Slavery and other property rights

Nils-Petter Lagerlöf*
Department of Economics, York University,
4700 Keele St., Toronto ON Canada M3J 1P3
e-mail: lagerlof@econ.yorku.ca

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Abstract:

The institution of slavery is found mostly at intermediate stages of agricultural development, and less often among hunter-gatherers and advanced agrarian societies. We explain this pattern in a growth model with land and labor as inputs in production, and an endogenously determined property rights institution. The economy endogenously transits from an egalitarian state with equal property rights, to a despotic slave society where the elite own both people and land; thereafter it endogenously transits into a free labor society, where the elite own the land, but people are free.

1 Introduction

One of the most significant institutional transformations of human societies involves property rights in man: slavery. It was not commonly practiced among hunter-gatherers, or in the most advanced agrarian societies. Rather, it has shown up mostly in societies at intermediate stages of pre-industrial development. We explain this pattern by linking slavery to property rights in another important production factor: land.

The basic idea is that the institution of most historical societies can be characterized by the property rights of the elite to land and to people. We argue that a distinct long-term property-rights pattern can be discerned throughout human history. All human societies started off in an egalitarian state with relatively equal division of resources. Over time they transformed first into a state of despotism and slavery, with the elite owning both people and land. Later a transition into a free labor society took place, where the elite owned the land, but people were free. We seek to set up a model replicating this three-stage process. More precisely: we want to model these transitions *endogenously*, and using a setting where the factors driving them, growth in population and technology, are endogenous as well.

The starting point is that slaves require guards (or a military), because slavery amounts to capturing, conquering, and/or suppressing people, and forcing them to work.[1] In our model slavery arises when food procurement technologies are productive enough to generate a surplus of output per agent above subsistence, because this enables the use of people for other tasks than

[1] Slaves have often been the fruit of war, but also when they are traded on a market they require some extra surveillance compared to free workers. For example, in the American South whites were drafted for slave patrols to chase runaway slaves (Hadden 2001).

immediate food production.[2] In that sense, slavery in our model need not be interpreted too literally; we can think of slaves as tax payers, and guards as tax collectors. The point is that the slave's consumption is held to the subsistence level and the "surplus" is extracted by someone else. For the rest of this paper we shall use the term slavery to describe this type of institution.

Our model has two production factors, land and labor, and there are three types of institution. Under slavery the elite own both the land and the subjects' labor. As described, this carries a cost of feeding unproductive guards to watch over the enslaved population. Another institution is that of free labor, where the elite own the land, but the subjects supply their labor on a free market, being paid their marginal product. The third institution is an egalitarian society where the elite and the subjects divide land (or output) equally. The elites across several societies collectively choose institution according to what maximizes their payoffs.[3]

Which institution generates a higher payoff to the elites depends on two state variables: the productivity (or total size) of land, and population size. Slavery dominates when land productivity is high enough, and population density is at intermediate levels: not too high, not too low. For densely populated societies, where free workers are relatively cheap, free labor pays better than slavery. In sparsely populated societies, keeping scarce workers as

[2]Such a surplus would typically arrive with the invention of agriculture. However, slavery also played an important role in many non-agricultural societies with abundant food supply, e.g. aboriginal tribes on the Northwest Coast of North America (Donald 1997). This suggests that the existence of a surplus (rather than the use of agriculture in itself) is what gives rise to slavery.

[3]As discussed in Section 2.6 and in Lagerlöf (2006), the outcome is similar under an equilibrium approach, where each society's elite choose institution independently, taking as given what institutions other elites choose.

unproductive guards is very costly, and an egalitarian structure dominates. Our model thus suggests that population growth has played different roles in history. It was initially a factor transforming egalitarian societies into slave societies, and later a factor driving the transition from slavery to free labor.

This brings us to the dynamic component of our model: the joint evolution of agricultural technology and population. First, consistent with the type of pre-industrial societies we are describing, we let children be a normal good. This gives the model the *Malthusian* feature that higher per-capita incomes induce higher fertility, and faster population growth. Second, we also allow for a "*Boserupian*" effect: population pressure spurs agricultural technological progress (cf. Boserup 1965).

The result is a feedback loop in which the economy moves from a state of low population density and simple agricultural technology toward increasingly dense population and more advanced usage of land. In this process the institution changes endogenously from egalitarianism, to slavery, to free labor.

Our model is also consistent with other historical observations. Under slavery reproductive success (fertility) is more unequally distributed across agents than under egalitarianism and free labor. This is consistent with slave societies being more polygynous than both hunter-gatherer societies, and the type of free labor societies we live in today (Betzig 1986, Lagerlöf 2005, Wright 1994).

Another result in our model is that if an initially densely populated group of societies colonizes a sparsely populated land mass, it may switch from free labor to slavery, as happened when Europeans discovered the Americas.

However, the theory described so far has one shortcoming: if the economy were to experience a slowdown in population growth and/or an acceleration in technological progress (an industrial revolution and a demographic transition), it would re-enter (or never leave) the slavery regime. This is avoided in an extended setting, where guarding costs begin to rise with the level of technology when technology reaches a certain threshold, interpreted as the production mode becoming industrial, or multi-task. This is in line with Fenoaltea (1984), who argues that multi-task production modes are less suitable for slavery.

The rest of this paper is organized as follows. This section continues with an overview of previous literature (Section 1.1), and presents the facts that motivate the whole exercise (Section 1.2). Section 2 sets up the model, and describes how the institution is determined. In Section 3 the dynamics of population and agricultural technology are derived, showing how these state variables evolve over time and generate transitions from one type of institution to another. Section 4 provides some further discussion, by extending the model to allow guarding costs to increase with technology (Section 4.1), and linking some features of the model to further empirical observations (Section 4.2). Section 5 concludes.

1.1 Previous literature

Existing theories of very long-run social evolution are often crafted outside the discipline of economics. These do not make use of explicit models, and typically do not focus on slavery as such (e.g., Flannery 1972, Diamond 1997). One theory specifically about slavery is that of Domar (1970). In his reasoning population density was a force behind the downfall of slavery, as it is in our model. Different from us, however, Domar treats population as exogenous. In reality, as in our model, rising population density seems to be due to improved technologies in food production, and technological change may in and by itself impact the viability of a slave institution, as suggested by Fenoaltea (1984). Abstracting from this Domar is not able to explain the rise of slavery, or why sparsely populated hunter-gather societies so rarely use slavery (cf. the critique in Patterson 1977). However, all this is accounted for in our model.

Aside from the general theories of Domar (1970) and Fenoaltea (1984), many economic historians have studied plantation slavery in the U.S. South,[4] and the rest of the Americas.[5] Our aim is to model the rise and fall of slavery as an institution in a broader world-historic context, and over time spans stretching back before the invention of agriculture.

There is also work on the microeconomics of slavery. Bergstrom (1971) and Findlay (1975) analyze, inter alia, slaves' incentives to work when they can buy their freedom. Genicot (2002) analyzes bound labor as an ex-ante voluntary choice. These papers take the slave system as given, and do not attempt any macroeconomic explanation of its rise or fall. Conning (2004) uses a general-equilibrium framework, and formalizes many of the mechanisms discussed by Domar (1970). (See also Conning 2003.) However, his setting is static, and fertility and population are treated as exogenous, so the model cannot really explain the facts we focus on here. (Section 1.2 below discusses the facts in more detail.) We find Conning's (2004) model complementary to ours.

Contractual relationships between land and labor in agricultural economies is the subject of a large literature (see e.g. Banerjee, Gertler and Ghatak 2002, Conning and Robinson 2006, and further references in these). How-

[4]Some classic works are Conrad and Meyer (1958) and Fogel and Engerman (1974). For an overview, see Hughes and Cain (1998, Ch. 10).

[5]See e.g. Curtin (1998). Sokoloff and Engerman (2000) discuss slavery in the context of Latin America's post-colonial growth experience.

ever, this literature does not share our very long-run perspective, going back to pre-agricultural times, and typically abstracts from property rights in humans (slavery) and how demographic and technological change can cause transitions from one institution to another.[6]

Theories on property rights include Demsetz (1967), who proposes an efficiency explanation, attributing their origin to increasing importance to internalize externalities. Our explanation rather focuses on their redistributive role. In a sense, this is not so much about the origin of property rights, as their reallocation: for example, the introduction of slavery can be interpreted as property rights to agents' labor being transferred from the agents themselves to the elite.

Our paper also relates to a recent literature on long-run economic and demographic development. We share some single components with this literature, like the focus on: land and agriculture (Kögel and Prskawetz 2001; Gollin, Parente and Rogerson 2002; Hansen and Prescott 2002; Lucas 2002); fertility (Galor and Weil 2000; Jones 2001; Tamura 2001; Galor and Moav 2002; Galor and Mountford 2006; Lagerlöf 2003a,b, 2005); and institutions (Acemoglu, Johnson and Robinson 2001, 2002, 2003; Acemoglu and Robinson 2006). However, none of these papers models institutional transformations of human societies endogenously; certainly nothing as complete as what we describe here: from egalitarianism into slavery, and further on into free labor.

In that regard, our modelling approach is conceptually closer to a literature on the origin of property rights. (See e.g. Skaperdas 1992, Hirshleifer 1995, Grossman 2001, Piccione and Rubinstein 2003, Hafer 2006, and further references in these, for models of property rights and conflicts.) The central

[6] See, however, Baker (2002) and Marceau and Myers (2006) for models of landownership in pre-agricultural environments.

theme which we share with these papers is that the exogenous component is not the property rights institution itself, but rather the technologies used in appropriation and production. Appropriation in our model amounts to enslaving an agent (i.e., stealing his labor), which requires an input of guards who do not produce food but still need to be fed.

1.2 The facts

Long-run human history is characterized by increasingly productive ways to use land: from *hunting and gathering*, via different stages of *horticulture* (farming without plows, like "slash-and-burn" cultivation), to *agriculture* (plow-based farming). As food production has evolved, so have other features of human societies, such as population density, the degree of stratification, gender roles, and technologies (e.g., the use of metal weapons and tools). All these changes do not happen at exactly the same stage of agricultural development across societies and regions, but the trend tends to go in the same direction when going from one stage to the next, e.g. from low population density to higher (see Diamond 1997, Flannery 1972, Nolan and Lenski 1999, Wright 2000).

Slavery is an exception. It was rarely practiced among hunter-gatherers, or among the most advanced agrarian societies: in Western Europe serfdom (which can be thought of as a mild form of slavery) had been replaced by free labor several centuries before the industrial revolution.[7] It is rather at

[7]In the first chapter of "Time On the Cross" Fogel and Engerman (1974, p. 12) note that slavery "came into being at the dawn of civilization, when mankind passed from hunting and nomadic pastoral life into primitive agriculture." According to North and Thomas (1971, p. 780) serfdom in Western Europe was "in an advanced state of decay by the end of the fifteenth century." See also Eltis (2000, Ch. 1).

intermediate levels of development that slavery shows up.

Consider some descriptive numbers based on the so-called Ethnographic Atlas, a data set consisting of some thousand human societies, both historic and present.[8] Figure 1 shows how average population density, landownership, and slavery vary across societies at different stages of agricultural development.[9] As seen, when transiting from hunting and gathering to agriculture, population density rises. This is not surprising: the more productive is agricultural technology, the more mouths can be fed. Figure 1 also shows the percent societies at a particular stage of development in which ownership to land is present. As seen, in the process of agricultural development ownership to land becomes more common. Different from the case with landownership, however, slavery, which essentially amounts to ownership of people, is most common among advanced horticultural societies, and less common among both hunter-gatherers and agrarian societies.[10]

The pattern for slavery in Figure 1 would be even clearer if we introduced a final industrial stage, at which slavery had vanished altogether. One could then describe the facts so that slavery *began* its decline in the agrarian stage, and ended it in the industrial stage. (The extension presented in Section 4.1 could be interpreted as capturing the transition into an industrial stage.)

With some simplification, one may thus describe this long-run process as passing through three stages. The first is an egalitarian stage, without property rights to land or people. The second stage is a slave society where

[8]This is a data set compiled originally by the anthropologist G.P Murdock. See Murdock (1967, pp. 3-6) for details.

[9]Figure 1 is based on numbers cited from Nolan and Lenski (1999). Simple horticultural societies in Figure 1 are distinguished from advanced by the use metallurgy in the latter.

[10]See also Patterson (1977), who documents a similar pattern when looking at a smaller subset of the Ethnographic Atlas.

both humans and land are held as property. At the final stage land is owned, but ownership to humans (slavery) is not practiced. In the next section we set up one unified growth model, which can replicate the transition through each of these three stages.

2 The Model

There are several land areas, or societies, each populated at time t by a continuum of (adult) agents of mass P_t, referred to by the male pronoun. A finite number of these agents belong to an (internal) elite, who do not work. The remainder are referred to as non-elite agents. Both (internal) elite and non-elite agents live in overlapping generations for two periods, adulthood and childhood. Children make no decisions, but carry a cost, q, to rear.

Outside each society live an "external" elite of mass one, who may be thought of as a foreign power. These agents are identical to the internal elite (e.g., they do not work), except that they are infinitely lived and have no influence over the choice of institution. However, the internal elite need their help to seize ownership of the land.

Adult agents spend income on own consumption and child rearing. For the moment, denote this income by w_t. We can then write an agent's budget constraint as

$$c_t = w_t - qn_t, \tag{1}$$

where c_t is his consumption, and n_t is his number of children.

Labor supply is indivisible, so that a (non-elite) agent supplies either one unit of labor, or none. Work requires energy: the agent must eat a certain amount of food, $\overline{c}$, to be able to work. We call $\overline{c}$ subsistence consumption.

To capture this, we let preferences take this form:

$$V_t^{\text{work}} = \begin{cases} (1-\beta)\ln c_t + \beta \ln n_t & \text{if } c_t \geq \overline{c}, \\ -\infty & \text{if } c_t < \overline{c}. \end{cases} \tag{2}$$

Solving the utility maximization problem amounts to maximizing the first line in (2), subject to the constraint that $c_t \geq \overline{c}$ (and whatever other constraints are relevant).

For an agent who is not working (which would here be the internal and external elites) the first line in (2) extends to the case when $c_t < \overline{c}$:[11]

$$V_t^{\text{no work}} = (1-\beta)\ln c_t + \beta \ln n_t. \tag{3}$$

2.1 The three institutions

The internal elites across all societies collectively choose one of three institutions. Under an **egalitarian institution** output (or land) is divided equally among non-elite agents and the internal elite[12]; the external elite get nothing. The other two institutions amount to the internal elite joining the external elite to enclose (seize exclusive ownership of) the land. Under a **slavery institution** the elite own *both* the land *and* the non-elite agents' labor, making the agents slaves. These must be paid subsistence to be able to work, as must a fixed number of guards per slave. Under a **free labor institution** the non-elite agents own their own labor and can migrate to work in other societies.

[11]The distinction between working and non-working agents' utilities is not crucial for any of our results, but facilitates the algebra somewhat when comparing payoffs later. In particular, as long as the non-working agent earns an income above $\overline{c}/(1-\beta)$ this distinction will not matter.

[12]We can interpret the model so that the internal elite can work under the egalitarian institution, which can then be thought of as equal division of land, rather than output.

2.2 Timing

In each period, events unfold as follows.

(1) P_t agents (born in the previous period) enter as adults into each society, and technology, A_t, is given.

(2) Taking as given A_t and P_t, the internal elites across all societies first decide collectively whether, or not, to enclose the land in each society. To enclose the land, they need the help of the external elites, with whom they must share profits; following the enclosure they then choose either slavery or free labor. If they choose no enclosure (egalitarianism), they share output equally with the non-elite agents; the external elite get nothing.

(3) Non-elite agents may migrate, if the institution chosen under (2) is not slavery.

(4) Factor prices are determined and payoffs to the elites are realized.

(5) Non-elite agents and elites make consumption and fertility decisions, which update population to P_{t+1}. A technology production function updates technology to A_{t+1}.

A couple of things are worth noting. First, there are no conflicts between the internal elites of different societies at stage (2): because all societies are identical, they unanimously (e.g., through voting) choose the institution that maximizes their payoffs at stage (4). (The non-elite agents and the external elites have no say.)

Second, the internal elites can cooperate only when choosing the institution, but not in other ways. For example, having chosen free labor, they cannot collude on paying a subsistence wage to free workers.[13] (If they could, that would make workers slaves without needing to guard them.) This seems

[13]See e.g. Conning (2003) for a model where landholders exert market power.

realistic, but is not a necessary assumption. The results change very little if there is no cooperation at all between the internal elites across societies, as is discussed in Section 2.6 (see also Lagerlöf 2006).

In what follows, unless otherwise stated, the term "elite" will refer to the internal elite if the institution is egalitarianism, and to the internal and external elite collectively if the institution is slavery or free labor. By "agents" we shall mean non-elite agents when there is no risk of confusion.

2.3 Production

Total output in period t, Y_t, depends on the society's total amount of land, M; agricultural productivity, $\widetilde{A}_t$; and the amount of labor working the land, L_t:

$$Y_t = \left(M\widetilde{A}_t\right)^{\alpha} L_t^{1-\alpha} \equiv A_t^{\alpha} L_t^{1-\alpha}, \tag{4}$$

where $\alpha \in (0,1)$ is the land share of output, and $A_t = M\widetilde{A}_t$ denotes the productivity-augmented size of the land. In other words, A_t can increase either due to a rise in the productivity of land, or due to an increase in the amount of available land (e.g., the discovery of new continents).

2.4 The elite's payoff

Denote the (internal) elite's payoff by π_t^i, where i indicates the institution: egalitarianism ($i = E$), free labor ($i = F$), and slavery ($i = S$).

2.4.1 Payoff in an egalitarian society

Consider first the egalitarian institution. Here, each agent consumes the average product, and that the elite's payoff is the same as that of every other agent, and given by[14]

$$\pi_t^E = A_t^\alpha P_t^{-\alpha}. \tag{5}$$

We implicitly assume that agents are able to work earning the average product ($A_t^\alpha P_t^{-\alpha} \geq \bar{c}$). We can choose initial conditions, (A_0, P_0), to ensure that this holds along the whole path (see Section 3.3 below).

2.4.2 Payoff in a free labor society

Consider next the free labor institution. Here the (internal and external) elite own all land. Agents are landless but can migrate across societies. As a result, the elite hire labor on a competitive market taking the wage rate, w_t, as given.[15] Their payoff is thus given by

$$\pi_t^F = \max_{L_t} \left\{ A_t^\alpha L_t^{1-\alpha} - w_t L_t \right\}. \tag{6}$$

Solving the maximization problem leads to a labor demand function:

$$w_t = (1-\alpha) A_t^\alpha L_t^{-\alpha}. \tag{7}$$

Since an agent must eat $\bar{c}$ to be able to work, labor supply is given by

$$L_t = \begin{cases} P_t & \text{if } w_t \geq \bar{c}, \\ 0 & \text{if } w_t < \bar{c}. \end{cases} \tag{8}$$

[14]This can be derived by dividing total output, $A_t^\alpha P_t^{1-\alpha}$, equally across all P_t agents (the internal elite and non-elite agents). Alternatively, each agent may be allocated property over a share $1/P_t$ of the (productivity-augmented) land, A_t. With his unit time endowment he then produces $[(1/P_t)A_t]^\alpha (1)^{1-\alpha} = A_t^\alpha P_t{}^{-\alpha}$. The latter interpretation assumes that the (internal) elite can work under egalitarianism.

[15]The free labor institution is here modelled as each member of the elite running a farm as his own estate. Equivalently, given the constant-returns-to-scale production function, agents could rent land from the elite.

Depending on A_t and P_t there are now two possible types of equilibrium: one where all agents work, and one where only some of them work. Consider first **Case A**. This is a society with a relatively small population, so that all agents can work and the marginal product of labor still exceeds subsistence consumption, i.e., $(1-\alpha)A_t^{\alpha}P_t^{-\alpha} > \overline{c}$, or $A_t > [\overline{c}/(1-\alpha)]^{1/\alpha} P_t$. The elite simply keep the land share of output, given by $A_t^{\alpha}P_t^{1-\alpha} - w_t P_t$, where $w_t = (1-\alpha)A_t^{\alpha}P_t^{-\alpha}$, i.e.,

$$\pi_t^F = \alpha A_t^{\alpha} P_t^{1-\alpha}. \tag{9}$$

Next, consider **Case B**. This refers to a situation where only some of the agents work and eat; the rest starve and/or die, and the equilibrium wage is kept down to subsistence. Put differently, the number of agents working, L_t, is determined by setting the marginal product of labor equal to subsistence consumption: $(1-\alpha)A_t^{\alpha}L_t^{-\alpha} = \overline{c}$, or $L_t = [(1-\alpha)/\overline{c}]^{1/\alpha} A_t$. Inserted into $A_t^{\alpha}L_t^{1-\alpha} - \overline{c}L_t$ this gives the payoff to the elite as:

$$\pi_t^F = \alpha \left[\frac{1-\alpha}{\overline{c}}\right]^{\frac{1-\alpha}{\alpha}} A_t. \tag{10}$$

We can thus write:

$$\pi_t^F = \begin{cases} \alpha A_t^{\alpha} P_t^{1-\alpha} & \text{if } A_t > \left[\frac{\overline{c}}{1-\alpha}\right]^{\frac{1}{\alpha}} P_t, \\ \alpha \left[\frac{1-\alpha}{\overline{c}}\right]^{\frac{1-\alpha}{\alpha}} A_t & \text{if } A_t \leq \left[\frac{\overline{c}}{1-\alpha}\right]^{\frac{1}{\alpha}} P_t. \end{cases} \tag{11}$$

Note that, as long as $A_t > [\overline{c}/(1-\alpha)]^{1/\alpha} P_t$ (and thus $w_t > \overline{c}$), total output equals $A_t^{\alpha}P_t^{1-\alpha}$ under both egalitarianism and free labor. In other words, no efficiency gains arise from the enclosure of the land, only a redistribution of resources from non-elite agents to the elite. If $A_t \geq [\overline{c}/(1-\alpha)]^{1/\alpha} P_t$ output is in fact lower under free labor because not all agents can survive and work with a competitive wage; an enclosure is then associated with an efficiency loss.

Note also that workers are always better off under egalitarianism than free labor: the average product, $(A_t/P_t)^\alpha$, always exceeds the marginal product, $(1-\alpha)(A_t/P_t)^\alpha$.[16]

2.4.3 Payoff in a slave society

Consider finally the slavery institution. Like under free labor, the (internal and external) elite own all land, but now non-elite agents are slaves. Each slave is paid the minimal amount required to keep him productive, $\overline{c}$. To prevent slaves from running away requires γ agents to guard each slave. We let each guard's consumption be kept to the same level as that of the slaves, $\overline{c}$.[17] Then the cost of keeping S_t slaves equals $(1+\gamma)\overline{c}S_t$.

As will be seen, to ensure that slavery can ever dominate the other two institutions we must assume that the guarding cost is not too high:

Assumption 1 $\alpha(1+\gamma)^{1-\alpha} < 1$.

Under slavery the elite can dispose freely of agents, and not all need to be held as slaves or guards; some may be killed (or given zero income so that they starve). The maximum number of slaves is restricted by the number of agents, P_t, minus the guards needed to watch over them (which, recall,

[16]This result relates to Samuelson's (1974) negative reply to the question "Is the Rent-Collector Worthy of His Full Hire?"

[17]We thus assume that guards are slaves too, and that they (like workers) must be watched over by other guards. More precisely, let $\widetilde{\gamma} < 1$ be the number of guards needed to watch each slave (guard or worker). The cost of keeping S_t working slaves then becomes:

$$\overline{c}S_t + \overline{c}\widetilde{\gamma}S_t + \overline{c}\widetilde{\gamma}^2 S_t + ... = \overline{c}S_t/(1-\widetilde{\gamma}),$$

which is equivalent to our formulation, if $\gamma = \widetilde{\gamma}/(1-\widetilde{\gamma})$.

amounts to γ per slave). Therefore, the number of slaves cannot exceed $P_t/(1+\gamma)$, so the payoff under slavery is given by

$$\pi_t^S = \max_{S_t \leq P_t/(1+\gamma)} \left\{ A_t^\alpha S_t^{1-\alpha} - (1+\gamma)\bar{c}S_t \right\}. \tag{12}$$

Let S_t^* denote the unconstrained choice of S_t in (12) above, given by $(1-\alpha)A_t^\alpha S_t^{-\alpha} - (1+\gamma)\bar{c} = 0$, i.e.,

$$S_t^* = \left[\frac{1-\alpha}{(1+\gamma)\bar{c}} \right]^{\frac{1}{\alpha}} A_t. \tag{13}$$

The elite are unconstrained if the desired number of slaves, plus the γS_t^* guards needed to guard them, are fewer than the total population.[18] This holds if $S_t^*(1+\gamma) \leq P_t$, or

$$A_t \leq \left(\frac{1}{1+\gamma} \right) \left[\frac{\bar{c}(1+\gamma)}{1-\alpha} \right]^{\frac{1}{\alpha}} P_t \equiv \Gamma(P_t;\gamma). \tag{14}$$

Call this **Case 1.** This amounts to keeping S_t^* agents as slaves, and γS_t^* guarding the slaves; the remainder are killed. The payoff is then given by $A_t^\alpha S_t^{*1-\alpha} - (1+\gamma)\bar{c}S_t^*$, which together with (13) and some algebra gives:

$$\pi_t^S = \alpha \left[\frac{1-\alpha}{(1+\gamma)\bar{c}} \right]^{\frac{1-\alpha}{\alpha}} A_t. \tag{15}$$

Next, consider **Case 2**, where the elite is constrained [i.e., $A_t > \Gamma(P_t;\gamma)$]. Thus, $P_t/(1+\gamma)$ agents are kept as slaves, and the remainder used for guarding the slaves. The payoff is thus given by:

$$\pi_t^S = A_t^\alpha \left(\frac{P_t}{1+\gamma} \right)^{1-\alpha} - \bar{c}P_t. \tag{16}$$

We can thus write:

$$\pi_t^S = \begin{cases} A_t^\alpha \left(\frac{P_t}{1+\gamma} \right)^{1-\alpha} - \bar{c}P_t & \text{if } A_t > \Gamma(P_t;\gamma), \\ \alpha \left[\frac{1-\alpha}{(1+\gamma)\bar{c}} \right]^{\frac{1-\alpha}{\alpha}} A_t & \text{if } A_t \leq \Gamma(P_t;\gamma). \end{cases} \tag{17}$$

[18] It can be seen that, in this case, slavery will be dominated by free labor.

An alternative way to derive the payoff in (17) is to let slaves be traded on a market at an endogenously given slave price. The slave price being positive in equilibrium can then be seen to be equivalent to $A_t > \Gamma(P_t; \gamma)$ (see Lagerlöf 2006).

2.4.4 A principal-agent interpretation of slavery and free labor

The payoffs under free labor and slavery can be derived from a principal-agent setting (see Lagerlöf 2006). The principal (the elite) chooses how much to pay each agent (slave or free worker), subject to three constraints. An incentive compatibility constraint states that the worker voluntarily chooses to work (exert effort); this requires that he is fed at least $\overline{c}$ (i.e., exerting effort costs $\overline{c}$ units of energy to the agent). A limited liability constraint constitutes a non-negativity restriction on payments to agents, regardless of effort level. Finally, a participation constraint requires that the agent does not run away: either guards can make running away impossible (slavery), or the worker can be paid as much as his best outside option (free labor).

The idea that guards prevent slaves from running away fits with evidence from some slave societies. For example, slave patrols in the U.S. South were used to catch runaway slaves (Hadden 2001). One can alternatively think of guards as inflicting pain on slaves who do not work. That would amount to a different formulation of the limited liability constraint, so that the agent could be made worse off if not working than merely losing his pay.

2.5 Comparing payoffs

The next step is to examine which payoff is larger: π_t^E, π_t^F, or π_t^S, as given by (5), (11), and (17), respectively.

Distinguishing between internal and external elites has served to make these payoff comparisons technically correct. Intuitively, the internal elite are a finite number of agents, and thus vanishingly small compared to the non-elite population, so under egalitarianism their share of the pie is also vanishingly small, and always less than the non-negligible fractions taken under slavery and free labor. However, π_t^F and π_t^S in (11) and (17) are divided among a continuum of agents of mass one, making them of the same order as π_t^E in (5). The elite effectively changes size from zero to unit mass when institutions change. The interpretation is that the internal elites decide what group to share output with: either the domestic non-elite agents (egalitarianism), or an external elite (landownership).[19]

The payoffs all depend on agricultural technology, A_t, and population size, P_t (and exogenous parameters), which thus determine what institution dominates the other two. Ranking the payoffs is algebraically quite messy, due to the way the subsistence consumption constraint affects how the payoffs are calculated, forcing us to consider several different cases. However, most of the details can be dealt with in the Appendix; once we know which payoff pairs are relevant for the comparisons we make, the results are quite intuitive.

Begin by defining

$$\Psi(P) = \left[\frac{\overline{c}(1+\gamma)^{1-\alpha}}{1-\alpha(1+\gamma)^{1-\alpha}}\right]^{\frac{1}{\alpha}} P, \tag{18}$$

[19] Alternatively, we could let there be only one elite carrying unit mass. If this elite can work under egalitarianism, total output equals $A_t^\alpha(1+P_t)^{1-\alpha}$ and the elite's payoff under egalitarianism becomes $\pi_t^E = A_t^\alpha(1+P_t)^{-\alpha}$. In such a setting, the qualitative results in Proposition 1 below still hold, but the analysis is more complicated. See Lagerlöf (2006).

where $1-\alpha(1+\gamma)^{1-\alpha}>0$ follows from Assumption 1;

$$\Omega(P)=\left[\frac{\overline{c}(1+\gamma)^{1-\alpha}P^{1+\alpha}}{P-(1+\gamma)^{1-\alpha}}\right]^{\frac{1}{\alpha}}; \tag{19}$$

and

$$\Phi(P)=\left(\frac{1}{\alpha}\right)^{\frac{1}{1-\alpha}}\left[\frac{\overline{c}}{1-\alpha}\right]^{\frac{1}{\alpha}}P^{-\left(\frac{\alpha}{1-\alpha}\right)}. \tag{20}$$

These functions separate the state space into three sets:

$$\begin{aligned}\mathcal{S}^S&=\{(A,P)\in\mathbb{R}_+^2: A\geq\max\{\Psi(P),\Omega(P)\}\text{ and }P>(1+\gamma)^{1-\alpha}\},\\ \mathcal{S}^F&=\{(A,P)\in\mathbb{R}_+^2: P\geq 1/\alpha\text{ and }\Phi(P)\leq A\leq\Psi(P)\},\\ \mathcal{S}^E&=\{(A,P)\in\mathbb{R}_+^2:(A,P)\notin\mathcal{S}^S\cup\mathcal{S}^F\}.\end{aligned} \tag{21}$$

We can now state the following (proven in the Appendix):

Proposition 1 *The payoffs associated with slavery, egalitarianism, and free labor are ordered as follows:*
(a) Slavery (weakly) dominates when

$$\pi_t^S\geq\max\{\pi_t^F,\pi_t^E\}\Longleftrightarrow(A_t,P_t)\in\mathcal{S}^S. \tag{22}$$

(b) Free labor (weakly) dominates when

$$\pi_t^F\geq\max\{\pi_t^S,\pi_t^E\}\Longleftrightarrow(A_t,P_t)\in\mathcal{S}^F. \tag{23}$$

(c) Egalitarianism (strictly) dominates otherwise, i.e., when $(A_t,P_t)\in\mathcal{S}^E$.

This is illustrated in Figure 2. The institutional borders are straightforward to derive when we know the relevant payoffs to compare. As shown in the Appendix, these are (with one exception): $\pi_t^S=A_t^\alpha[P_t/(1+\gamma)]^{1-\alpha}-\overline{c}P_t$, $\pi_t^F=\alpha A_t^\alpha P_t^{1-\alpha}$, and $\pi_t^E=A_t^\alpha P_t^{-\alpha}$. Some algebra then easily verifies that:

$\pi_t^S \geq \pi_t^F$ when $A_t \geq \Psi(P_t)$; $\pi_t^S \geq \pi_t^E$ when $A_t \geq \Omega(P_t)$ [if the denominator in (19) is positive; else $\pi_t^S < \pi_t^E$]; and $\pi_t^F \geq \pi_t^E$ when $P_t \geq 1/\alpha$.[20]

Slavery thus dominates the other two institutions when $A_t \geq \Psi(P_t)$ and $A_t \geq \Omega(P_t)$, i.e., at high enough levels of land productivity, A_t, and intermediate population levels, P_t. The productivity of land determines the size of the pie to be split; the larger is the pie, the greater is the reward to taking a larger fraction of it at the cost of diminishing its size a little, which is what slavery amounts to doing.

The impact of population size works through the marginal product of labor. If labor is scarce, keeping workers as guards is very costly, so slavery is not an attractive option to the elite. Also, a high land-labor ratio implies a low payoff to owning the land and hiring free workers. The (internal) elites may thus prefer egalitarianism, where their share is larger the smaller is population. Vice versa, a very large population makes it attractive to own land, since the marginal product of land is high. Also, a large population favors free labor over slavery, because it implies a relatively low competitive price on free workers, who do not need guards.

2.6 The equilibrium institution

We could instead look at what institution arises in equilibrium if the (internal) elites choose institutions independently, taking as given all other elites' choices, rather than acting cooperatively. One may suspect this to generate

[20]When comparing the last pair of payoffs the exception shows up: for free labor to dominate egalitarianism $P_t \geq 1/\alpha$ is not sufficient. If the competitive wage rate is so low that it does not cover the subsistence consumption of free workers, the relevant payoff under free labor is given by the second line in (11). Egalitarianism then turns out to dominate free labor if $A_t \leq \Phi(P_t)$.

different results because institutional choices carry many potential externalities which are not internalized under the equilibrium approach. For example, wages depend on aggregate labor supply and thus on the number of elites choosing free labor.

However, as shown in Lagerlöf (2006), the equilibrium approach in fact generates results which are similar to the optimal approach taken here. For any given (A_t, P_t), there exists an equilibrium where all elites choose the same institution as the one given in Proposition 1. This equilibrium need not be unique: for example, there exists an interval around $P_t = 1/\alpha$, where all elites may choose egalitarianism, or all may choose free labor, in equilibrium. However, if we make the (arguably plausible) assumption that the elites in egalitarian societies can prevent immigration from free labor societies, even uniqueness is guaranteed.

The mentioned externalities do not matter because they are neutralized by symmetric effects on the supply side. For example, by choosing free labor the elite increase both supply and demand for free labor, by both freeing their agents and hiring free workers. As long as all societies are identical these demand and supply effects cancel.

3 Dynamics

Having determined how the institution depends on population and agricultural technology, we next look at how these evolve over time.

3.1 Agricultural technology

We let A_t evolve according to

$$A_{t+1} = \overline{A} + D(A_t - \overline{A})^{1-\theta} P_t^{\theta}, \tag{24}$$

where $D > 0$, and $\theta \in (0, 1)$, and $\overline{A} > 0$ is a minimum level of agricultural technology, imposed to ensure the existence of steady states with non-growing levels of A_t and P_t.

The Boserupian feature of this relationship is that A_t grows faster the higher is population pressure, i.e., when P_t is large relative to A_t. One example could be the very birth of farming, which may have followed the extinction of big mammals, like the mammoth (Smith 1975, 1992). Other examples could be intensified land use, or rising cropping frequency, in response to increasing population density in agricultural societies. It could also capture a scale effect from population density to technological progress (see, e.g., Kremer 1993, Nestmann and Klasen 2000, Lagerlöf 2003a).

3.2 Population

The population dynamics are more complicated, since fertility depends on total income, how it is allocated (i.e., the institution), and whether, or not, the subsistence consumption constraint binds for agents. However, we can impose a parametric restriction which implies that, when it does bind, population is falling (see Assumption 2 below).

3.2.1 Population dynamics in a free labor society

The landowning (internal and external) unit-mass elite have $n_t^{\text{landowner}}$ children and the P_t workers have n_t^{worker} children each. Since all agents in the society die after adulthood, population dynamics are given by[21]

$$P_{t+1} = n_t^{\text{worker}} P_t + n_t^{\text{landowner}}. \tag{25}$$

Consider the elite's fertility first. They do not work so the ($c_t \geq \overline{c}$)-constraint is irrelevant, and fertility is given by maximizing (3), subject to (1), with π_t^F replacing w_t. This gives $n_t^{\text{landowner}} = \beta\pi_t^F/q$.

For workers the ($c_t \geq \overline{c}$)-constraint matters. Maximizing each worker's utility function in (2), subject to (1), gives the worker fertility rate as

$$n_t^{\text{worker}} = \begin{cases} \frac{w_t - \overline{c}}{q} & \text{if } w_t < \frac{\overline{c}}{1-\beta}, \\ \frac{\beta w_t}{q} & \text{if } w_t \geq \frac{\overline{c}}{1-\beta}. \end{cases} \tag{26}$$

The case when $w_t < \overline{c}/(1-\beta)$ complicates things, but is simplified by the following assumption:

Assumption 2 $\frac{\beta\overline{c}}{(1-\beta)q} < 1 - \alpha.$

We can now state the following:

Proposition 2 *In a free labor society population evolves as follows:*
(a) If $w_t \geq \overline{c}/(1-\beta)$,

$$P_{t+1} = \frac{\beta A_t^\alpha P_t^{1-\alpha}}{q}. \tag{27}$$

(b) If $w_t < \overline{c}/(1-\beta)$, *population is falling:* $P_{t+1} < P_t$.

The proof is in the Appendix. Part (b) hinges on Assumption 2.

[21]Note that children of the external elite enter the society's population as non-elite agents.

3.2.2 Population dynamics in an egalitarian society

In an egalitarian society all agents have the same income, which (recall) is given by $\pi_t^E = A_t^\alpha P_t^{-\alpha}$ [see (5)]. Let fertility be denoted n_t^{egal}, which is given by maximizing (2) subject to $c_t = \pi_t^E - qn_t$. Fertility thus takes the same form as in the free labor case in (26) above:

$$n_t^{\text{egal}} = \begin{cases} \frac{\pi_t^E - \bar{c}}{q} & \text{if } \pi_t^E < \frac{\bar{c}}{1-\beta}, \\ \frac{\beta\pi_t^E}{q} & \text{if } \pi_t^E \geq \frac{\bar{c}}{1-\beta}. \end{cases}$$

Since all P_t agents have the same fertility it must hold that $P_{t+1} = P_t n_t^{\text{egal}}$. (The external elite have no income and thus zero fertility.) We can now state the following:

Proposition 3 *In an egalitarian society population evolves as follows:*
(a) If $\pi_t^E \geq \bar{c}/(1-\beta)$, P_{t+1} is given by (27).
(b) If $\pi_t^E < \bar{c}/(1-\beta)$, population is falling: $P_{t+1} < P_t$.

The proof is in the Appendix. Again, part (b) uses Assumption 2.

3.2.3 Population dynamics in a slave society

In a slave society, the consumption of slaves is constrained to subsistence. Given the way we have formulated preferences in (2), slave fertility is thus zero, and all children are fathered by the (internal and external) elite.[22] This is consistent with the historical evidence. In despotic societies (corresponding to slave societies here) elites have been strongly polygynous in both mating and marriage, with rich rulers having more wives and offspring than their

[22] The feature that the elite rear all children is not important. Introducing, for example, a subsistence level for fertility in (2), as we have for consumption, slaves too would have some offspring.

subjects; hunter-gatherer societies, and free societies (like the one we live in today), have been more monogamous, displaying a more equal distribution of women and fertility (Betzig 1986, Wright 1994).[23]

Thus, population in period $t+1$ is given by the elite's fertility in period t, denoted $n_t^{\text{slaveowner}}$. This is given by maximizing (3), subject to (1), with π_t^S replacing w_t, giving $n_t^{\text{slaveowner}} = \beta\pi_t^S/q$. We can now state the following:

Proposition 4 *In a slave society, population evolves as follows:*
(a) If $A_t > \Gamma(P_t;\gamma)$,

$$P_{t+1} = \frac{\beta}{q}\left[A_t^{\alpha}\left(\frac{P_t}{1+\gamma}\right)^{1-\alpha} - \bar{c}P_t\right]. \tag{28}$$

(b) If $A_t \leq \Gamma(P_t;\gamma)$, *population is falling:* $P_{t+1} < P_t$.

The proof is in the Appendix. Again, part (b) uses Assumption 2.

3.3 The phase diagram

To analyze the dynamics of A_t and P_t in a phase diagram we begin by deriving expressions for the loci along which A_t and P_t are constant.

Proposition 5 *(a) Population is constant* ($P_{t+1} = P_t$) *when*

$$A_t = \begin{cases} \left(\frac{q}{\beta}\right)^{\frac{1}{\alpha}} P_t \equiv \mathbf{L}^{E/F}(P_t) & \text{if } (A_t, P_t) \in \mathcal{S}^E \cup \mathcal{S}^F, \\ (1+\gamma)^{\frac{1-\alpha}{\alpha}} \left(\frac{q}{\beta} + \bar{c}\right)^{\frac{1}{\alpha}} P_t \equiv \mathbf{L}^S(P_t) & \text{if } (A_t, P_t) \in \mathcal{S}^S. \end{cases} \tag{29}$$

[23] Polygynous mating habits were widespread among the elites of all early human civilizations in Mesopotamia, Egypt, China, India, and Middle and South America (Betzig 1993), and in the Roman Empire (Betzig 1992). The Mongolian Empire is another example: geneticists have estimated that, across a large region of Asia from the Pacific to the Caspian Sea, about 8% of the male population (16 million men) are descendents of Genghis Kahn (Zerjal et al. 2003). See also Lagerlöf (2005).

(b) Technology is constant ($A_{t+1} = A_t$) when

$$A_t = \overline{A} + D^{\frac{1}{\theta}} P_t \equiv \mathbf{L}^A(P_t). \tag{30}$$

Proof: Part (a) follows from Propositions 2, 3, and 4. Part (b) follows from (24). ‖

Examples of these loci are shown in Figures 3 and 4. A steady state is a point where both A_t and P_t are constant, as given by an intersection of the functions in (29) and (30). The motion arrows show how the state variables evolve off the loci. Exogenous parameters determine the shape of the loci, and in what institutional regions the steady state(s) lie (if any steady state exists at all). Initial conditions, (A_0, P_0), determine what regions the economy passes in the transition.

Note that it follows from (5), (29), and Assumption 2 that for any economy starting off in the egalitarian region above $\mathbf{L}^{\mathrm{E/F}}(P_t)$, it must hold that $\pi_t^E > \overline{c}$ along the path throughout the egalitarian region.

The following proposition tells us when a free labor or egalitarian steady state may exist.

Proposition 6 *(a) If, and only if,*

$$\left(\frac{q}{\beta}\right)^{\frac{1}{\alpha}} > D^{\frac{1}{\theta}}, \tag{31}$$

$$\frac{q}{\beta} \leq \frac{\overline{c}(1+\gamma)^{1-\alpha}}{1-\alpha(1+\gamma)^{1-\alpha}}, \tag{32}$$

then there exists a finite $\overline{A}^F > 0$, such that for any $\overline{A} \geq \overline{A}^F$ there exists a steady state in the free labor region, $\mathcal{S}^F$.
(b) If, and only if, (31) holds, then for some (sufficiently small) $\overline{A} > 0$ there exists a steady state in the egalitarian region, $\mathcal{S}^E$.

The proof is in the Appendix. Intuitively, the condition in (31) ensures that the mutually reinforcing Boserupian and Malthusian forces are weak enough so that, under the free-labor/egalitarian population dynamics in (27), population and technology converge in levels. The condition in (32) ensures that the cost of children (q) is low enough, and the utility weight on children (β) is high enough, so that population is not falling throughout the free labor region; in terms of Figure 3, (32) ensures that $\mathbf{L}^{\mathrm{E/F}}(P_t)$ is flatter than $\Psi(P_t)$. We can then choose $\overline{A}$ to make $\mathbf{L}^{\mathrm{A}}(P_t)$ intersect $\mathbf{L}^{\mathrm{E/F}}(P_t)$ in either the free labor, or the egalitarian, region (but not in both).[24]

Next we examine when a steady state with slavery may exist.

Proposition 7 *If, and only if,*

$$(1+\gamma)^{\frac{1-\alpha}{\alpha}}\left(\frac{q}{\beta}+\overline{c}\right)^{\frac{1}{\alpha}} > D^{\frac{1}{\theta}}, \tag{33}$$

$$\frac{q}{\beta} \geq \frac{\alpha\overline{c}(1+\gamma)^{1-\alpha}}{1-\alpha(1+\gamma)^{1-\alpha}}, \tag{34}$$

then there exists a finite $\overline{A}^S > 0$*, such that for any* $\overline{A} \geq \overline{A}^S$ *there exists a steady state in the slavery region,* $\mathcal{S}^S$*.*

The proof is the Appendix. The intuition resembles that behind Proposition 6. If (33) holds population and technology converge in levels. This condition is weaker than (31), because for any given (A_t, P_t) population growth is slower under slavery than under the other two institutions [cf. (27) and (28)]; this follows from total income under slavery being lower because agents are used as unproductive guards. The condition in (34) implies that the child

[24]From (29) and (30), the levels of A_t and P_t in a steady state with free labor or egalitarianism are $P^* = \overline{A}/[(\beta/q)^{\frac{1}{\alpha}} - D^{\frac{1}{\theta}}]$, and $A^* = (\beta/q)^{\frac{1}{\alpha}}\overline{A}/[(\beta/q)^{\frac{1}{\alpha}} - D^{\frac{1}{\theta}}]$.

cost and preference parameters (q and β) are such that population is not growing throughout the slavery region. That is, using (18), (29), and some algebra, it is seen that (34) ensures that $\mathbf{L}^{\mathrm{S}}(P_t)$ is steeper than $\Psi(P_t)$ (cf. Figure 4). We can then choose $\overline{A}$ to make $\mathbf{L}^{\mathrm{A}}(P_t)$ intersect $\mathbf{L}^{\mathrm{S}}(P_t)$ in the slavery region.[25]

3.3.1 A full transition

Figure 3 illustrates the case when a steady state with free labor exists, but none with slavery (or egalitarianism). That is, the conditions in Proposition 6 (a) hold, but not those in Proposition 7,[26] and $\overline{A}$ exceeds $\overline{A}^F$. We can now choose initial conditions so that the economy passes all three institutional regions. To see this, let the economy start off within the egalitarian region, above $\overline{A}$. [Note from (24) that A_t cannot fall below $\overline{A}$.] If this initial point is close to the slavery region the path goes through the slavery region before converging to the steady state in the free labor region. Such a trajectory is illustrated in Figure 3.[27]

[25]From (29) and (30), the levels of A_t and P_t in a steady state with slavery are:

$$\begin{aligned} P^* &= \frac{\overline{A}}{(1+\gamma)^{\frac{1-\alpha}{\alpha}}(\beta/q+\overline{c})^{\frac{1}{\alpha}} - D^{\frac{1}{\theta}}}, \\ A^* &= \frac{(1+\gamma)^{\frac{1-\alpha}{\alpha}}(\beta/q+\overline{c})^{\frac{1}{\alpha}}\overline{A}}{(1+\gamma)^{\frac{1-\alpha}{\alpha}}(\beta/q+\overline{c})^{\frac{1}{\alpha}} - D^{\frac{1}{\theta}}}. \end{aligned}$$

[26]More precisely, (34) does not hold, and therefore $\mathbf{L}^{\mathrm{S}}(P_t)$ does not pass through $\mathcal{S}^S$. However, because (31) holds, so does (33).

[27]Figure 3 only shows the qualitative dynamics, i.e., the direction in which technology and population move. In fact, the trajectory will not be a straight line; its path changes slope as the economy enters the slavery region, where it starts to evolve according to (28) instead of (27). However, as long as the inequality in (34) is reversed, population continually grows in the slavery region, and eventually exits into the free labor region.

In this transition, population and technology grow in tandem through mutual reinforcement: advances in agricultural technology raise incomes and thus generate population growth in a Malthusian fashion; this feeds back into more technological progress through the Boserupian effect.

3.3.2 Multiple steady states

As illustrated in Figure 4, a steady state in the free labor region may coexist with one in the slavery region.[28] This requires that the conditions in both Proposition 6 (a), and Proposition 7 hold, and that $\overline{A}$ exceeds both $\overline{A}^F$ and $\overline{A}^S$. That is, q/β lies on the interval defined by the right-hand sides of (34) and (32). Both steady states can be seen to be locally stable, so that an economy which enters the slavery region never exits, and likewise for an economy which enters the free labor region (absent shocks to population, technology, or exogenous parameters). Initial conditions thus determine where the economy ends up. The slavery steady state is a stagnant trap in the sense that it has relatively low levels of both population and technology.

Figure 4 may illustrate how two groups of societies (two empires, if you wish) may co-exist, one in the slavery trap, and one in the free labor region. The free labor society has larger population and higher levels of technology. One can also imagine a scenario where one society is initially leading but converges to a slavery trap, and another society starts off behind in the egalitarian region, but follows a trajectory into free labor. (The two societies could have different initial conditions, or be subject to different shocks.) Such changing leadership may capture something about Western Europe's overtaking of other (more despotic, less free) Eurasian regions in the centuries

[28]However, a steady state in the free labor region cannot coexist with one in the egalitarian region, since $\mathbf{L}^{\mathrm{E/F}}(P_t)$ cannot intersect $\mathbf{L}^{\mathrm{A}}(P_t)$ more than once.

leading up to the industrial revolution (cf. Landes 1999).

4 Discussion

4.1 Industrial technology and Fenoaltea (1984)

This model has the feature that (all else equal) slavery tends to dominate over free labor in more technologically advanced societies. This fits with some examples: the U.S. South during the slave era was more technologically advanced than Western Europe when serfdom ended there; Prussian serfdom was technologically superior to the free labor system that preceded it.

However, there is one problem with this feature of the model. A couple of hundred years ago, (parts of) the world experienced accelerating growth in technology, followed by declining population growth: an industrial revolution and a demographic transition. This would suggest that the industrialized world should return to slavery, quite contrary to the evidence.

There are extensions of our model where this does not happen. So far we have talked about advances in pre-industrial technologies. Some argue that slavery died out due to the rise of industrial production modes, involving a larger number of work tasks, thus making slavery more costly in terms of supervision.[29] Put differently, industrial production is more "care intensive" as opposed to "effort intensive." In essence, this is what Fenoaltea (1984) suggests.

To model this in more detail we could let the slave have better information about how long time each task takes, or the quality of the work performed.

[29] By "industrial production modes" we here mean that they involve many tasks. For example, on manors in feudal Europe, serfs were used, rather than chattel slaves, because of the many tasks involved (North and Thomas 1973, p. 20).

In more multi-task environments, an award system closer to that of free labor may then be more cost efficient.[30]

To introduce a similar mechanism within the framework applied here we can assume that the number of guards needed per slave, γ, begins to increase in A_t once production leaves the agrarian mode, and enters an industrial mode. Define this as A_t exceeding some threshold, $\widetilde{A}$. Thus, for $A_t \geq \widetilde{A}$, the payoff under slavery, π_t^S, may increase less (relative to π_t^F and π_t^E) in response to advances in A_t.

The qualitative change is illustrated in Figure 5.[31] For $A_t \leq \widetilde{A}$, the diagram is identical to that in Figure 2. For $A_t \geq \widetilde{A}$, the new institutional borders are denoted $\widetilde{\Omega}(P_t)$ and $\widetilde{\Psi}(P_t)$. Compared to Figure 2, the free labor and egalitarian regions are larger at the expense of the slavery region, reflecting that slavery is more expensive in terms of supervision. For A_t high enough, slavery never dominates. In this setting slavery must eventually die out if either population or technology exhibit sustained growth.

[30] Aghion and Tirole (1997) is one example of a principle-agent model where the principal (here a slaveowning elite) may find it in his interest to transfer formal authority (freedom) to the agent (the slave). See also Banerjee et al. (2002) and the discussion in Section 2.4.4.

[31] Figure 5 is drawn letting the number of guards per slave be given by

$$\gamma(A_t) = \begin{cases} \overline{\gamma} & \text{if } A_t \leq \widetilde{A}, \\ (1+\overline{\gamma})(A_t/\widetilde{A})^{\theta} - 1 & \text{if } A_t \geq \widetilde{A}, \end{cases}$$

where $\overline{\gamma} > 0$, and $\widetilde{A} > 0$. It can be seen that a slavery region exists for large enough $\widetilde{A}$. See Lagerlöf (2006) for details.

4.2 Empirical applications

4.2.1 An exogenous increase in the supply of land

In this model, an exogenous increase in the supply of land at any given population size can be thought of as a fall in population per unit of land, and thus a movement to the left on the P_t-axis in any of the phase diagrams. [Alternatively, it can be thought of as an upward shift on the A_t-axis due to a rise in M; see (4)]. This may cause a (reversed) transition from free labor to slavery.

Domar (1970) provides two examples of such scenarios. First, the discovery of the Americas, at the time when serfdom and slavery had died out in most of Europe, led to the reintroduction of slavery on a large scale. The other example is the Russian 16th century military land conquests, which expanded Russian territory and made peasants migrate to these new lands. Landowners (by lobbying the central government) then imposed restrictions on the peasants' freedom of movement, thus introducing serfdom.

4.2.2 Slavery in the Americas

Consistent with our model, slavery in the Americas was used mostly where the marginal product of labor was high, i.e., in regions where valuable commodities could be grown (Sokoloff and Engerman 2000).

It also seems that scarcity of free (white) labor meant more (African) slave imports. Slavery was less common where Europeans migrated, i.e., to regions with a temperate climate, and low (European settler) mortality (cf. Coelho and McGuire 1997; Acemoglu et al. 2001, 2002; Mitchener and Mclean 2003, p. 93).

Preceding African slavery was the practice of *white servitude*, meaning that European migrants paid for the ticket across the Atlantic by committing to a work contract. White servitude was not comparable to chattel slavery, but neither was it the same as free labor. For example, the work process often involved physical punishment (see Grubb 1994, Emmer 1986). White servitude seems to have been driven by labor shortage, being practiced in e.g. the sparsely populated Canada, but absent in Latin America, where native labor was more abundant. It seems to have vanished with advances in shipping, which made some regions experience an inflow of free migrants, and others African slaves.

4.2.3 European serfdom and the Black Death

The centuries leading up to the Black Death in Europe saw fast population growth, explaining the decline of serfdom in this period (Domar 1970, pp. 27-28). However, the fall in population following the Black Death did not lead to a transition back to slavery, or serfdom, as our model may suggest.

However, attempts to reintroduce serfdom were made. These failed due to a lack of a central authority able to control peasants' movements (see, e.g., North and Thomas 1971). An extension of our model which could capture this would be one where freedom gradually empowers agents, making the cost of guarding, γ, increase. Note also that a fall in population in our model will always make workers better off as long as the economy does not transit back into slavery. This is perfectly consistent with the rise in living standards following the Black Death.

As a final point, in a wider historical perspective the population reduction following the Black Death may not have been large enough. According to McEvedy and Jones (1978, p. 18) European population fell from 79 million in 1350 to 60 million in 1400 (back to the levels of 1200; it had recovered by 1500). By comparison, population at the time of the fall of the Roman Empire in A.D. 600 was 26 million.

5 Conclusions

This paper presents a unified explanation of a long-run three-stage process through which human societies, from hunter-gatherer times up until recently, have changed property rights institutions. In our model, an economy starting off in an egalitarian state with communal property rights transits endogenously into a despotic slave society, where the elite own both people and land. Thereafter it transits endogenously into a free labor society, where the elite own the land, but people are free.

The institution at any point in time is selected according to what maximizes the elites' payoffs. Two state variables, agricultural technology and population, grow endogenously over time. In an initial state with low levels of technology and small population an egalitarian regime dominates. As population and technology expand the egalitarian regime is replaced by a slave regime. Further population expansion pushes the economy from slavery into free labor, by lowering the marginal product of labor, and thus the wage rate. As a potentially countervailing force, however, growth in technology may keep the marginal product of labor from declining, thus making the economy either re-enter a slavery state, or never leave it. However, allowing for rising costs of guarding as industrial (or multi-task) production modes are introduced, slavery must always die out if population and/or technology keep growing.

In this model, transitions from one institution to another do not involve conflicts, because all societies are identical. To relax this assumption we could assume that slave labor is relatively more productive in some societies compared to others. For example, climate may determine which crops can be grown, and some crops (like cotton, tobacco, and sugar) can be more suitable for slave labor than others (Sokoloff and Engerman 2000). Then the type of externalities discussed in Section 2.6 matter: some elites may e.g. want other elites to free their slaves to reduce wages. This may describe conflicts between U.S. states in the 19th century.

Our aim has been to seek an *ultimate*, as opposed to proximate, explanation of the rise and fall of slavery (cf. Diamond 1997). Another approach would be to explain the rise or downfall of slavery in one particular context, by one particular event (or set of events), e.g. the Civil War in the case of the U.S. This would leave open the question what caused that event, and would not explain why similar scenarios played out elsewhere, in other contexts (e.g. the decline of serfdom in Europe), and sometimes in the reverse (e.g. the re-birth of slavery after the discovery of the Americas). To find an ultimate explanation we must identify the underlying economic fundamentals that determine institutions. This of course comes at the cost of leaving many proximate factors out, i.e., "black-boxing" how fundamental economic conditions transmit themselves into institutional outcomes. Opening this box is an important challenge for future work.

APPENDIX. PROOFS

Proof of Proposition 1: The proof is done by first finding conditions for $\pi_t^S \geq \pi_t^E$, $\pi_t^F \geq \pi_t^E$, and $\pi_t^F \geq \pi_t^S$, and then deriving conditions for $\pi_t^S \geq \max\left\{\pi_t^F, \pi_t^E\right\}$, $\pi_t^F \geq \max\left\{\pi_t^E, \pi_t^S\right\}$, and $\pi_t^E \geq \max\left\{\pi_t^F, \pi_t^S\right\}$.

Conditions for $\pi_t^S \geq \pi_t^E$: Here we need to distinguish between two cases for calculating π_t^S. Consider first Case 1, which upon recalling (14) can be written as $A_t \leq \Gamma(P_t;\gamma)$. Using (5) and the second line of (17), we see that $\pi_t^S \geq \pi_t^E$ when $\alpha\{(1-\alpha)/[(1+\gamma)\overline{c}]\}^{\frac{1-\alpha}{\alpha}} A_t \geq A_t^\alpha P_t^{-\alpha}$, or

$$A_t \geq \left(\frac{1}{\alpha}\right)^{\frac{1}{1-\alpha}} \left[\frac{\overline{c}(1+\gamma)}{1-\alpha}\right]^{\frac{1}{\alpha}} (P_t)^{-\left(\frac{\alpha}{1-\alpha}\right)} \equiv \Lambda(P_t). \tag{A1}$$

Consider next Case 2: $A_t > \Gamma(P_t;\gamma)$. Using (5) and the first line of (17), we see that $\pi_t^S \geq \pi_t^E$ when $A_t^\alpha \left(P_t/[1+\gamma]\right)^{1-\alpha} - \overline{c}P_t \geq A_t^\alpha P_t^{-\alpha}$. This requires both that $P_t > (1+\gamma)^{1-\alpha}$ and $A_t \geq \Omega(P_t)$, where $\Omega(P_t)$ is defined in (19). Considering both cases together we thus conclude:

$$\pi_t^S \geq \pi_t^E \iff \text{either } \Gamma(P_t;\gamma) \geq A_t \geq \Lambda(P_t) \text{ or } \left\{\begin{array}{c} A_t \geq \max\left\{\Omega(P_t), \Gamma(P_t;\gamma)\right\} \\ \text{and} \\ P_t > (1+\gamma)^{1-\alpha} \end{array}\right\}. \tag{A2}$$

Conditions for $\pi_t^F \geq \pi_t^E$: Here we need to distinguish between the two cases for calculating π_t^F. Consider first Case A: $A_t > [\overline{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t$. Using (5) and the first line in (11) we see that $\pi_t^F \geq \pi_t^E$ when $\alpha A_t^\alpha P_t^{1-\alpha} \geq A_t^\alpha P_t^{-\alpha}$, or

$$P_t \geq \frac{1}{\alpha}. \tag{A3}$$

Consider next Case B: $A_t \leq [\overline{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t$. Using (5) and the second line in (11) we see that $\pi_t^F \geq \pi_t^E$ when $\alpha\left[(1-\alpha)/\overline{c}\right]^{\frac{1-\alpha}{\alpha}} A_t \geq A_t^\alpha P_t^{-\alpha}$. This gives $A_t \geq \Phi(P_t)$, where $\Phi(P_t)$ is defined in (20).

It can be seen that $[\bar{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t$ is always greater than $\Phi(P_t)$ when P_t exceeds $1/\alpha$. Considering both cases together we thus conclude:

$$\pi_t^F \geq \pi_t^E \iff P_t \geq \frac{1}{\alpha} \text{ and } A_t \geq \Phi(P_t). \tag{A4}$$

Conditions for $\pi_t^F \geq \pi_t^S$: Here the payoffs involve two cases each. Consider first the combination of Case A under free labor and Case 2 under slavery, which we shall name **Case I**. Because $\Gamma(P_t;\gamma) > [\bar{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t$ [see (14) and recall that $\gamma > 0$] this case prevails if $A_t \geq \Gamma(P_t;\gamma)$. Using the first lines in (11) and (17) we see that $\pi_t^F \geq \pi_t^S$ when $\alpha A_t^\alpha P_t^{1-\alpha} \geq A_t^\alpha [P_t/(1+\gamma)]^{1-\alpha} - \bar{c}P_t$. This can be written as $A_t \leq \Psi(P_t)$, where $\Psi(P_t)$ is defined in (18).

Consider next the combination of Case A under free labor and Case 1 under slavery, which we name **Case II**. This case prevails if $[\bar{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t < A_t < \Gamma(P_t;\gamma)$. Using the first line in (11) and the second line in (17) we see that $\pi_t^F \geq \pi_t^S$ when $\alpha A_t^\alpha P_t^{1-\alpha} \geq \alpha \{(1-\alpha)/[(1+\gamma)\bar{c}]\}^{\frac{1-\alpha}{\alpha}} A_t$, or

$$A_t < \left[\frac{\bar{c}(1+\gamma)}{1-\alpha}\right]^{\frac{1}{\alpha}} P_t = (1+\gamma)\Gamma(P_t;\gamma), \tag{A5}$$

which always holds in Case II, since $A_t < \Gamma(P_t;\gamma)$.

Consider finally the combination of Case B under free labor and Case 1 under slavery, which we name **Case III**. This amounts to $A_t \leq [\bar{c}/(1-\alpha)]^{\frac{1}{\alpha}} P_t$. Using the lower rows of (11) and (17) we see that $\pi_t^F \geq \pi_t^S$ can be written $\alpha [(1-\alpha)/\bar{c}]^{\frac{1-\alpha}{\alpha}} A_t \geq \alpha \{(1-\alpha)/[(1+\gamma)\bar{c}]\}^{\frac{1-\alpha}{\alpha}} A_t$. This amounts to $(1+\gamma)^{\frac{1-\alpha}{\alpha}} > 1$, which always holds.

To sum up, in Cases II and III $\pi_t^F \geq \pi_t^S$ always holds; in Case I, $\pi_t^F \geq \pi_t^S$ holds unless $A_t > \Psi(P_t)$. Note that $A_t > \Psi(P_t)$ can only hold in Case I, since $\Psi(P_t) > \Gamma(P_t;\gamma)$. Considering all Cases I–III together we thus conclude:

$$\pi_t^F \geq \pi_t^S \iff A_t \leq \Psi(P_t). \tag{A6}$$

Conditions for $\pi_t^S \geq \max\left\{\pi_t^F, \pi_t^E\right\}$: This holds when both $\pi_t^S \geq \pi_t^F$ and $\pi_t^S \geq \pi_t^E$. Reversing (A6), $\pi_t^S \geq \pi_t^F$ is equivalent to that $A_t \geq \Psi(P_t)$.

The condition for $\pi_t^S \geq \pi_t^E$ is given in (A2). As long as $\pi_t^S \geq \pi_t^F$ and thus $A_t \geq \Psi(P_t)$, it must hold that $A_t > \Gamma(P_t;\gamma)$, because $\Psi(P_t) > \Gamma(P_t;\gamma)$. It is then straightforward to use (A2) to see that $\pi_t^S \geq \max\left\{\pi_t^E, \pi_t^F\right\}$ when A_t is greater than both $\Psi(P_t)$ and $\Omega(P_t)$, and P_t is strictly greater than $(1+\gamma)^{1-\alpha}$, i.e.,

$$P_t > (1+\gamma)^{1-\alpha} \text{ and } A_t \geq \max\left\{\Psi(P_t), \Omega(P_t)\right\}, \tag{A7}$$

which is equivalent to (A_t, P_t) being in $\mathcal{S}^S$, defined in (21). This proves part (a).

Conditions for $\pi_t^F \geq \max\left\{\pi_t^E, \pi_t^S\right\}$: This holds when both $\pi_t^F \geq \pi_t^E$ and $\pi_t^F \geq \pi_t^S$. As seen from (A6), $\pi_t^F \geq \pi_t^S$ requires that $A_t \leq \Psi(P_t)$. The condition for $\pi_t^F \geq \pi_t^E$ is given in (A4): both $P_t \geq 1/\alpha$ and $A_t \geq \Phi(P_t)$ must hold. Thus, $\pi_t^F \geq \max\left\{\pi_t^E, \pi_t^S\right\}$ holds when

$$\Phi(P_t) \leq A_t \leq \Psi(P_t) \text{ and } P_t \geq \frac{1}{\alpha}, \tag{A8}$$

which is equivalent to (A_t, P_t) being in $\mathcal{S}^F$, defined in (21). This proves part (b).

Conditions for $\pi_t^E \geq \max\left\{\pi_t^F, \pi_t^S\right\}$: This holds when both $\pi_t^F \geq \max\left\{\pi_t^E, \pi_t^S\right\}$ and $\pi_t^S \geq \max\left\{\pi_t^F, \pi_t^E\right\}$ fail to hold, i.e., when (A_t, P_t) is not in either $\mathcal{S}^F$ or $\mathcal{S}^S$. This proves part (c). ‖

Proof of Proposition 2: For part (a), note that $w_t \geq \overline{c}/(1-\beta)$ implies that $w_t > \overline{c}$, so all P_t agents work and the wage rate is given by $w_t = (1-\alpha)A_t^\alpha P_t^{-\alpha}$. Thus, $\pi_t^F = \alpha A_t^\alpha P_t^{1-\alpha}$, and $n_t^{\text{landowner}} = (\beta/q)\alpha A_t^\alpha P_t^{1-\alpha}$. Then (25) gives (27). To show part (b), consider first the case when $A_t \leq \left[\overline{c}/(1-\alpha)\right]^{1/\alpha} P_t$ so that the labor force, L_t, adjusts so that the wage rate equals subsistence consumption: $w_t = \bar{c}$. Thus $n_t^{\text{worker}} = 0$, and (11) and $P_{t+1} = n_t^{\text{landowner}} = (\beta/q)\pi_t^F$ give

$$P_{t+1} = \frac{\beta\alpha}{q}\left[\frac{1-\alpha}{\bar{c}}\right]^{\frac{1-\alpha}{\alpha}} A_t < \frac{\beta\alpha}{q}\left[\frac{1-\alpha}{\bar{c}}\right]^{\frac{1-\alpha}{\alpha}}\left[\frac{\bar{c}}{1-\alpha}\right]^{\frac{1}{\alpha}} P_t < P_t, \qquad \text{(A9)}$$

where we have used Assumption 2, $\alpha < 1$, and $1-\beta < 1$. Next, consider the case when $A_t > [\bar{c}/(1-\alpha)]^{1/\alpha} P_t$, and thus $w_t > \bar{c}$. This gives $n_t^{\text{worker}} = (w_t - \bar{c})/q > 0$, and $P_{t+1} = (\beta/q)\alpha A_t^\alpha P_t^{1-\alpha} + (w_t - \bar{c})P_t/q$. Since all P_t agents are working it must hold that $w_t = (1-\alpha)A_t^\alpha P_t^{-\alpha}$. Using $w_t < \bar{c}/(1-\beta)$ and some algebra then shows that $P_{t+1} < \{\bar{c}\beta/[q(1-\alpha)(1-\beta)]\}P_t$. Assumption 2 demonstrates that $\bar{c}\beta/[q(1-\alpha)(1-\beta)] < 1$ and thus $P_{t+1} < P_t$. ‖

Proof of Proposition 3: Part (a) follows from $P_{t+1} = P_t n_t^{\text{egal}}$ and (5). Part (b) follows from noting that $n_t^{\text{egal}} = (\pi_t^E - \bar{c})/q < [\bar{c}/(1-\beta) - \bar{c}]/q = \beta\bar{c}/[q(1-\beta)] < 1-\alpha < 1$, where we have used $\pi_t^E < \bar{c}/(1-\beta)$ and Assumption 2. Since $P_{t+1} = P_t n_t^{\text{egal}}$, $n_t^{\text{egal}} < 1$ implies that $P_{t+1} < P_t$. ‖

Proof of Proposition 4: Part (a) follows from $A_t > \Gamma(P_t;\gamma)$, (17), and $P_{t+1} = n_t^{\text{slaveowner}} = (\beta/q)\pi_t^S$. To prove part (b) first use $A_t \leq \Gamma(P_t;\gamma)$, (14), and (17), which together imply that

$$\begin{aligned}\pi_t^S &= \left(\tfrac{\alpha A_t \bar{c}}{1-\alpha}\right)\left\{\left(\tfrac{1-\alpha}{\bar{c}}\right)^{\frac{1}{\alpha}}\left(\tfrac{1}{1+\gamma}\right)^{\frac{1-\alpha}{\alpha}}\right\} \\ &= \left(\tfrac{\alpha A_t \bar{c}}{1-\alpha}\right)\left\{\tfrac{P_t}{\Gamma(P_t;\gamma)}\right\} \leq \tfrac{\alpha\bar{c}P_t}{1-\alpha},\end{aligned} \qquad \text{(A10)}$$

where (14) verifies that the factors in curly brackets are equal, and the inequality follows from $A_t \leq \Gamma(P_t;\gamma)$. The inequality in (A10) implies that $P_{t+1} = n_t^{\text{slaveowner}} = (\beta/q)\pi_t^S \leq \{\beta\alpha\bar{c}/[q(1-\alpha)]\}P_t \leq \alpha(1-\beta)P_t < P_t$, where the second inequality follows from Assumption 2, and the third from $\alpha < 1$ and $\beta > 0$. ‖

Proof of Proposition 6: Consider first part (a). First note from (29), (30), and $\overline{A} > 0$, that (31) is a necessary and sufficient condition for $\mathbf{L}^{\mathrm{E/F}}(P_t)$ and $\mathbf{L}^{\mathrm{A}}(P_t)$ to intersect. A free labor steady state exists if $\mathbf{L}^{\mathrm{A}}(P_t)$ and $\mathbf{L}^{\mathrm{E/F}}(P_t)$ intersect in $\mathcal{S}^F$; cf. Figure 3. From (18) and (29), it is seen that (32) is a necessary and sufficient condition for $\mathbf{L}^{\mathrm{E/F}}(P_t)$ to pass through $\mathcal{S}^F$; see (21). Changing $\overline{A}$ shifts the intercept of $\mathbf{L}^{\mathrm{A}}(P_t)$, and moves the intersection along $\mathbf{L}^{\mathrm{E/F}}(P_t)$. Thus, if, and only if, (31) and (32) hold, for some $\overline{A}$ they intersect in $\mathcal{S}^F$. Let $\overline{A}^F$ be the lowest $\overline{A}$ such that they do. Then a steady state exists in $\mathcal{S}^F$ for any $\overline{A} \geq \overline{A}^F$. Next consider part (b). Recall that (31) is a necessary condition for $\mathbf{L}^{\mathrm{E/F}}(P_t)$ and $\mathbf{L}^{\mathrm{A}}(P_t)$ to intersect at all. The intersection must be in $\mathcal{S}^E$ if $\overline{A}$ is sufficiently small; see (21). ‖

Proof of Proposition 7: Similar to the proof of Proposition 6, a steady state with slavery is given by an intersection of $\mathbf{L}^{\mathrm{A}}(P_t)$ and $\mathbf{L}^{\mathrm{S}}(P_t)$ in $\mathcal{S}^S$; cf. Figures 3 and 4. From (18) and (30), if (34) holds, $\mathbf{L}^{\mathrm{S}}(P_t)$ must pass through $\mathcal{S}^S$; see (21). If (33) holds, then $\mathbf{L}^{\mathrm{S}}(P_t)$ slopes steeper than $\mathbf{L}^{\mathrm{A}}(P_t)$, ensuring that $\mathbf{L}^{\mathrm{A}}(P_t)$ and $\mathbf{L}^{\mathrm{S}}(P_t)$ do intersect. Shifting $\overline{A}$ moves the intersection along $\mathbf{L}^{\mathrm{S}}(P_t)$, ensuring that for some $\overline{A}$ sufficiently large they intersect in $\mathcal{S}^S$. Let $\overline{A}^S$ be the lowest $\overline{A}$ such that they do. Then a steady state exists in $\mathcal{S}^S$ for any $\overline{A} \geq \overline{A}^S$. The "only if" part is seen from reversing either (33) or (34), or both; this rules out an intersection of $\mathbf{L}^{\mathrm{A}}(P_t)$ and $\mathbf{L}^{\mathrm{S}}(P_t)$ in $\mathcal{S}^S$ for any $\overline{A}$. ‖

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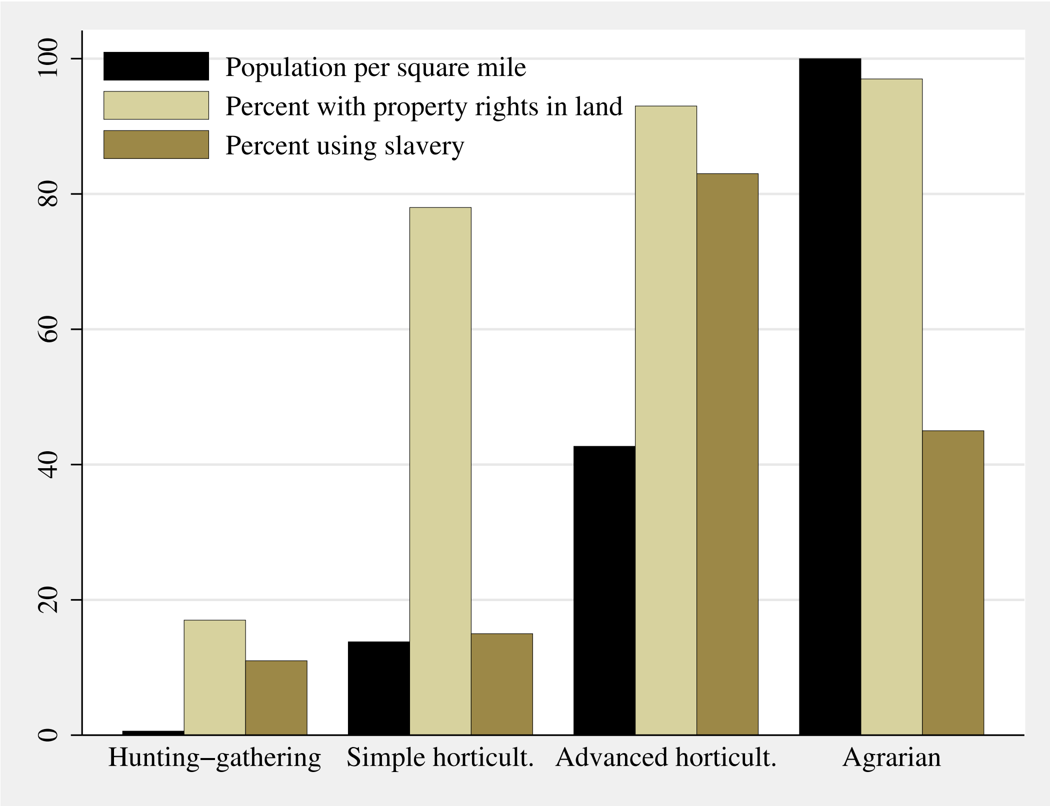

Figure 1: Population density and property rights to land and people at different stages of long-run development. Source: Nolan and Lenski (1999, pp. 107, 125, 144).

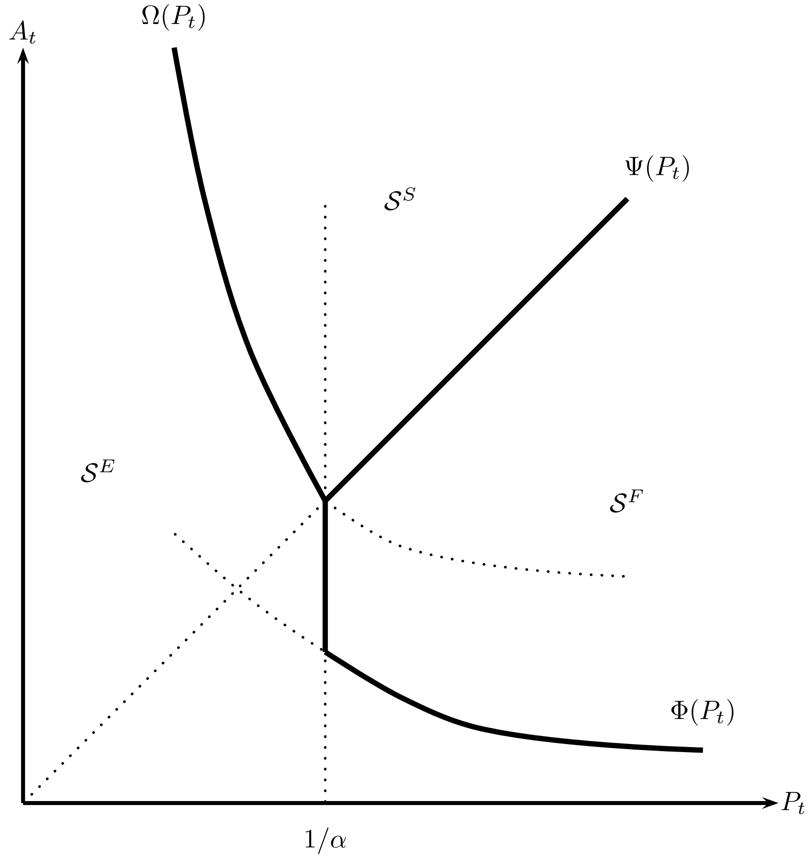

Figure 2. Institutional regions.

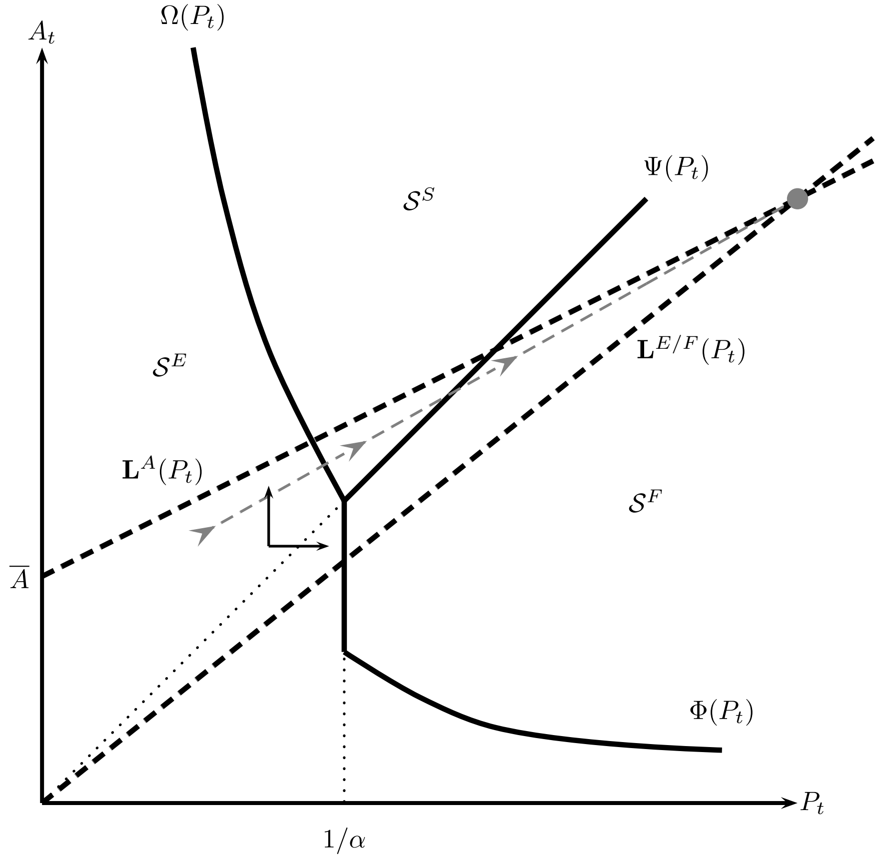

Figure 3. A transition through all three institutions.

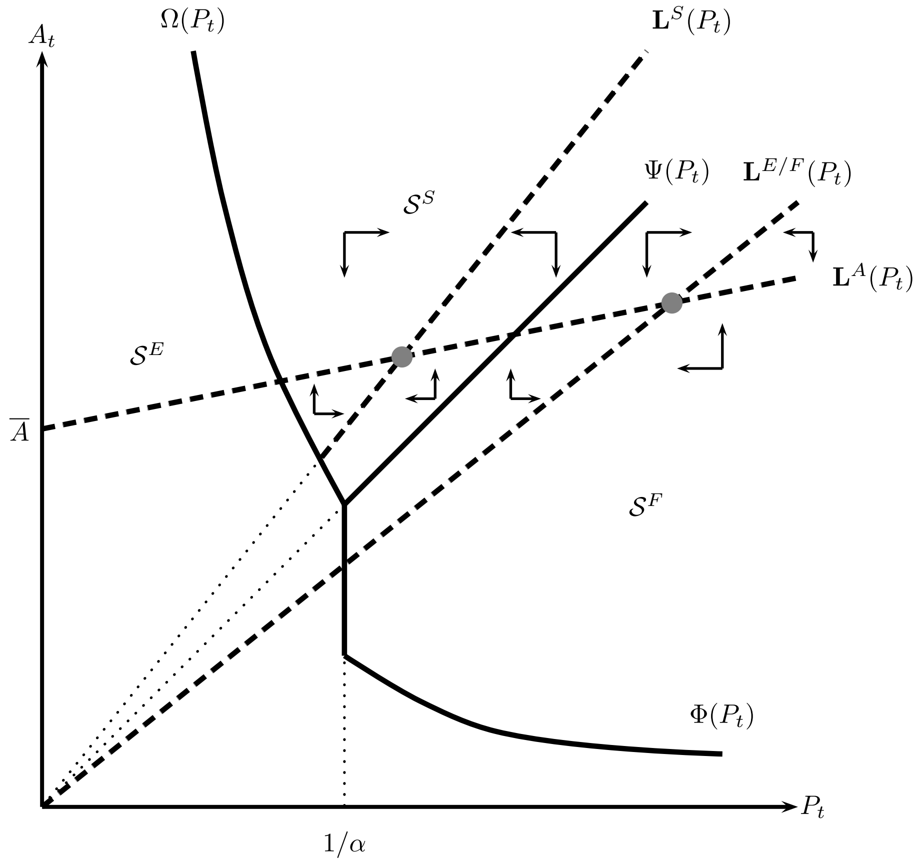

Figure 4. Phase diagram with both a slavery and a free labor steady state.

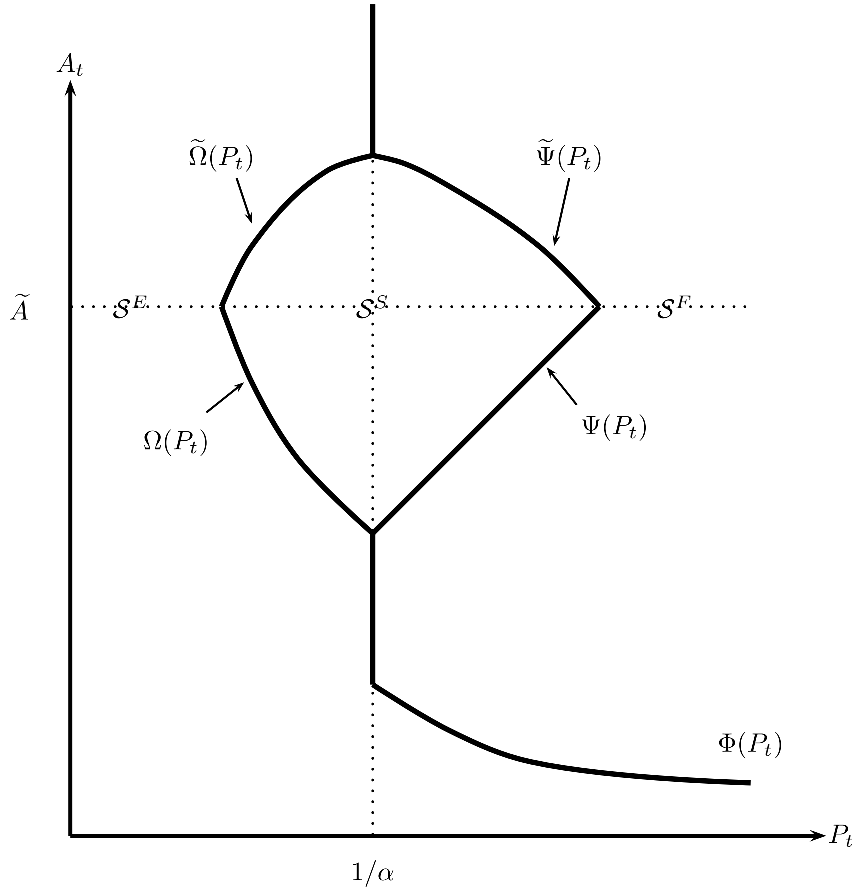

Figure 5. Institutional regions with increasing guarding costs.