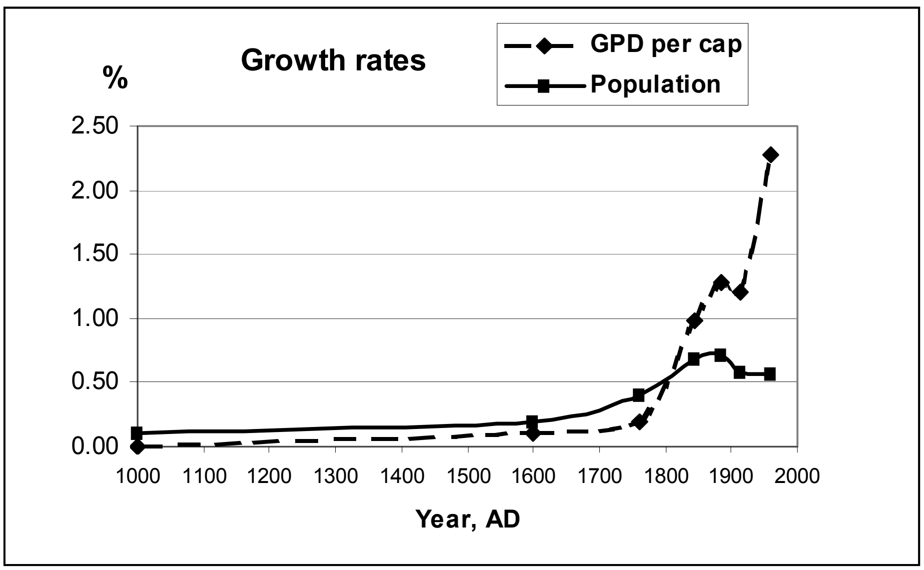

Figure 2.1: Annual growth rates in Western Europe. Sources: Maddison (1982, Table 1.2; and 1995, Table G). The years are chosen as midpoints of the periods reported.

Figure 2.1 suggests that the Malthusian Regime prevailed in Europe up until the 17th century. Starting around that time, the economy began transiting into what Galor and Weil call a *Post-Malthusian Regime*, with simultaneous increases in the growth of *both* population and per-capita income, indicating that the relationship between the two was still positive, as in the Malthusian Regime.

The final stage of development is the *Modern Growth Regime*, starting towards the end of the 19th century. Here per-capita income growth accelerates to even faster rates than in the Post-Malthusian stage, whereas population growth rates decline, indicating a negative relationship between the two for the first time in human history.

Our model can replicate all of these three regimes. Moreover, the timing of the forces driving the population dynamics is consistent with another known empirical regularity of the demographic transition in many countries. This is our **Stylized Fact # 2: mortality rates fall before birth rates**. This seems to be well documented and not particularly controversial (see e.g. Jones 2001 and Livi-Bacci 1997).

Stylized Fact # 3: long-term changes in equality and monogamy. Archaeologists identify six "pristine" civilizations on earth: in Mesopotamia, Egypt, China, India, South America (the Incas), and Mesoamerica (the Aztecs). With today's standards, and compared to the hunter-gatherer societies that preceded them, all these were highly unequal and despotic (Betzig 1993, Nolan and Lenski 1999, Diamond 1999). They were also strongly polygynous, i.e., they had a very unequal distribution of reproductive resources, women: multiple wives and/or sex partners was the privilege of the ruling classes (Betzig 1993).

In most societies – whether they tolerate explicit polygyny or not – it is the richest and most powerful high-status men who have the greatest reproductive success (Daly and Wilson 1978, Wright 1994, Perusse 1993). Across human societies measures of polygyny are also positively correlated with measures of despotism and hierarchy (Betzig 1986). In short, more inequality in income and power should thus imply more inequality in the distribution of reproductive resources – i.e., more polygyny. The observation that hunter-gatherers are more monogamous can thus be explained by the fact that they have less resources to distribute unequally, with all men living close to the same subsistence level (Wright 1994,

p. 94).

Monogamy in modern societies may also be the result of more equality compared to the early civilizations on earth. It seems obvious enough that Western Europe (and its offshoots) have become more equal over the last couple of millennia, at least in the distribution of power: witness the birth of democracy, the abolishment of serfdom, and the egalitarian values associated with the French and American revolutions. We also have some direct indications of this trend. Data presented by Campernowne and Cowell (1998, Ch. 3) show that income inequality in Ancient Rome (about 2,000 years ago) was higher than in Medieval England (1,000 years ago), which in turn was more unequal than Ante Bellum America (150 years ago). The same long-term trend appears in British data from the 1400's up until today. As we should suspect, Western Europe has also become more monogamous from the early middle ages and on. Upper class marriages were often polygynous among the Franks in seventh century. The Carolingians practiced polygyny in the form of serial monogamy and concubinage; for instance, Charles the Great (Charlemagne) had five wives and four concubines (Dickemann 1979, p. 358).

We should note, however, that it is not clear that the shift to monogamy in Europe was only due to more equality. Alexander et al. (1979 pp. 418-420) define European monogamy as "socially imposed," (by the law and/or the church; cf. Edlund and Lagerlöf 2002 and Dickemann 1979), as opposed to monogamy among hunters-gatherers which is "ecologically imposed." The question then is what makes some unequal cultures impose monogamy, and others not. One possibility, in line with the story we tell here, is that equality had an indirect impact: imposing monogamy became necessary due to a more equal distribution of power and income.[4] Another way to explain socially imposed monogamy is to allow for an exogenously given maximum rate of fertility, which plays a role only in very

[4]In the words of Robert Wright (1994, p. 98): "This explanation of monogamy – as a divvying up of sexual property among men – has the virtue of consistency with the fact that [...] it is men who usually control sheerly political power, and men who, historically, have cut most of the big political deals. This is not to say, of course, that men ever sat down and hammered out the one-woman-per-man compromise. The idea, rather, is that polygyny has tended to disappear in response to egalitarian values—not values of equality between the sexes, but equality among men."

unequal societies, where rich men desire a larger number of children. This could give the upper classes a reason to oppose legally imposed monogamy (see the concluding discussion in Section 5).

Stylized Fact # 4: 20th century spurt in trend towards equality. The trend towards more equality accelerated around the 20th century, as the economy transited into the Modern Growth Regime. Fogel (2000, Ch. 4) presents data over a number of measures from the 20th century US and Europe, where improved equality shows up in the Gini ratio for the income distribution; in homelessness; and in class differences in life expectancy, stature, and weight. The pattern for the 18th and 19th centuries is more mixed. Two-thirds of the reduction from 1700 to 1973 in the Gini ratio for England took place in the 20th century (Fogel 2000, p. 143).

Stylized Fact # 5: improved equality driven by diminished role of agriculture. Fogel's suggested explanation for the reduction in inequality in the 20th century is also consistent with the mechanism driving our model: "The factor accounting for most of the reduction that has so far been achieved in the inequality of the income distribution is the decline in the relative importance of land and physical capital, and the increasing importance of human capital (labor skills), in the process of production" (Fogel 2000, p. 157). Notably, Fogel downplays the importance of e.g. government programs.

Stylized Fact # 6: population is not the whole story. Most earlier models trying to explain the phenomenon of an industrial revolution focus on links from population size (or density), via some scale effect, to technological progress, and economic growth. This is probably important when thinking about why the industrial revolution happened on the Eurasian continent, rather than in, say, Australia, or the Americas (see e.g. Kremer 1993). But this does not explain why growth rates did not spurt in China, or India, where the size and density of the population exceeded that in Western Europe (see Table 2.1).

Stylized Fact # 7: differences in inequality and monogamy across regions. Western Europe before the industrial revolution had a more equal income distribution than had contemporary China and India (Jones 1987 p. 5; Landes 1999 pp. 217-221). This was also reflected in the distribution of women: European royal courts around 1500 had no harems, nor any eunuchs assigned to guard

	Europe	China	India
Population size, millions	**81**	**100**	**105**
Population density, people per km^2	**8**	**25**	**23**

Table 2.1: Eurasian population A.D. 1500. Sources: Jones (1987, p. 232), and McEvedy and Jones (1978, pp. 18, 171, and 183).

them, and did not practice concubinage, as did China well into the twentieth century (Goode 1963; Mitamura 1970).

India is a harder case to make. Today it is largely monogamous, but the picture painted by e.g. Dickemann (1979) is that in the 19th century many regions of India had a more polygynous marriage system than that of contemporary Europe. In fact, India fits well into the pattern described above: to take more than one wife was a privilege reserved for the wealthiest and most powerful men. Although most marriages were between one man and one woman, for a small number of rich men among the higher castes marriages were often polygynous; men from lower castes often did not marry at all. This also fits well with the common practice in India that women marry upwards, to a caste above that in which they were born (so-called hypergyny), and vice versa for men.

3. The basic structure of the model

Consider the following overlapping-generations model. In every period t there is a continuum of agents, each living for two periods: childhood and adulthood. Each individual also belongs to either one of two sexes: male or female. In every period t there are P_t adult men and equally many adult women. (In the same period there are also P_{t+1} boys and P_{t+1} girls living in childhood.)

Men belong to either one of two *classes*: landowners, or rulers, and landless subjects. In period t there are P_t^R landowners and P_t^S landless agents:

$$P_t^R + P_t^S = P_t. \tag{3.1}$$

Let λ_t denote the fraction of the population belonging to the landowning class:

$$\lambda_t = \frac{P_t^R}{P_t}. \tag{3.2}$$

The total amount of land in productivity terms is denoted by M. Letting m_t denote average landholdings among members of that class we can write:

$$m_t = \frac{M}{P_t^R}. \tag{3.3}$$

3.1. Human capital and income

A landowner's income is given by

$$y_t^R = BH_t + m_t, \tag{3.4}$$

where H_t denotes human capital, earning an income of B per unit.

We normalize output per unit of land to one, and m_t (recall) denotes land per landowner. This formulation can be thought of as short-hand for a simple two-sector model: one sector uses only land, one only human capital, and both have linear technologies.

As described in Stylized Facts # 5 above, human capital has historically been more evenly distributed than land. To capture this we here make the extreme assumption that H_t is identical across classes, i.e., a public good. The landless thus earn

$$y_t^S = BH_t. \tag{3.5}$$

Human capital of generation $t+1$ is built up according to

$$H_{t+1} = A_t H_t + \overline{H}. \tag{3.6}$$

where A_t measures human capital productivity, i.e., how well knowledge is accumulated from one generation to the next, and $\overline{H}$ constitutes the minimum level of human capital.

3.2. Thinkers

The general idea we want to capture is that knowledge is accumulated through intellectual activity, which can be performed only by agents who have the luxury of not being forced to spend all their time and effort working for their subsistence. One way to model this would be through a time allocation decision between "thinking" and "working," made subject to some subsistence consumption constraint. Only those who have large enough work-free income, and/or agents who need to work only part time to survive, would be spending time thinking.

To simplify the analysis we instead just postulate that intellectual activity is performed by agents whose total income exceeds some threshold level, $\overline{y}$. Call such agents thinkers, and denote their number by X_t, as given by

$$X_t = \begin{cases} 0 & \text{if } y_t^R < \overline{y} \\ P_t^R & \text{if } y_t^S < \overline{y} \leq y_t^R \\ P_t & \text{if } y_t^S \geq \overline{y} \end{cases}. \tag{3.7}$$

In other words, when only landowners' incomes exceed the threshold, only they are thinkers; when the income of the landless (and thus also landowners) exceed the threshold, they are all thinkers; and when not even the landowners' incomes exceed the threshold, there are no thinkers.

Next, let human capital productivity, A_t, be a function of the number of thinkers in this economy. We choose the following functional form

$$A_t = A^* \left(\frac{X_t}{\theta + X_t} \right), \tag{3.8}$$

where $\theta, A^* > 0$; this functional form ensures that A_t is bounded from above as the number of thinkers grows indefinitely.

3.3. Budget constraints and preferences

Let variables referring to agents belonging to the landowning and landless classes be distinguished by the super-index i ($i = S, R$). Consumption takes place only in adulthood and class-i consumption is denoted by c_t^i, and (recall) a class-i agent earns y_t^i. Moreover, he has z_t^i wives, each of whom gives birth to n_t^i children. Both z_t^i and n_t^i are continuous. Men invest q_t^i units of the consumption good in each child, so the budget constraint can be written:

$$c_t^i = y_t^i - z_t^i n_t^i q_t^i. \tag{3.9}$$

Preferences are given by

$$U_t^i = (1-\beta)\ln(c_t^i) + \beta \ln\left\{ n_t^i z_t^i \left(s_t^i\right)^{\rho(H_t)} \right\}, \tag{3.10}$$

where $\beta \in (0,1)$ and s_t^i denotes the survival rate of each offspring.

The exponent $\rho(H_t)$ denotes the weight agents put on the quality (the survival rate, s_t^i) of children, relative to quantity, $z_t^i n_t^i$. We assume that $\rho'(H_t) > 0$, i.e., parents with more human capital put a higher weight on their children's quality.

3.4. The survival function

The function which determines the survival rate of each child is given by

$$s_t^i = \exp\left[\frac{-1}{q_t^i}\right], \tag{3.11}$$

where we note that $\lim_{q_t^i \to \infty} s_t^i = 1$ and $\lim_{q_t^i \to 0} s_t^i = 0$, i.e., infinite (or zero) quality investment in children drives the survival rate to 100 % (or zero). The exponential functional form, together with the logarithmic utility function, will give us nice closed-form solutions.

3.5. Male behavior

Maximizing utility in (3.10), subject to the consumption budget constraint in (3.9) and the survival function in (3.11) the first-order condition for n_t^i becomes:

$$(1-\beta)\left[c_t^i\right]^{-1} q_t^i z_t^i = \beta \left[n_t^i\right]^{-1}. \tag{3.12}$$

The first-order condition for q_t^i becomes

$$(1-\beta)\left[c_t^i\right]^{-1} n_t^i z_t^i = \beta\rho(H_t)\left(\frac{1}{q_t^i}\right)^2. \tag{3.13}$$

Using (3.12) and (3.13) we see that

$$q_t^i = \rho(H_t), \tag{3.14}$$

i.e., quality investment depends only on the weight on quality in the utility function, $\rho(H_t)$. This in turn is a function of human capital, which is assumed to be the same across classes. Thus, the survival rate is identical across classes, so we can disregard the index i.

$$s_t = \exp\left[\frac{-1}{\rho(H_t)}\right]. \tag{3.15}$$

3.6. Allocation of women

Women choose which man to marry, choosing among all men. We assume that women simply marry so as to maximize the number of surviving offspring, which is given by $s_t n_t^i$. [Recall from (3.15) that s_t is the same across classes.] Using the budget constraint in (3.9), together with the first-order condition in (3.12), and the optimal choice of q_t^i in (3.14), we see that per-woman fertility, n_t^i, is given by

$$n_t^i = \frac{\beta}{\rho(H_t)} \frac{y_t^i}{z_t^i}, \tag{3.16}$$

which is increasing in the income of the man, and falling in the number of wives he has. As a consequence, women simply allocate themselves so as to equalize the income-per-wife ratio (y_t^i/z_t^i) across men.[5] Thus n_t^i is the same across classes, so we can suppress the subindex i, i.e., $n_t^R = n_t^S = n_t$.

3.7. Marriage market equilibrium

Total "demand" for wives is given by $z_t^R P_t^R + z_t^S P_t^S$, and total supply is given by the total number of women, which is the same as the total number of men, P_t. Setting supply equal to demand and using the notation in (3.2) we can write the marriage market equilibrium as

$$z_t^R \lambda_t + z_t^S (1 - \lambda_t) = 1. \tag{3.17}$$

Next, setting $n_t^i = n_t$ in (3.16) we can write

$$\frac{z_t^R}{z_t^S} = \frac{y_t^R}{y_t^S} = \frac{BH_t + m_t}{BH_t}, \tag{3.18}$$

[5] This result relates to what anthropologists call the *polygyny threshold*: in a society with sufficient inequality among men, if the only single man's income falls below a certain level, a woman would choose to share a richer man with another woman (Gaulin and Boster 1990, pp. 995-996).

where the second equality uses the expressions for y_t^R and y_t^S in (3.4) and (3.5). We can use (3.17) and (3.18) to solve for the number of wives in each class:

$$z_t^R = \frac{BH_t + m_t}{BH_t + \lambda_t m_t}, \tag{3.19}$$

and

$$z_t^S = \frac{BH_t}{BH_t + \lambda_t m_t}. \tag{3.20}$$

This result can be seen as a special case of Proposition 6 in Bergstrom (1994a). It tells us that wives per man in each respective class is proportional to how much the class members' incomes deviate from the mean. The mean income in the population is given by the denominators in (3.19) and (3.20), i.e., the sum of income from human capital, BH_t, which is the same across classes, and the mean income from landholdings, $\lambda_t m_t = M/P_t$ [see (3.2) and (3.3)]. Note that the average number of wives is one, which must hold whenever there are equally many men as women, but since there are only two classes there is no man who has exactly one wife.

4. Dynamics

4.1. Class dynamics

The number of male offspring of landowners is $z_t^R n_t s_t/2$. (Half of the children are sons, half are daughters.) We assume that the only way to become a member of the landowning class is to be born into it (and being a man). If landowners have slow reproduction rates, i.e. if $z_t^R n_t s_t/2 < 1$, the next generation of landowners will be fewer than the preceding. That is, if the average landowner has less than one son all sons stay in the landowning class, and P_t^R falls over time.

4.1.1. Primogeniture

If $z_t^R n_t s_t/2 \geq 1$, it is not clear what fraction of the sons should inherit. The most natural theoretical approach would be to assume that landowners allocate land among sons in order to maximize their sons' reproductive success, i.e., the total number of grandchildren their sons produce. As shown in Appendix A.1, it then turns out that the father is *indifferent* as to how the land is allocated. Intuitively, concentrating the inheritance to fewer offspring implies higher income and higher reproductive success for those who do inherit – but, trivially, that higher reproductive success is allocated to fewer sons. In our model, these effects cancel: the total number a grandchildren is the same, only reared by different sons.

Nor is it empirically clear what is a right assumption to make here. A common guess would probably be that landowners in most historic societies have practiced perfect primogeniture, meaning that only one son inherited. As a logical consequence, the remaining offspring would move to the landless class. Such extreme social mobility was rarely observed in early human civilizations. Rather, those of the ruler's offspring who did not inherit joined intermediate classes, such as the military, or bureaucracy; they would rarely be left without any spoils altogether (Betzig 1993). This is also consistent with the fact that human societies have evolved in a direction of increased complexity and stratification, with a growing number of classes and levels of government (Nolan and Lenski 1999, Ch. 6). For that reason, we believe that *imperfect* primogeniture is a more accurate assumption. Indeed, the implications in our model of imperfect primogeniture differ from those of perfect primogeniture.

To model imperfect primogeniture in a setting with only two classes we let the number of landowners in period $t+1$ be given by the sum of (a) the P_t^R legitimate heirs of generation t; and (b) some small fraction δ of the remaining offspring. That is,

$$P_{t+1}^R = \begin{cases} \left(\frac{z_t^R n_t s_t}{2}\right) P_t^R & \text{if } z_t^R n_t s_t/2 < 1 \\ P_t^R + \delta\left\{\left(\frac{z_t^R n_t s_t}{2}\right) P_t^R - P_t^R\right\} & \text{if } z_t^R n_t s_t/2 \geq 1 \end{cases} . \tag{4.1}$$

Note that $\delta = 0$ amounts to perfect primogeniture, and $\delta > 0$ to imperfect primogeniture.

4.2. Population dynamics

Every woman has $(n_t s_t)/2$ surviving sons, and equally many daughters, so the total number of men (and the total number of women) in the economy grows at rate $(n_t s_t)/2$:

$$P_{t+1} = \left(\frac{n_t s_t}{2}\right) P_t. \tag{4.2}$$

Setting $n_t^i = n_t$ in (3.16), and using either (3.19) or (3.20), we can write the fertility rate as

$$n_t = \beta \frac{BH_t + \lambda_t m_t}{\rho(H_t)} = \beta \frac{BH_t + M/P_t}{\rho(H_t)}, \tag{4.3}$$

where the second equality uses (3.2) and (3.3) to note that $\lambda_t m_t = M/P_t$, i.e., average land income equals the total amount of land divided by the total number of people. As seen, the fertility rate is rising in the average income, $BH_t + M/P_t$, and falling in the quality preference, $\rho(H_t)$.

Using (4.2) and (4.3), together with the expression for the survival rate, $s_t = \exp\{-1/\rho(H_t)\}$, gives a dynamic equation for population:

$$P_{t+1} = \underbrace{\frac{\beta}{2} \frac{BH_t + M/P_t}{\rho(H_t)}}_{n_t/2} \underbrace{\exp\left[\frac{-1}{\rho(H_t)}\right]}_{s_t} P_t. \tag{4.4}$$

4.3. The phase diagram

For the moment, hold human capital productivity fixed, and denote it by A^0. We begin by deriving the loci along which population and human capital are constant in this society. Setting $P_{t+1} = P_t$ in (4.4) we can write the $(\Delta P_t = 0)$-locus as

$$P_t = \frac{M}{\left(\frac{2}{\beta}\right) \rho(H_t) \exp\left[\frac{1}{\rho(H_t)}\right] - BH_t}. \tag{4.5}$$

Setting $H_{t+1} = H_t$ in (3.6) we see that $\Delta H_t = 0$ when

$$H_t = \frac{\overline{H}}{1 - A^0}. \tag{4.6}$$

The dynamics are shown in the phase diagram in Figure 4.1. As seen, there is a unique globally stable steady-state equilibrium. A one-time increase in the number of thinkers leads to an increase in human-capital productivity, A^0, shifting out the $(\Delta H_t = 0)$-locus, thus raising the steady-state levels of population and human capital.

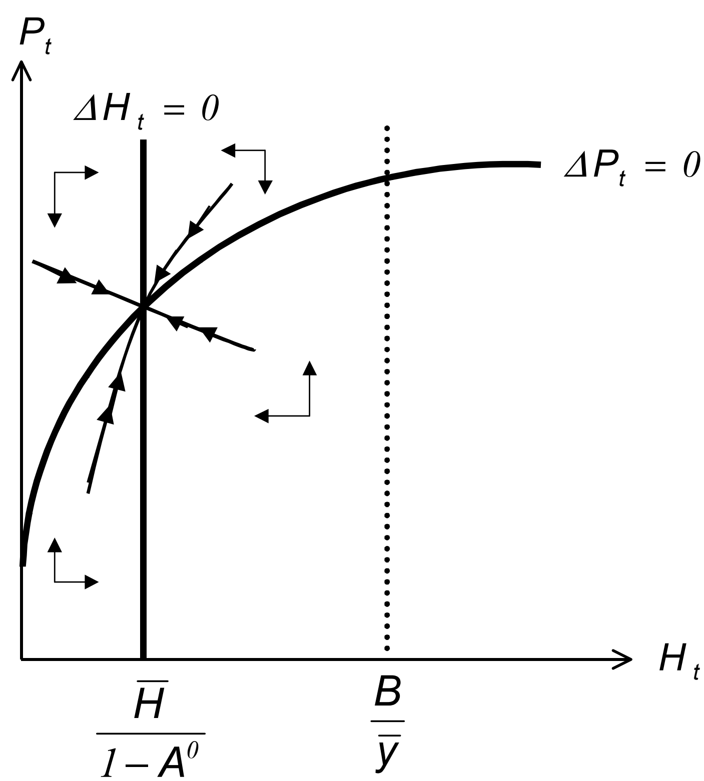

Figure 4.1: The phase diagram.

This equilibrium is a *temporary* steady state, in the sense of Galor and Weil (2000): it assumes a constant number of agents with incomes above $\overline{y}$ – i.e., a constant number of thinkers.

4.3.1. How the number of thinkers evolve

The number of thinkers can increase for three reasons. First, it can increase due to the very creation of a landowning class, e.g. following an increase in agricultural productivity, M, the fruits of which are concentrated to a small enough fraction of the population to lift their incomes above the threshold, $\overline{y}$. This would correspond to the agricultural revolution 10,000 B.C. and the resulting establishment of the first cities and civilizations on earth.

The landowning class can also grow in size due to its greater reproductive success, if primogeniture is imperfect ($\delta > 0$).

Finally, the number of thinkers can expand if the landless class reaches an income above the threshold $\overline{y}$. This could correspond to the introduction of public schooling.

4.3.2. A hunter-gatherer society

Consider first a society with low productivity of land, M, and evenly distributed landholdings. This could be a society without property rights to land – a hunter-gatherer society – implying that all men in effect belong to the landholding class: $P_t^R = P_t$. If human capital is low, no man has an income above the threshold level for thinking, i.e., $BH_t + M/P_t < \overline{y}$. Thus there are no thinkers in the economy ($X_t = 0$) and human capital productivity, given by (3.7), is zero. Human capital is thus stuck at $\overline{H}$, and the associated steady-state level of population, which we may denote $\overline{P}$, is given by (4.5), i.e.,

$$\overline{P} = \frac{M}{(2/\beta)\,\rho(\overline{H})\exp\left[\frac{1}{\rho(\overline{H})}\right] - B\overline{H}}. \tag{4.7}$$

Such an equilibrium exists if

$$B\overline{H} + \frac{M}{\overline{P}} = (2/\beta)\,\rho(\overline{H})\exp\left[\frac{1}{\rho(\overline{H})}\right] < \overline{y}, \tag{4.8}$$

which holds for low enough $\overline{H}$ and/or high enough $\overline{y}$.

Note that increased agricultural productivity leads to larger population but not higher per-capita income in steady state.

4.3.3. Early civilizations

If M becomes high enough, and/or if a small enough fraction of the population establishes property rights to the land, the income of each landowner rises above the threshold: the class of landowners becomes a class of thinkers. This captures the creation of early human civilizations and happens if

$$BH_t + \frac{M}{P_t^R} > \overline{y}, \tag{4.9}$$

which always holds for a sufficiently small landowning class (ensuring that M/P_t^R is large enough). These early civilizations always have more human capital than hunter-gatherer societies.

With imperfect primogeniture ($\delta > 0$) the landowning class will grow over time. To landowners, this has two effects pulling in opposite directions: (1) landowner income falls since each agent has less land (M/P_t^R is lower); and (2) landowners and landless alike earn more, since more thinkers implies higher human capital productivity, and more human capital for all.

This can be seen by using (3.6) and (3.8) to derive an expression for the temporary steady-state level of human capital as a function of the number of thinkers. For the moment set the number of thinkers, X_t, equal to the landowning population, P_t^R. We can then write the (temporary) steady-state human capital stock as

$$H(P_t^R) = \frac{\overline{H}(\theta + P_t^R)}{\theta - P_t^R[A^* - 1]}, \tag{4.10}$$

where we are assuming that $A^* > 1$, implying that $H'(P_t^R) > 0$. This also implies that sufficiently many thinkers would generate sustained growth in human capital [see (3.8) again], i.e., $H(P_t^R) \to \infty$ as $P_t^R \to \theta/[A^* - 1]$.

Using (4.10), together with (3.4) and (3.3), we can write the (temporary steady-state) landowner income as a function of the number of landowners:

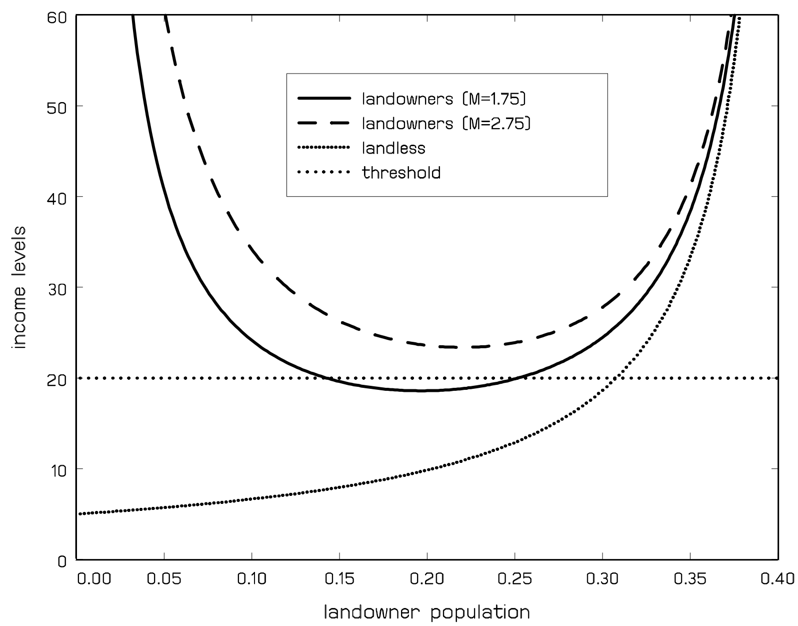

Figure 4.2: Income levels for landowners (y_t^R) and landless (y_t^S) in the temporary steady state, as a function of the size of the landowning class, P_t^R.

$$y_t^R = BH(P_t^R) + \frac{M}{P_t^R}. \tag{4.11}$$

We also recall that the first term in (4.11) constitutes the income of the landless: $y_t^S = BH(P_t^R)$. Figure 4.2 shows how income of the two classes depend on P_t^R, for two levels of land, M. The landless' income is monotonically increasing, and that of the landowners is U-shaped. The figure also displays the threshold for thinking, $\overline{y}$. The parameter values are chosen as in Table 4.1 (see explanation below).

4.3.4. A path to an industrial revolution and a demographic transition

Consider first the case with a high level of land productivity, $M = 2.75$. In this case, landowner income always exceeds the threshold. With more thinking landowners there comes a point in time when also the income of the landless exceeds the threshold, turning the landless class into thinkers and (if total population is large enough) raises human-capital productivity above one, thus pushing the economy onto a sustained growth path. In other words, the economy experiences an industrial revolution.

We can also understand this process in terms of Figure 4.1: a slowly rising number of thinkers first shifts out the $(\Delta H_t = 0)$-locus, little by little. At some point in time the locus passes the critical level $B/\overline{y}$, the point at which non-land income exceeds the threshold, and the economy goes through an industrial revolution.

As human capital starts growing, the weight on quality, $\rho(H_t)$, rises. This leads to a quality-quantity shift in children: a fall in mortality and – with a slight lag – fertility, with an associated spike in population growth in between. The way we have drawn the phase diagram in Figure 4.1 explains why. Note that the $(\Delta P_t = 0)$-locus becomes asymptotically horizontal, implying that population becomes constant in levels as human capital goes to infinity. (This need not be the case, but it holds for e.g. the numerical example in Table 4.1.) Since sustained growth in human capital pushes mortality to zero [recall (3.15)] the new constant population level must be associated with a lower rate of fertility: a demographic transition must has taken place.

4.3.5. The downfall of an early civilization

With low land productivity, $M = 1.75$, the diluting effects of a growing landowning class will at some stage push landowners income below the threshold, at which all thinkers vanish and human capital falls to its minimum, $\overline{H}$: the civilization goes under. From there on, population slowly approaches the long-run hunter-gatherer level, given in (4.7). Since landowners still have higher incomes, and thus higher reproductive success, the landowning class keeps growing, so that eventually all agents become landowners.

4.4. Numerical simulations

To understand better how the different components of the model interact we next demonstrate two simple numerical simulations. The first shows an economy experiencing an industrial revolution; the other shows an economy collapsing (and

B	β	k_1	k_2	M	θ	A^*	$\overline{H}$	$\overline{y}$	P_0^R	H_0	P_0	δ
5	.99	2	4.995	2.75	12	30	1	20	.05	1.14	0.44	.005

Table 4.1: Parameter values

thereafter slowly converging back to a hunter-gatherer society). We do not try to fit the model to any numerical data.

We first need to specify a functional form for the quality-preference function, $\rho(H_t)$:

$$\rho(H_t) = k_1 + k_2 H_t, \tag{4.12}$$

where $k_1, k_2 > 0$.

The parameter values are chosen (largely arbitrarily) as in Table 4.1. We choose the values for k_2, β, and B so that the fertility rate in (4.3) converges to two as human capital goes to infinity, i.e., we set $k_2 = B\beta/2$. Since the survival rate goes to unity [see (3.15)], each couple having two surviving children implies a constant population.

Given these parameter values, we let the initial number of landowners, P_0^R, be .05. As seen from Figure 4.2 (which uses the same parameter values) landowner income thus exceeds the threshold, ensuring that the economy starts off with a positive number of thinkers. The initial level of human capital is calculated from (4.10); then initial population can be derived from (4.5). We can calculate the initial fraction of the population who are landowners, λ_0, as $.05/.44 \approx 11\%$.

Given these initial values we then simulate the path the economy follows over time. Since $\delta > 0$ the landowning class grows over time – see (4.1) – which sets the dynamics in motion as described above. The path referring to the values in Table 4.1 is shown in Figure 4.3; Figure 4.4 then shows the effects of a lower M.

4.4.1. An industrial revolution

Figure 4.3 displays the time path when $M = 2.75$. The diagram in the upper left corner illustrates the levels of income for both classes. At the very point in time when income of the landless class comes to exceed the threshold both classes' incomes shoot off into sustained growth, as human capital productivity jumps up when all agents become thinkers. Higher levels of human capital also generate a sharp fall in mortality, and – with a slight lag – fertility, as shown in the upper right diagram.[6] In between, the growth rate of population leaps up, as seen in the lower left diagram.[7] At the same time growth in per-capita income (i.e., the change in $BH_t + M/P_t$) jumps up and then stabilizes at a sustained positive rate.

4.4.2. The downfall of a civilization

Consider next the same economy, but with lower land productivity: M equal to 1.75, instead of 2.75. As seen from Figure 4.2 this means that at some point in time landowner income falls below the threshold, implying that all thinkers vanish. Human capital drops to $\overline{H}$ and stays there forever. As a result, the mortality rate rises. So does the fertility rate, due to a reversed quality-quantity switch following the fall in human capital, a sort of reversed demographic transition. In between there is a sharp dip in population growth to negative numbers.

At the new stable levels of population and human capital the landowning class is still growing, and the landless class is shrinking, due to the higher reproductive success of the landowners and the assumption of imperfect primogeniture. In the long-run the economy thus converges to an equal hunter-gatherer state in which all agents are landowners.

5. Conclusions

We have presented a model which is able to explain a number of empirical regularities in the long-run development of human societies. We listed these as seven stylized facts in Section 2. Going back we can now point to exactly how our model replicates each fact.

To see how our model explains Stylized Fact # 1 – Galor and Weil's (1999, 2000) Three Regimes – consider the phase diagram in Figure 4.1 again. At a given level of human capital productivity, A^0, the economy gravitates toward a Malthusian-Regime type of stable equilibrium. Over time, as the landowning

[6]The fertility rate is calculated as $n_t/2 - 1$. (This would be the population growth rate if all children survived; the mother dies after the adult phase and she has $n_t/2$ daughters.) The mortality rate is calculated as $1 - s_t$. Note that population is constant when $s_t n_t/2 = 1$, so $n_t/2 - 1$ need not equal $1 - s_t$ when population is constant.

[7]There is an increase in the vertical distance between the fertility and mortality curves around generation 600, but it is hard to see.

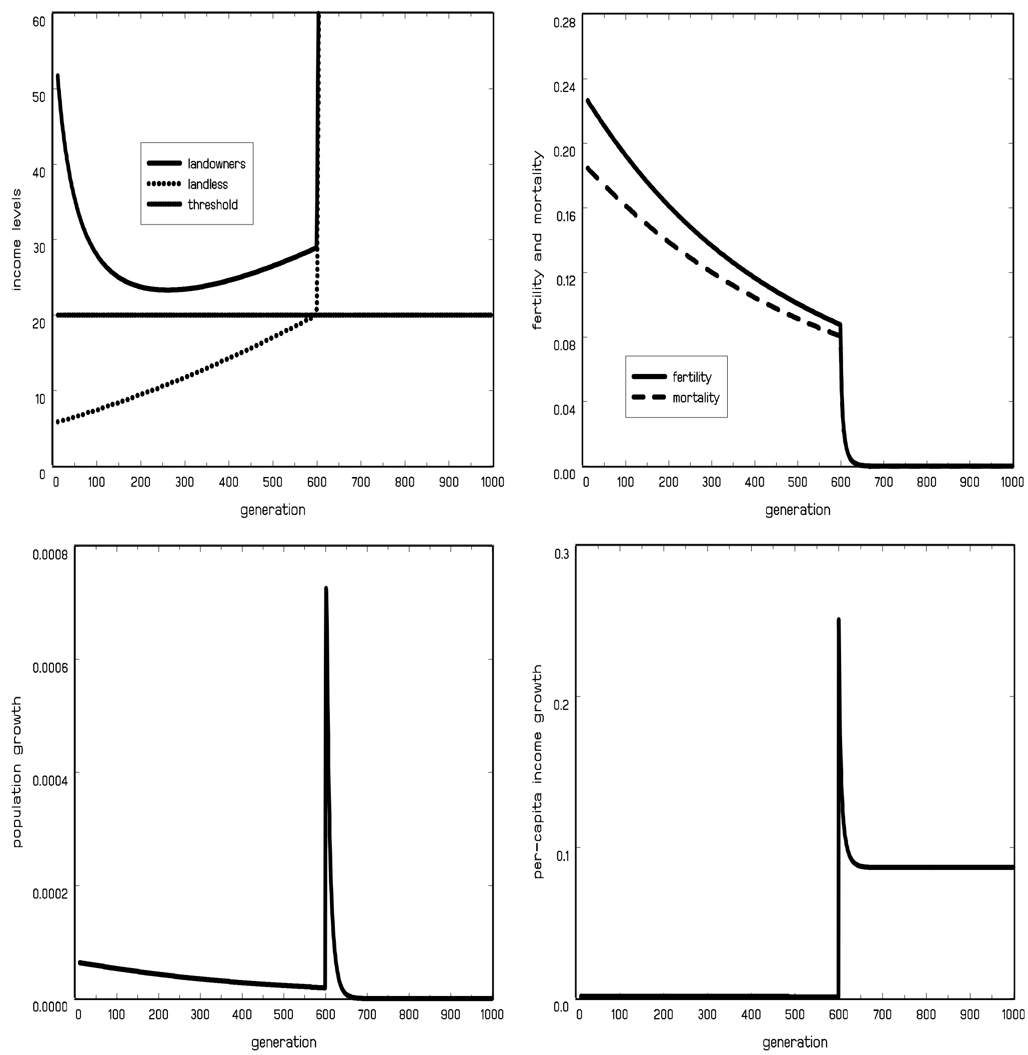

Figure 4.3: A path leading to an industrial revolution and a demographic transition.

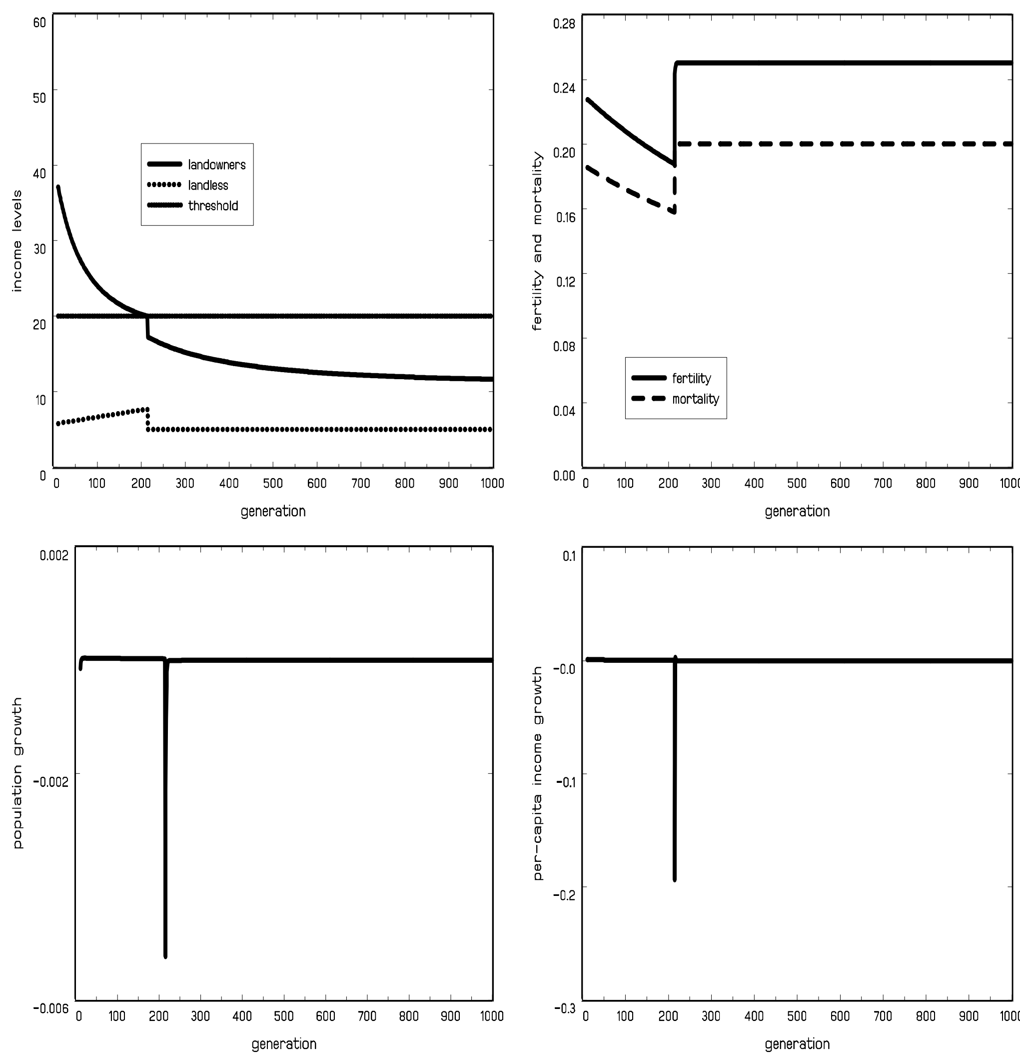

Figure 4.4: A path leading to the demise of an early civilization.

class expands, human capital productivity increases. This makes the $(\Delta H_t = 0)$-locus shift out, generating higher levels of population and human capital. As the $(\Delta H_t = 0)$-locus passes the threshold, $B/\overline{y}$, landless agents become thinkers. This raises human capital productivity, pushing the economy to sustained growth in human capital. As human capital starts growing parents shift from quantity of children to quality, due to the higher utility-weight on quality, $\rho(H_t)$. This leads to a fall in both mortality and fertility, but the fall in fertility comes a little later because higher incomes have a demand effect on children. Population growth thus shoots up temporarily (cf. Figure 4.3), implying a short phase of simultaneously increasing income and population growth – a Post-Malthusian Regime. As population growth falls again, human capital and income keep growing at a sustained rate – a Modern Growth Regime.

As noted, the mechanism driving the temporary rise in population growth is the slight lag between the fall in mortality and the fall in fertility, so the model also fits with Stylized Fact # 2.

Stylized Fact # 3 is at the center of the model: differences in the number of wives men can take reflect differences in income. A completely monogamous society in our model would be either (A) a society where landholdings are distributed equally, which we can think of as a society without property rights to land – a hunter-gatherer society; or (B) a society with very high and growing levels of human capital, so that earnings from human capital (here assumed to be completely equal) dwarf earnings from land – which essentially is the society we live in today. Polygynous societies are those where land represents a large share of earnings for the landowning class, and land is concentrated to very few agents.

Thus, a shift to sustained growth in human capital is associated with increased equality; a rise in equality should arrive around the same time as incomes start growing at sustained rates – which is our Stylized Fact # 4. The reason is that we have assumed human capital to be completely equal across men, which is a caricature of Stylized Fact # 5. (Needless to say, in the real world no measure of human capital would be completely equally distributed; the point is that human capital is *more* equal than landholdings.)

Our model can also account for Stylized Fact # 6, if we assume exogenous differences in land productivity between China and India on the one hand, and

Europe on the other. In our model, a society with higher land productivity, M, will have a larger population in its temporary steady state. [To see this, note from (4.5) that a rise in M shifts up the $(\Delta P_t = 0)$-locus in Figure 4.1.] At the same time, the level of human capital in the temporary steady state depends only on the number of thinkers – i.e., the number of agents in the landholding class – and not on their incomes (as long as their incomes lie above the threshold). Thus, a society with a rich but small ruling class – like China or India – is less likely to experience an industrial revolution than is a society with a larger ruling class, but with smaller income gaps – like Europe.

Since the degree of polygyny – as measured by the difference in the number of wives between classes – is the mirror image of the income gap between classes, the assumption of different land productivity between China/India and Europe would also explain differences in marriage systems, i.e. Stylized Fact # 7.

As discussed in the context of Stylized Fact # 3, monogamy need not be the outcome of income equality. Europe and parts of Asia practice so-called *socially imposed monogamy*, i.e., the rule of one-man-one-wife is imposed an all men, even though the societies are strongly hierarchical and stratified. Quite surprisingly, in our model such imposed monogamy would not change any of the results. To see this, set $z_t^i = 1$ in (3.16); differential reproductive success then still prevails, but is reflected not in the number of wives but in the number of children per wife, n_t^i. With imperfect primogeniture, the slow expansion in size of the landowning class is operative, so all our results still go through.

However, with such a reformulation we would not be able to explain the mentioned differences in marriage forms over time and across societies. But one additional assumption would enable us to endogenously replicate a shift from polygyny to socially imposed monogamy: let there be some upper limit to the number of children a woman can bear, $\overline{n}$ say. Consider a society with a very small and rich landowning class, so that the landowners' desired number of children exceeds $\overline{n}$. Then landowners would insist to be allowed to take more than one wife; polygyny would be necessary for landowners to be able to reach their desired rate of reproduction. In a society where landowners are not so rich their desired number of children is less than $\overline{n}$. Then landowners would not object to monogamy, since they need only one wife to reach their desired number of children. Assume next that the landowning class can veto any such law; then our model could generate an *endogenous* shift from polygyny to such socially imposed monogamy at the very point in time when the landowners' desired number of children falls below $\overline{n}$.

A. Appendix

A.1. Indifference to primogeniture

Let π_t denote the fraction of the $z_t^R n_t s_t/2$ sons who inherit land; the remainder get nothing. Perfect primogeniture – meaning one son inherits – would thus correspond to $\pi_t = 1/[z_t^R n_t s_t/2]$. Since we have a continuum of sons, however, we can allow for the case where *less* than one son inherits (as long as $\pi_t > 0$).

Without loss of generality, let those sons (or the son) who inherits receive the same amount of land. The father owns m_t units of land, so those sons who inherit each earns an income of

$$y_{t+1}^R = BH_{t+1} + \frac{m_t}{\pi_t z_t^R n_t s_t/2} \tag{A.1}$$

in the next period. Those who inherit nothing earn

$$y_{t+1}^S = BH_{t+1}. \tag{A.2}$$

Next, recall that children per wife, n_{t+1}, is the same across classes [see (4.3)]. Using the expressions for the number of wives of landowners and landless in (3.19) and (3.20), forwarded one period, we see that the total number of grand children is given by n_{t+1}, times

$$\begin{aligned} &\pi_t \left(\tfrac{z_t^R n_t s_t}{2}\right) \overbrace{\left[\frac{BH_{t+1} + \frac{m_t}{\pi_t z_t^R n_t s_t/2}}{BH_{t+1} + \lambda_{t+1} m_{t+1}}\right]}^{y_{t+1}^R} \\ &+(1-\pi_t)\left(\tfrac{z_t^R n_t s_t}{2}\right) \underbrace{\left[\frac{BH_{t+1}}{BH_{t+1} + \lambda_{t+1} m_{t+1}}\right]}_{y_{t+1}^S} \\ &= \left(\tfrac{z_t^R n_t s_t}{2}\right) \tfrac{BH_{t+1} + m_t}{BH_{t+1} + \lambda_{t+1} m_{t+1}}, \end{aligned} \tag{A.3}$$

which is clearly independent of π_t. Thus, the landowner is indifferent as to how π_t is set and how the land is split up between sons.

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