INSTITUTO DE ECONOMÍA

TESIS de DOCTORADO

2007

Three Essays on Pre-Market Economies

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Three essays on pre-market economies

by

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Submitted to the Instituto de Economía
in partial fulfillment of the requirements for the degree of

PhD in Economics

at the

PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

September 2007

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Acknowledgments

So many people helped me through this journey. I thank them all...

Javier Pinto, for inspiring me to become a scientist. Javier was one of the brightest men I've ever known, and his life was a model of human and scientific integrity. I miss him dearly.

Carlos Rodríguez-Sickert, for his generous advice, his friendship, and for giving my chaotic research a sense of direction and a purpose. With monkish patience, Carlos persuaded me to submit to the conventions of the economic tribe. (Yet his success, I'm glad to say, was only partial.)

Robert Rowthorn, for sharing his wisdom with me. Meeting Bob was a mind-opening experience. Working with him, a privilege and some of the most fun I've ever had during my academic life.

Marcos Singer, for being a friend and always standing up for me. Marcos, you are truly a Jedi. Thank you for keeping me away from the Dark Side.

My father, Ricardo Guzmán Sr., who didn't want me to be a scholar, but gave me nonetheless all his loving support. I'm happy I've always obeyed him on everything, except on this particular thing...

Finally, a big thank to all those friends and teachers who were always there for me: Marcelo Arenas, Jorge Baier, Leopoldo Bertossi, Juan Camilo Cárdenas, Gonzalo Edwards, Carmen Garcés, Rodrigo Harrison, Julio Israel, Mitch Gómez, Victor Lima, Juan Pablo Montero, Will Mullins, José Miguel Sánchez, Klaus Schmidt-Hebbel, Rodrigo Troncoso, and Felipe Varas. I could have never pulled this darn thing off without them!

Chapter 1

Introduction

Most of our knowledge about the economic laws that rule behavior comes from the observation of modern western world; that is, from the study of monetized economies where property rights and contracts are, to a lesser or greater extent, enforced by governments and courts (Williamson, 1990). But before money emerged as the prevalent means of exchange, and well before governments and courts regulated economic life, our prehistoric ancestors allocated their scarce resources to satisfy infinite needs, and benefited from economic exchange even among military enemies. It has been argued that his unique ability to trade and to divide labor allowed Homo sapiens to outcompete other members of the genus Homo, until he remained the only surviving human species (Horan et al., 2005). We must understand our ancestors if we are ever to understand our contradictory economic nature: Self-interested, but moral and other-regarding as well (Fehr & Fischbacher, 2002).

I am also convinced that economics can collaborate with anthropology to decipher our remote past. By bringing to the attention of anthropologist the fundamental roles that scarcity, incentives and choice played on prehistoric societies, economics can illuminate a number of existing anthropological puzzles. Not all anthropologists will be receptive to our intrusion. Substantivists, the mainstream of the anthropological profession, believe that each culture can only be understood on its own terms, and they condemn any attempt of generalization as an ethnocentric bias. Fortunately, a growing number of anthropologists now agree with us economists in that general accounts of behavior are possible (Wilk & Cliggett, 2007). Both ideas, that studying our ancestors we learn about ourselves, and that economic theory can make sense of our remote past, are the themes that underlie the three essays that form this thesis.

In the first chapter, written with my supervisors Carlos Rodríguez and Robert Rowthorn, we investigate whether altruistic punishment and conformist learning could have coevolved, allowing cooperation to be sustained in large groups. My coauthors and me model the coevolution of behavioral strategies and social learning rules in the context of a cooperative dilemma, a situation in which individuals must decide whether or not to subordinate their own interests to those of the group. There are two learning rules in our model, conformism and payoff-dependent imitation, which evolve by natural selection, and three behavioral strategies, defect, cooperate, and cooperate plus punish defectors, which evolve under the influence of the prevailing learning rules. Group and individual level selective pressures drive evolution. We also simulate our model for conditions that approximate those in which early hominids lived. We find that conformism can evolve when the only problem that individuals face is a cooperative dilemma, in which prosocial behavior is always costly to the individual. Furthermore, the presence of conformists dramatically increases the group size for which cooperation can be sustained. The results of our model are robust: They hold even when migration rates are high, and when conflict among groups is infrequent.

In the second chapter I deal with the shift from hunting an gathering to agriculture, some 10,000 years ago. That revolutionary event triggered the first demographic explosion in history. Along with population, working time increased, while food consumption remained at the subsistence level. For that reason, most anthropologists regard the adoption of agriculture as an economic puzzle. I show, using a neoclassical economic model, that there is nothing puzzling about the adoption of agriculture. Agriculture brings four technological changes: An increase in total factor productivity, a stabilization of total factor productivity, less interference of children on production, and the possibility of food storage. In my model, each of those changes induces free, rational and self-interested hunter-gatherers to adopt agriculture. As a result, working time increases while consumption remains at the subsistence level, and population begins to grow until diminishing returns to labor bring it to a halt. Welfare, which depends on consumption, leisure, and fertility, rises at first; but after a few generations it falls below its initial level. Still, the adoption of agriculture is irreversible. The latter generations choose to remain farmers because, at their current levels of population, reverting to hunting and gathering would reduce their welfare.

In the third and final chapter of my thesis, written with Carlos Rodríguez and Camilo Cárdenas, we model the dynamic effects of external enforcement on the exploitation of a common pool resource, and test our model using experimental data. That is a problem hunter-gatherers faced everyday, and the indigenous communities that took part in these experiments resemble their primitive counterparts to the extent that the exploitation of the common resource is only regulated by social norms. This chapter addresses the following question: Given a set social of social preferences that evolved in an environment that lacked externally enforced rules, do those preferences remain intact if social norms are externally enforced? In other words, do the moral virtues of primitive people survive the introduction of capitalist institutions? Fitting our model to experimental data we find that institutions do influence social preferences. We solve two puzzles in the data: The increase and later erosion of cooperation when commoners vote against the imposition of a fine, and the high deterrence power of low fines. When fines are rejected, internalization of a social norm explains the increased cooperation; violations (accidental or not), coupled with reciprocal preferences, account for the erosion. Low fines stabilize cooperation by preventing a spiral of negative reciprocation.

Chapter 2

The coevolution of altruistic punishment, conformist learning, and cooperation

This chapter was written with Robert Rowthorn and Carlos Rodríguez. It has been published in Evolution and Human Behavior 28, pp. 112–117, under the title "When in Rome, do as the Romans do: The coevolution of altruistic punishment, conformist learning, and cooperation."

We are a cooperative species. Experimental evidence and field data show that humans often sacrifice resources in order to benefit nonrelatives, even when those who benefit are not expected to return the favor (Gintis, Bowles, Boyd, & Fehr, 2003). People sometimes use altruistic punishment to enforce cooperation, whereby they pay a cost in order to punish noncooperators whom they will never meet again (Fehr & Gaechter, 2000, 2002; Ostrom, Walker, & Gardner, 1992). The combination of unrequited cooperation between nonrelatives and altruistic punishment is known as strong reciprocity (Gintis, 2000). Both of these components of strong reciprocity pose a puzzle for the standard evolutionary theories of cooperation: Kin selection (Hamilton, 1964) and reciprocal altruism (Axelrod & Hamilton, 1981; Trivers, 1971).

Some authors argue that human cooperation may be explained by the selection of cultural traits at the group level (Bowles, Choi, & Hopfensitz, 2003; Boyd & Richerson, 1985; Cavalli-

Sforza & Feldman, 1981; Sober & Wilson, 1994). Assuming that cooperative groups outcompete less cooperative ones in the struggle for survival, then it may be possible for group level selective pressure to outweigh the maladaptive nature of altruism at the individual level. For this to occur, either noncooperative individuals must invade cooperative groups infrequently or else the amount of intergroup conflict must be very high. Analytical models suggest that two factors play a crucial role in the emergence of cooperation: Altruistic punishment and conformism (i.e., the tendency of individuals to imitate the most common form of behavior; see Boyd & Richerson, 1985, and Henrich & Boyd, 1998). Gintis (2000) proves that, when a group faces the threat of extinction, a small number of altruistic punishers may induce selfish individuals to behave cooperatively. Henrich and Boyd (2001) show that the presence of conformists may permit altruistic punishment to persist and thereby facilitate the emergence and survival of cooperation. Boyd, Gintis, Bowles, and Richerson (2003) report simulations that mimic the environment in which early hominids lived. They show that altruistic punishment enhances cooperative behavior when social learning takes the form of payoff-dependent imitation (i.e., when individuals imitate the most successful forms of behavior). However, this mixture of group selection and punishment cannot sustain cooperation in large groups if the migration rate between groups is high and conflict between groups is low.

Boyd and Richerson (2005) argue that cultural group selection is especially strong in human populations due to the fact that variation among human groups is maintained by an unusual combination of strong reciprocity and conformist social learning. Following their lead, this article uses a group selection approach to explore the coevolution of behavioral strategies and learning rules in the context of a cooperative dilemma. By cooperative dilemma we mean a situation in which an individual must choose whether or not to behave cooperatively, and benefit the group, or uncooperatively, and benefit himself. In our model, there are two social learning rules, conformism and payoff-dependent imitation, which evolve by natural selection, and three behavioral strategies, cooperate, defect, and cooperate, plus punish defectors, which evolve under the influence of the prevailing learning rules.

To the extent that our analysis is concerned with competing learning rules, it relates to the literature on endogenous learning. There is, however, one important difference. This literature is primarily concerned with social and individual learning as alternative ways to acquire information about the natural environment. Within such a framework, Boyd and Richerson (1985) demonstrate how the balance between social and individual learning depends on the accuracy of learning and the variability of the environment. Feldman, Aoki, and Kumm (1996) show that social learning can evolve if there is a fixed fitness cost to learning errors, while Henrich and Boyd (1998) show that social learning can evolve as long as the environment is not too variable.

The aims of this article are as follows: Firstly, to determine if conformist transmission can evolve within the context of a cooperative dilemma, and secondly, to explore the impact of conformism on cooperation. Henrich and Boyd (2001) and Henrich (2004) observe that conformism to norms that are costly to the individual is most likely to evolve in tandem with individually beneficial conformism. Individuals may find it very difficult to distinguish between actions that are eventually costly to them and those that are eventually beneficial. Under these conditions, it may be best to conform blindly to the prevailing norm, even though this may sometimes involve taking actions that harm oneself. The alternative of doing it alone or seeking to be more selective may be worse. Henrich and Boyd (2001) and Henrich (2004) also observe, without elaboration, that costly conformism might evolve on its own through natural selection. In this article, we show the second observation is correct. We also show that the presence of conformists dramatically increases the group size for which cooperation can be sustained.

2.1 Model

Here we develop a model in which evolution determines both the learning rules that individuals adopt and the behavioral strategies which they follow. The learning rules evolve at the biological level and the strategies chosen by individuals at any time are based on these rules. Our model builds on the work of Boyd et al. (2003), but departs from it by allowing conformist learning, and by making learning rules endogenous.

There are G groups, each of which has N members. Following Boyd et al. (2003) we assume that the size of each group is kept constant through local density-dependent competition. Every year the members of a particular group play a societal game. This game is divided into five phases: Hunting, war, learning, reproduction, and migration.

During the hunting phase, each individual follows one of three possible behavioral strategies: Defect (D), cooperate(C), and cooperate plus punish defectors (P). Denote by $\sigma(s) \in [0,1]$, the fraction of the group that chooses strategy $s \in \{\text{C,D,P}\}$. Someone who intends to cooperate may erroneously defect with probability e, so the ex post fraction of defectors will be $\sigma(\text{D}) + e[\sigma(\text{C}) + \sigma(\text{P})]$. We assume that punishers who unintentionally fail to cooperate continue to punish. Let $\pi(s, \sigma)$ be the payoff of an individual who follows strategy s when the distribution of types in his group is $\sigma(\cdot)$. We define $\pi(s, \sigma)$ as follows:

$$\begin{aligned}
\pi(\text{D}, \sigma) &= -p\sigma(\text{P}) + z, \\
\pi(\text{C}, \sigma) &= -(1-e)c - ep\sigma(\text{P}) + z, \\
\pi(\text{P}, \sigma) &= -(1-e)c - ep\sigma(\text{P}) - k\{\sigma(\text{D}) + e[\sigma(\text{C}) + \sigma(\text{P})]\},
\end{aligned}$$

where $z = \max[(1-e)c + k, p]$. The positive constants c, k, and p capture the costs of cooperating, punishing, and being punished, respectively. We assume that $(1-e)(p-c) > ke$, so that defection does not pay if every member of the group is a punisher. The inclusion of z in the payoff function guarantees that payoffs are always positive. This condition is required to ensure that the imitation rule given below is meaningful.

Note that there is no need to specify the immediate benefits of cooperation in the above equations since these are enjoyed by all members of the group equally and therefore do not affect relative fitness within the group. Moreover, these immediate benefits are cancelled out by the environmental pressures that keep the size of the group constant. The only role that cooperation plays in our model is in intergroup conflict through its influence on the probability of victory. This is also the case in Boyd et al. (2003).

In each period, all groups pair at random. Each pair of groups makes war with probability ε. Only one group in each warring pair survives. Suppose Groups g and g' enter into conflict. Group g will survive with probability $\frac{1}{2}[1 + \sigma'(\text{D}) - \sigma(\text{D})]$, where $\sigma(\text{D})$ is the fraction of defectors in group g and $\sigma'(\text{D})$ is the fraction of defectors in group g'. The surviving group fissions and repopulates the site of the extinct group in the following fashion. First, every individual in the surviving group produces a clone of himself. Second, individuals and their clones intermingle and are randomly reassigned to the site of the surviving group or to the site of the extinct one, creating two new groups of size N. [For a discussion of fission as a mechanism by which successful groups propagate themselves, see Richerson and Boyd (1998).]

Individuals come in two genetic types that differ according to their learning rules: Payoff-dependent imitators and conformists. Every individual uses the same learning rule throughout his life. The evolution of learning rules is governed by natural selection. Individuals die with probability q. A dead individual is replaced by a son of some member of his group. The probability that a dead individual will be replaced by a son of i is given by

$$\frac{\pi_i}{\sum_{j=1}^{N} \pi_j}.$$

The newborn son will be an exact replica of his father. Thus, he will have the same genetically determined learning rule as his father, and will start life with his father's behavioral strategy. With probability ν the son will immediately mutate and adopt a random learning rule and behavioral strategy.

During the learning phase, each payoff-dependent imitator meets a role model from his group. Let s be the behavioral strategy used by the imitator, and let s' be the strategy used by the role model. The probability that the imitator will adopt the behavioral strategy of the role model is

$$\frac{\pi\left(s', \sigma'\right)}{\pi\left(s, \sigma\right) + \pi\left(s', \sigma'\right)}.$$

After meeting the role model, the imitator may still decide to innovate and switch to a randomly chosen behavioral strategy with probability μ. Note that mutation and innovation are distinct. Mutation occurs only at birth and hence at most once, whereas innovation may occur several times during a lifetime. Conformists do not innovate and just play their group's modal strategy s^*, where

$$s^* = \underset{s \in \{\text{C},\text{D},\text{P}\}}{\arg\max}\ \sigma\left(s\right)$$

In order to introduce a migration-like force, we assume that each individual meets a stranger from another group with probability m. Let π be the last payoff of the individual, and let π' be the last payoff of the stranger. Following Boyd et al. (2003), we assume that the individual will be replaced by the stranger with the following probability:

$$\frac{\pi'}{\pi + \pi'}.$$

The above process can be justified as follows. Since each group is of constant size, an immigrant must compete with some local individual for a place in the group. It is reasonable to assume that the probability of victory in this contest will be determined by the contenders relative payoffs. Finally, we assume that at the beginning of time there are $G-1$ groups of payoff-dependent imitators who all use the behavioral strategy defect and one group of conformists that all use the behavioral strategy cooperate plus punish.

2.2 Results

2.2.1 Baseline scenario

Following Boyd et al. (2003)., we simulate the model of the previous section for conditions that approximate those in which early hominids lived. Each simulation spans 2000 years of model time. Baseline parameters are given in Table 2.2.1. Most of these parameters are taken from Boyd et al. (2003). and we do not justify them here. Our model introduces two new parameters: The death rate and the mutation rate. We set the death rate at $q = 0.1$, which implies a reproductive life of 10 years. The mutation rate is assumed to be one order of magnitude lower than the innovation rate.

Figure 2-1 presents the simulation results for our model using the baseline parameters (the solid square lines), along with simulation results for three other models. These other models make different assumptions about the availability of behavioral strategies and learning rules: One model contains punishment but rules out conformism (the empty square lines); one contains conformism but rules out punishment (the empty triangle lines); and in one, both punishment and conformism are ruled out (the empty circle lines). The model with punishment but not conformism corresponds to the model in Boyd et al. (2003). The figure plots averages of frequencies over the final 1000 years of 20 simulations.

TABLE 2.2.1

Parameters of the baseline model

Parameter	Symbol	Value
Number of groups	G	128
Group size	N	64
Cost of cooperation	c	0.2
Cost of punishing	k	0.2
Cost of being punished	p	0.8
Probability of erroneous defection	e	0.02
Migration rate	m	0.01
Innovation rate (behavioral strategies)	μ	0.01
Conflict rate	ε	0.015
Death rate	q	0.1
Mutation rate (learning rules)	ν	0.001

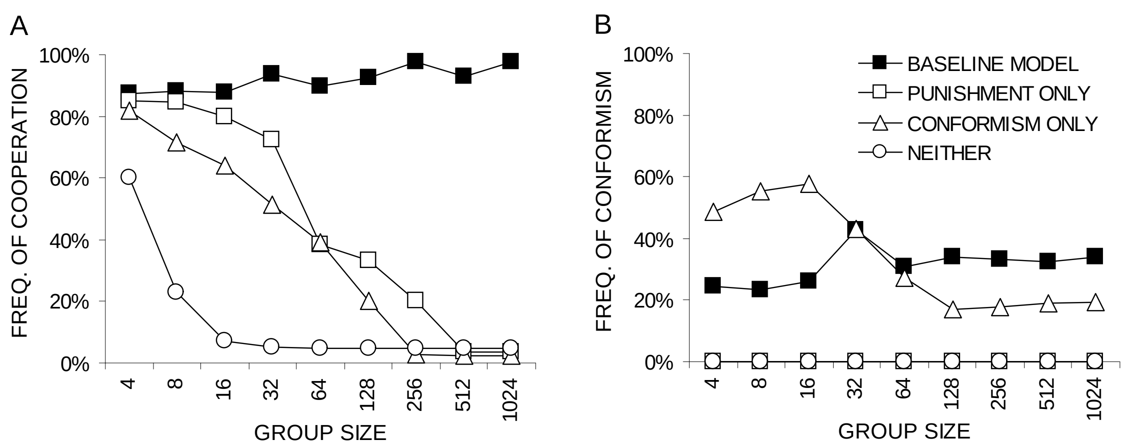

Figure 2-1: Cooperation (A) and conformism (B) in alternative models.

To understand these results, it is convenient to analyze first the dynamics of the societal game for a group that lives in isolation, subject to no mutation, no migration, and no war, and is comprised entirely of payoff-dependent imitators. In such a group, there are no conformists. Under these conditions, the societal game will have two kinds of equilibrium: One composed entirely of defectors and one with no defectors at all. In the latter type of equilibrium the condition $\sigma(\text{P}) > a$ must be satisfied, where $a = c/p$ is the fraction of punishers such that cooperation and defection yield the same payoff. If this condition is not satisfied, then defectors can invade and eventually take over. Consider an equilibrium in which the fraction of punishers is equal to $\sigma_0(\text{P}) > a$. If someone innovates and becomes a defector he will be driven out by punishers. However, this will require a finite period of time during which punishers will incur the extra cost of policing defectors and hence will be less fit than cooperators. During the transition period to the new equilibrium, the ratio of punishers to cooperators will therefore decrease. When the population restabilizes after the innovator has been driven out, this will be in a new equilibrium with $\sigma_1(\text{P}) < \sigma_0(\text{P})$. Eventually, as a result of successive innovations $1, 2, ..., j$, there will come a point where $\sigma_j(\text{P}) > a$, and from then onward defectors will prosper and take over. In consequence, the only stable equilibrium of the societal game is the one in which everybody defects.

Now consider the case with migration and war between groups. As before, assume there is no mutation and that all individuals are payoff-dependent imitators, but this time suppose that no peer-to-peer sanctioning is available. In this scenario there are no conformists and no punishers, and the only strategies available are cooperation and defection. The long-run values of cooperation in this scenario are depicted by the circle line in Figure 2-1 A. In small groups, moderate levels of cooperation are achieved by group selection alone. When two groups enter into conflict, the one with more cooperators is more likely to win and repopulate the site of the other. In this way cooperation will spread between groups. For group selection to produce high levels of cooperation, however, intergroup variation is needed. If it is absent, group selection will have nothing to select from when groups go to war. The extent of intergroup variation depends on the balance between the homogenizing effect of migration and the diversity arising from innovation and fissioning within groups. When group size is small, innovation and fissioning can generate enough intergroup diversity to offset the homogenizing effect of migration.

In larger groups, however, the law of large numbers comes into play so that innovation and fissioning produce less variation, with the result that diversity arising from this source is no longer sufficient to offset migration and preserve the intergroup variation required to sustain cooperation.

As can be observed from the empty square line in Figure 2-1 A, the addition of punishers ameliorates the negative effect of large group size. With a high proportion of punishers the first-order free-riding problem —the irruption of defectors— is solved. Although a second-order free-riding problem emerges —cooperators failing to punish defectors— this problem is less serious: Whereas the payoff advantage of defectors over cooperators does not depend on the frequency of defection, the payoff advantage of cooperators over punishers decreases as defectors become rare. As Boyd et al. (2003) point out, this helps to explain why group selection may favor the evolution of substantial levels of punishment and maintain punishment once it is common.

Even when peer-to-peer sanctioning is available, random variation is still needed to sustain high levels of cooperation. To see why, suppose that all groups are in a cooperative equilibrium without defectors, and let $\sigma_0(\text{P}) > a$ be the fraction of punishers in the overall population. Also suppose the homogenizing effect of migration has operated long enough so that the share of punishers is the same in all groups. If groups are large, the law of large numbers entails that the same fraction of every group will innovate and start defecting. Punishers will drive them out, but during the transition period the share of punishers in all groups will decrease to $\sigma_1(\text{P}) < \sigma_0(\text{P})$. Since this process will generate no intergroup variation, when war happens, group selection will have nothing to select. As in the isolated group case, the share of punishers will eventually fall to the point where innovating defectors can successively invade and cooperation will break down. Even if groups are too small for the law of large numbers to operate effectively, migration may still reduce intergroup differences, thereby undermining cooperation.

The triangle lines in Figure 2-1 show that conformism and cooperation coevolve in our model even when no peer-to-peer sanctioning is available. The mere presence of conformists raises the frequency of cooperation in comparison to the no conformism and no punishment scenario, and makes cooperative behavior possible in much larger groups. To see why, imagine a group of cooperative conformists, which is colonized by a foreign defector. Since cooperation will still be the modal behavior of the group, conformists will not react to the payoff advantage of the newcomer; they will just keep on cooperating. In this example, conformism acts as a shield against the homogenization across groups, reinforcing the effect of innovation and fissioning.

The solid square lines in Figure 2-1 show what happens in our baseline model, which contains both conformism and punishment. In this model, cooperation achieves a very high level and is an increasing function of group size. The combination of conformism and punishment encourages cooperation in several ways. Consider a group in which punishment is the modal strategy. Over the course of time, such a group will absorb a stream of newcomers in the form of immigrants and newborns, together with existing members who modify their strategies by innovating. If the newcomer is a conformist, he will adopt the modal strategy and become a punisher who reinforces group cooperation. However, if he is a payoff-dependent imitator, then, according to his previous experience, he may adopt another course of action. He may defect, in which case he will directly weaken the group, or else he may simply cooperate, but fail to punish defectors, thereby encouraging defection by others. In a group where punishment is the modal strategy, conformist newcomers will immediately start to punish, whereas payoff-dependent imitators may choose some other form of behavior. In such a group, conformism stabilizes punishment and reinforces cooperation.

Conformism has another positive effect on cooperation. Consider a conformist-defector who migrates into a population consisting mainly of punishers. On arriving in his new group he will immediately switch to the modal behavior, so that punishers will have no reason to punish him. This benefits both the group and the newcomer, who avoids being punished. That conforming is convenient for immigrants is no new discovery. On the contrary, it was long ago captured by conventional wisdom: When in Rome, do as the Romans do.

In sum, conformism preserves between-group variation and stabilizes punishment; punishment protects groups from the spread of defection and may also give conformists a fitness advantage over payoff-dependent imitators. For these reasons, punishment, conformism, and cooperation coevolve in our model, and cooperation is high even in large groups. Our findings confirm the observation of Henrich and Boyd (2001) that conformist transmission, operating directly on cooperative strategies, is unlikely to maintain cooperation in the absence of punishment.

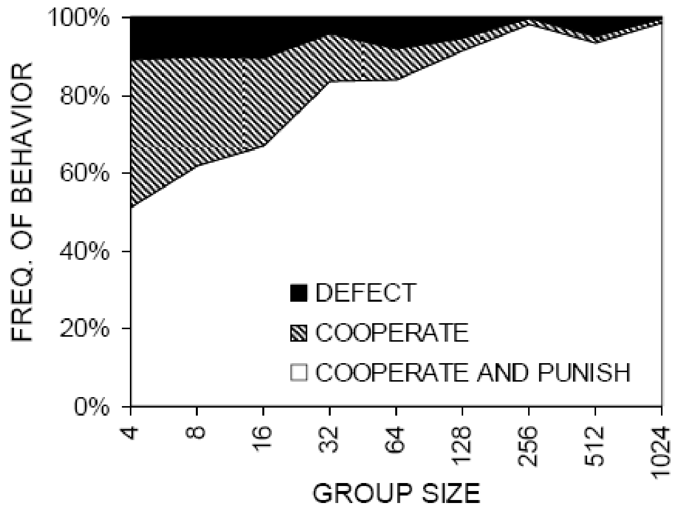

Figure 2-2: Distribution of strategies for the baseline model.

Perhaps the most puzzling of our findings is the fact that cooperation increases with group size, instead of decreasing, as one might expect. Figure 2-2 shows the frequencies of the three strategies in the baseline model, for different group sizes. As groups become larger, so does the share of punishers, until almost everyone is a punisher. This may be for the following reason. When groups are small, innovation and fissioning are likely to move groups out of the equilibrium favored by group selection: The one where everybody punishes. In addition to its impact on the number of punishers, such noise may also turn conformism into a drawback, since out of equilibrium the modal strategy of the group need not coincide with the strategy that is optimal for the group as a whole. In large groups, the law of large numbers dissipates the effects of random variation, and the mix of punishment and conformism displays its full potential.

2.2.2 Sensitivity analysis

Figure 2-3 shows how our model responds to a low conflict rate ($\mu = 0.0075$) and to a high migration rate ($m = 0.05$). As can be observed, the combination of conformism and altruistic punishment is able to sustain high levels of cooperation for all group sizes under these very

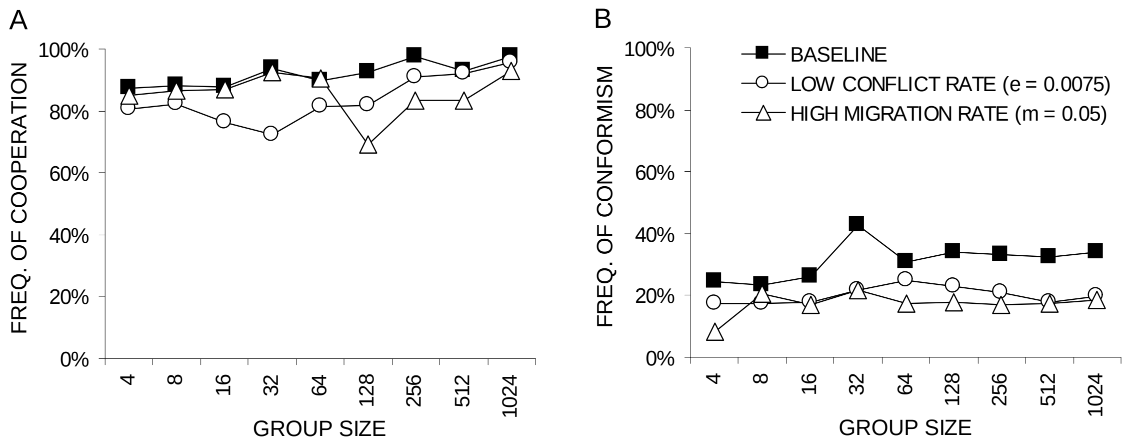

Figure 2-3: How conflict and migration affect cooperation (A) and conformism (B).

adverse conditions. Note that cooperation falls slightly at intermediate group sizes. This can be explained as follows. When groups are small, random variation keeps cooperation high, even though the variation weakens the combined effect of conformism and altruistic punishment. At intermediate group sizes, the law of large numbers dilutes random variation enough to dampen group selection, but not enough for conformism and altruistic punishment to fully counter the homogenizing force of migration. Finally, when groups are large, random variation vanishes completely, conformism and punishment thrive, and so does cooperation.

2.3 Conclusion

We have shown that conformism can evolve when the only problem that individuals face is a cooperative dilemma. There is no need to assume that costly conformism is a spin-off from individually beneficial conformism. We have also shown that conformism and altruistic punishment coevolve, allowing groups of greater size to sustain cooperation. This occurs because conformism preserves between-group variation and stabilizes punishment, and because punishment protects groups from the spread of defection and gives conformists a fitness advantage over payoff-dependent imitators.

Chapter 3

Why agriculture is *not* a puzzle

The shift from hunting and gathering to agriculture, usually termed the Neolithic Revolution (10,000 to 5,000 B.P.), triggered the first demographic explosion in the history of humankind (Bocquet-Appel, 2002). In the course of few centuries, typical communities grew from about 30 individuals to 300 or more, and population densities increased from less than one hunter-gatherer per square mile, to 20 or more farmers on the same surface (Johnson & Earle, 2000, pp. 43, 125, 246).

Population was not the only thing that expanded during the Neolithic Revolution. Working time expanded as well. Ethnographical studies indicate that hunter-gatherers worked less that six hours per day, whereas primitive horticulturists worked seven hours on average, and intensive agriculturalists worked nine (Sackett, 1996, pp. 338–42). The increase in working time was, however, not accompanied by an increase in food consumption. If anything, food consumption fell a bit (Armelagos et al., 1991; Cohen and Armelagos, 1984), though certainly not much, as hunter-gatherers were already chronically undernourished and constantly threatened by famine (Kaplan, 2000). The lost of leisure without an increase in food consumption has convinced most anthropologists that the Neolithic Revolution reduced welfare. For that reason, they regard our ancestors' decision to farm as a puzzle in need of explanation.

I will show, using a neoclassical economic model, that there is nothing puzzling about the facts of the Neolithic Revolution. In my model, rational and self-interested hunter-gatherers freely adopt agriculture. The adoption of agriculture increases working time while consumption remains at the subsistence level, and the initially stable population begins to grow until diminishing returns to labor bring it to a halt. Welfare, which depends on consumption, leisure, and fertility, rises at first; but after few generations it falls below its initial level. Still, the shift from hunting and gathering to agriculture is irreversible. The latter generations choose to remain farmers because, at their current levels of population, reverting to hunting and gathering would reduce their welfare. Many hands make hard work, but there is nothing the hands can do about it.

The adoption of agriculture brings four technological changes: An increase in total factor productivity, a stabilization of total factor productivity, less interference of children on productive activities, and the possibility of food storage. In my model, each technological change reproduces, by itself, the facts of the Neolithic Revolution. Hence, not only are the facts of the Neolithic Revolution not puzzling: From an economist's perspective, they were inevitable.

Most models of the Neolithic Revolution assume that the total factor productivity of agriculture is larger than that of hunting and gathering, at least when the revolution takes place (Weisdorf, 2005). Since that assumption is common, I will not discuss it here. The other three technological changes, on the other hand, have been (to my knowledge) disregarded by modelers, and thus merit some attention.

The instability of total factor productivity is probably the main problem of contemporary hunter-gatherers (Kaplan, 2000; Johnson & Earle, 2000, p. 57). Their resources increase and decrease periodically (daily for hunters, yearly for gatherers), and every once in a while they fail altogether. Domestication of plants and animals alleviates the problem, by smoothing (though not completely) the yield of the land (Johnson & Earle, 2000, p. 127).

Instability is further alleviated by the possibility of storing food. Most hunter-gatherers are nomads, and carrying food around is too costly a burden for them. The alternative would be to settle down; but as they quickly deplete local resources, the trade-off is solved in favor of moving (Sahlins, 1998). Early farmers, on the contrary, led sedentary lives, and produced starchy crops suitable for storing (Johnson & Earle, 2000, p. 33).

Sedentism also reduces the cost of children, mainly because caring for them interferes with food gathering tasks requiring a high degree of mobility (Kramer and Boone, 2002).

Related literature

The theories of agriculture adoption have been extensively surveyed elsewhere (Weisdorf, 2005). Hence, I will limit the discussion to the two models that share with mine the inclusion of leisure in the utility function; an essential feature, if one is to assess the welfare effects of expanding working time. Those models are Marceau and Myers' (2006) and Weisdorf's (2004).

Marceau and Myers model the adoption of agriculture as a common resource problem. At low levels of technology, the whole population forms a unique band of hunter-gatherers. The members of this band coordinate to prevent the overexploitation of a common resource. As technology improves, the prospect of leaving the band to be a farmer gets more and more attractive. When technology surpasses a certain threshold, the lure of agriculture becomes irresistible and the band breaks apart into a myriad of small communities of farmers. The farmers don't cooperate to preserve the common resource and, as a result, consumption falls while working time increases.

I sustain Marceau and Myers' model fails to provide a good account of the Neolithic Revolution, for two reasons. First, the model predicts that farmers will live in smaller groups than hunter-gatherers, while the opposite is true. Second, the model builds on the unsound assumption that hunter-gatherers coordinate to prevent overexploitation, whereas farmers do not. There is mounting evidence that contemporary hunter-gatherers use individually optimal foraging strategies. They are perfectly willing to exhaust their resources, and when they fail to do so, it is due to their low population densities and inefficient technologies (Penn, 2003). Farmers, on the other hand, organize themselves hierarchically, and their leaders often take measures that mitigate the tragedy of the commons. For example, they may regulate the fallow cycle to maximize the yield of the land, or manage the use of pastures to prevent overgrazing (Johnson & Earle, 2000, 271, pp. 299, 310, 311, 318, 327, 328, 388).

In *Weisdorf's* model, early farmers give away leisure in exchange for other goods produced by an emerging class of non-food specialists (e.g., craftsmen, chiefs, bureaucrats, and priests). Weisdorf's hypothesis is compelling because non-food specialists were needed to develop the innovations that followed agriculture (e.g., writing, metallurgy), and that characterize civilization. Although I will show that the demand for non-food specialists is not necessary to explain agriculture, the relevance of Weisdorf's explanation relative to my neoclassical account will have to be settled on empirical grounds.

Marceau and Myers, and also Weisdorf, assume population is constant during the transition to agriculture. That is a serious limitation, as the possibility of raising more children probably played a crucial role in our ancestors' decision to become farmers. The population explosion that took place during the Neolithic Revolution clearly points in that direction. My model addresses the issue by assuming reproduction to be a personal decision. A realistic assumption, as it is known that contemporary hunter-gatherers do control population, using such mechanisms as abortion, infanticide, prolonged lactation, and postpartum sex taboos (Cashdan, 1985).

Finally, my model is also linked to the family of endogenous fertility models, pioneered by Razin and Ben-Zion (1975). In particular, it is closely related to those models in which the diminishing returns to labor operate as a Malthusian population check; for example, Boldrin and Jones (2002), Eckstein et al. (1988), and Nerlove et al. (1986).

3.1 A model of agriculture adoption

3.1.1 Model setup

Time is divided in $t = 1, 2, 3, \ldots$ periods. Each period has two seasons, indexed by $j \in \{1, 2\}$. During period t, a tribe has $N_t > 0$ identical adult members or *tribesmen*. Their lives last exactly one period. Generations do not overlap.

At the beginning of the first season, each tribesman decides how many children to have. Denote by $n_t > 0$ the number of children of a typical tribesman. In the next period, the size of the tribe will thus be $N_{t+1} = n_t N_t$.

To survive, a tribesman must eat at least $\bar{c} > 0$ units of food during each season. Denote by $c_{tj} \geq \bar{c}$ his food consumption during season j. He must also provide $\bar{c}$ units of food per season to each of his children.

Tribesmen work to earn their food. Let $w_{tj} \geq 0$ be a typical tribesman's working time during season j. He will produce $A_{tj} w_{tj}$ units of food during that season; $A_{tj} > 0$ being the typical tribesman's productivity, which he takes as given. A part of production will be lost due to children interference: κ units of food per child, where κ is high if the tribe is nomadic, and low if it is sedentary.

If the tribe is sedentary, a tribesman may store some food at the end of season one, for future consumption during season two. Denote by $s_t \geq 0$ a tribesman's food savings, and let $\sigma = \mathrm{N}$ if the tribe is nomadic and $\sigma = \mathrm{S}$ if it is sedentary. The tribesman is subject to the following food budget constraints:

$$
\begin{aligned}
A_{t1}w_{t1} - \kappa n_t &= c_{t1} + \bar{c}n_t \; + s_t, \\
\underbrace{A_{t2}w_{t2} - \kappa n_t}_{\text{Income}} &= \underbrace{c_{t2} + \bar{c}n_t}_{\text{Expenses}} \; \underbrace{- s_t \mathbf{1}_{\mathrm{S}}(\sigma)}_{\text{Savings}},
\end{aligned}
$$

where $\mathbf{1}_{\mathrm{S}}(\sigma)$ is an indicator function that takes value 1 when $\sigma = \mathrm{S}$, and otherwise takes value 0.

Eating food and having children make a tribesman happy, whereas work makes him unhappy. The utility function of a period t tribesman is given by

$$
u(c_{t1}, c_{t2}, w_{t1}, w_{t2}, n_t) = v(c_{t1}) + v(c_{t2}) - \frac{\gamma}{\rho+1} w_{t1}^{1+\rho} - \frac{\gamma}{\rho+1} w_{t2}^{1+\rho} + \beta n_t.
$$

Parameter $\beta > 0$ implies that children are valued, whereas $\gamma > 0$ implies tribesmen dislike work. Parameter $\rho > 0$ indicates that, everything else being equal, a tribesman will want to spread his workload evenly between the two seasons. The utility of consumption is strictly increasing and concave: $v' > 0$ and $v'' < 0$. Function u is an instance of Becker's (1992) Malthusian utility function, which doesn't include the quality of children as an argument. As Becker points out, before the Industrial Revolution there were virtually no opportunities to invest on the quality of children; medical care, education, and training were just too rudimentary. Hence, for our purposes, omitting the quality of children from the tribesman utility function is harmless.

The tribe chooses between two production technologies: Hunting and gathering, and agriculture. In order to draw a clear "before and after" picture of agriculture adoption, assume all members of the tribe must use the same technology. Which of the two alternatives, they must agree by vote. The equality of all tribesmen entails the election of technology will always be unanimous.

The efficiency of hunting and gathering declines the more people engage on it (Johnson & Earle, 2000, p. 54). Everyday, the tribesmen must venture a little farther from camp in order to obtain food. Eventually, the value of the remaining food falls short of the costs of obtaining it, plus the opportunity cost of lifting the camp and moving somewhere else. A large tribe of hunter-gatherers consumes the "cheaper" food sources near camp faster than a smaller tribe, and also has to incur in the costs of relocating more often. In that spirit, define the productivity of a hunter-gatherer during season j as follows:

$$A_{tj} = a_j \left(N_t w_{tj}\right)^{-\theta}, \tag{3.1}$$

where $a_j > 0$ is season j total factor productivity, and $0 < \theta < 1$. This condition guarantees that total production increases when the tribe's total work effort increases (i.e. $N_t w_{tj} A_{tj} = a_j \left(N_t w_{tj}\right)^{1-\theta}$ is increasing in $N_t w_{tj}$).

Just as hunting and gathering, agriculture is subject to diminishing returns. Early farmers were mostly slash-and-burners. When population increased, they were forced to speed up the fallow cycle, reducing the productivity of land (Boserup, 1965). Therefore, we will also model the productivity of farmers using the formulation in (3.1), changing the values of a_1 and a_2.

For future use, define average working time ($\bar{w}$), average total factor productivity (μ), and the instability of total factor productivity (δ), as follows:

$$\begin{aligned} \bar{w} &= \frac{w_{t1} + w_{t2}}{2}, \\ \mu &= \frac{a_1 + a_2}{2}, \\ \delta &= \left| \frac{a_1 - a_2}{2} \right|. \end{aligned}$$

Table 3.1 (page 33) summarizes the notation.

3.1.2 The tribesman problem

Before solving the tribesman problem, two assumptions are in order. First, assume $a_1 > a_2$, so an abundant season precedes a scarce season. As a result, A_{t1} will always be larger than A_{t2} *in equilibrium*, and tribesmen will want to store some food at the end of season one, even if storing turns out to be impossible (we will confirm that $A_{t1} > A_{t2}$ in Section 3.1.3). Second, assume

$$\frac{\beta}{\bar{c}+\kappa} > \left\{1+\left[\frac{a_1}{a_2}\right]^{\frac{1+\rho}{1-\theta}}\right\} v'(\bar{c}), \tag{3.2}$$

which implies that a tribesman will use any income over $\bar{c}$ to have children. Before the Industrial Revolution, any raise in income induced an increase in population, while consumption remained close to the subsistence level. Inequality 3.2 guarantees the model will produce a reasonable approximation to the dynamics of consumption before the Industrial Revolution, while letting us focus our attention on the interaction between work and fertility. The inequality will hold if children are cheap enough ($\bar{c}+\kappa$ is sufficiently low).

A tribesman solves

$$\begin{aligned}
\max_{\{c_1,c_2,w_1,w_2,n,s\}} \quad & u = v(c_1) + v(c_2) - \tfrac{\gamma}{\rho+1} w_1^{\rho+1} - \tfrac{\gamma}{\rho+1} w_2^{\rho+1} + \beta n, \\
\text{s.t.} \quad & A_1 w_1 = c_1 + (\bar{c}+\kappa) n + s, \\
& A_2 w_2 = c_2 + (\bar{c}+\kappa) n - s\mathbf{1}_{\mathrm{S}}(\sigma), \\
& c_1, c_2 \geq \bar{c}, \\
& w_1, w_2, n, s \geq 0,
\end{aligned}$$

where the t subscripts have been dropped to simplify the expressions. Table 3.2 (page 34) displays the solution to the tribesman problem, for the cases without and with storage (i.e. for $\sigma = \mathrm{N}$ and $\sigma = \mathrm{S}$).

3.1.3 Short-run equilibrium

In the short-run, population is fixed at N° (the empty dot indicates the short-run value of a variable). Equilibrium requires labor productivity to satisfy equation (3.1). Using that equation, together with the tribesman optimal choices (Table 3.2), we can solve for the short-run equilibrium values of all variables. Table 3.3 (page 35) displays the short-round results, for the cases without and with storage.

Inspecting Table 3.2, and recalling that $a_1 > a_2$ and $0 < \theta < 1$, we confirm that labor productivity is always larger during the abundant season ($A_1^\circ > A_2^\circ$). Also, when storing is unfeasible, the tribesmen work more during the scarce season ($w_1^\circ < w_2^\circ$), while if storing is feasible, they work more during the abundant season ($w_1^\circ > w_2^\circ$).

3.1.4 Long-run equilibrium

In the long-run, diminishing returns to labor operate as a Malthusian check. As population grows, labor productivity declines, until the optimal tribesman's choice is to bear exactly one child: $n^\bullet = 1$ (the full dot indicates the long-run value of a variable). From then onwards, population will remain constant.

Imposing the one child condition on the short-run results (Table 3.3), we can compute the long-run equilibrium values of all variables. Table 3.4 (page 36) displays the long-run results, for the cases without and with storage.

Proposition 1 (Stability of the long-run equilibrium.) *The long-run equilibrium is stable, meaning that a small deviation from the equilibrium population level ($N^\bullet$) will always be reversed.*

3.1.5 The adoption of agriculture

Consider a tribe of hunter-gatherers that has reached the long-run equilibrium: Each tribesman bears one child ($n^\circ = 1$) and population is at its long-run equilibrium level ($N^\circ = N^\bullet$). One good day, the tribe stumbles upon a new technology: Agriculture. Suppose the tribe decides to adopt this new technology (later we will prove that was the rational decision). Agriculture brings four technological changes: An increase in average total factor productivity ($\triangle^+\mu$), a stabilization of total factor productivity ($\triangle^-\delta$), less interference of children on production ($\triangle^-\kappa$), and the possibility of food storage (a change from $\sigma = \mathrm{N}$ to $\sigma = \mathrm{S}$).

Proposition 2 (Short-run effects of agriculture.) *Each technological change of agriculture produces a short-run increase in fertility ($\triangle^+ n^\circ$), average working time ($\triangle^+\bar{w}^\circ$), and* *utility* ($\triangle^+ u^\circ$). *In sum:*

$$\begin{aligned}
\frac{\partial n^\circ}{\partial \mu} &> 0, & \frac{\partial \bar{w}^\circ}{\partial \mu} &> 0, & \frac{\partial u^\circ}{\partial \mu} &> 0, \\
\frac{\partial n^\circ}{\partial \delta} &< 0, & \frac{\partial \bar{w}^\circ}{\partial \delta} &< 0, & \frac{\partial u^\circ}{\partial \delta} &< 0, \\
\frac{\partial n^\circ}{\partial \kappa} &< 0, & \frac{\partial \bar{w}^\circ}{\partial \kappa} &< 0, & \frac{\partial u^\circ}{\partial \kappa} &< 0, \\
n^\circ[\mathrm{N}] &< n^\circ[\mathrm{S}]\,, & \bar{w}^\circ[\mathrm{N}] &< \bar{w}^\circ[\mathrm{S}]\,, & u^\circ[\mathrm{N}] &< u^\circ[\mathrm{S}]\,.
\end{aligned}$$

The generation that adopts agriculture suddenly finds children to be more affordable: Feeding one child requires less work when productivity is higher ($\triangle^+\mu$, $\triangle^-\kappa$); a more stable productivity ($\triangle^-\delta$) implies the required work will be a bit more tiring during the abundant season, but much less strenuous during the scarce one; the possibility of storing food ($\sigma = \mathrm{S}$) allows tribesmen to use first season abundance to provide for the times of scarcity. As one would expect, cheaper children translate into increased fertility ($\triangle^+ n^\circ$). The effect of cheaper children on working time, on the other hand, is not as clear cut. Each tribesman could work less hours and still afford more than one children. In our case, the substitution of children for leisure dominates the income effect, so working time increases ($\triangle^+\bar{w}^\circ$). Finally, as working time increases, labor productivity falls, reducing the efficiency gains of agriculture. The loss in efficiency attenuates the surge in fertility and work, but does not change the direction of the effects.

From proposition 2 we learn that the generation that adopts agriculture is be happy with the changes. In other words, a tribe of selfish, utility-maximizing people will freely abandon hunting and gathering to become farmers. Working time will expand, but the additional toil will be more than compensated by the larger families the tribesmen will be able to afford.

As a consequence of increased fertility, population will start to grow. Eventually, it will stabilize at a new equilibrium with higher population.

Proposition 3 (Long-run effects of agriculture.) *In the long-run, fertility converges to* $n^\bullet = 1$. *The four changes of agriculture produce a long-run increase in population* ($\triangle^+ N^\bullet$). *Working time will be longer* ($\triangle^+\bar{w}^\bullet$) *as a result of the increase in average total factor productivity* ($\triangle^+\mu$), *the stabilization of total factor productivity* ($\triangle^-\delta$), *and the reduction of the* *interference of children on production* ($\triangle^{-}\kappa$)*. The possibility of food storage* ($\sigma = \text{S}$) *has an ambiguous effect on working time, which may increase or decrease. Only a reduction of the interference of children on production will have a long-run effect on utility, which will fall below its pre-agriculture level* ($\triangle^{-}u^{\bullet}$)*. In sum:*

$$\begin{array}{rclrclrcl}
\dfrac{\partial N^{\bullet}}{\partial \mu} & > & 0, & \dfrac{\partial \bar{w}^{\bullet}}{\partial \mu} & > & 0, & \dfrac{\partial u^{\bullet}}{\partial \mu} & = & 0, \\
\dfrac{\partial N^{\bullet}}{\partial \delta} & < & 0, & \dfrac{\partial \bar{w}^{\bullet}}{\partial \delta} & < & 0, & \dfrac{\partial u^{\bullet}}{\partial \delta} & = & 0, \\
\dfrac{\partial N^{\bullet}}{\partial \kappa} & < & 0, & \dfrac{\partial \bar{w}^{\bullet}}{\partial \kappa} & < & 0, & \dfrac{\partial u^{\bullet}}{\partial \kappa} & > & 0, \\
N^{\bullet}[\text{N}] & < & N^{\bullet}[\text{S}]\,, & \bar{w}^{\bullet}[\text{N}] & \gtrless & \bar{w}^{\bullet}[\text{S}]\,, & u^{\bullet}[\text{N}] & = & u^{\bullet}[\text{S}]\,.
\end{array}$$

Proposition 3 tells us that the descendants from the original farmers will be worse off than their hunter-gatherer ancestors. In spite of that, the transition to agriculture is irreversible. From proposition 2 we infer that, once the new long-run equilibrium has been reached, reverting to hunting and gathering will reduce the utility of the current generation. Hence, they will choose to remain farmers.

Proposition 4 (Long-run effect of food storage on working time.) *In the long-run, the possibility of food storage* ($\sigma = \text{S}$) *will increase working time* ($\triangle^{+}\bar{w}^{\bullet}$) *if* $2\theta + \rho > 1$.

In other words, if the returns to labor fall quickly enough (θ is high), or if the tribesmen are sufficiently averse to workload instability (ρ is high), then the possibility of food storage will end up increasing working time. When storage is feasible, ρ^{-1} is the uncompensated labor supply elasticity. The overwhelming majority of estimations locate that elasticity between 0 and 1 (Blundell and MaCurdy 1999). Hence, reasonable values of ρ should be larger than 1. That dispels the ambiguity from proposition 4. If food storage becomes possible, working time will eventually increase ($\triangle^{+}\bar{w}^{\bullet}$).

In the long-run, all tribesmen eat the minimum amount and can only afford to have one child. But in the long-run the tribe is larger and, everything else being equal, that means labor productivity is lower than before. As a result, each tribesmen must work more than his ancestors just to feed himself and his child... unless the tribesman has the chance to store some food. Storing allows the tribesman to substitute a large amount of effort in the scarce season by a smaller amount in the abundant season, when he is more efficient. But even with storage things can get nasty if the returns to labor fall too fast (θ is high): All the additional work during the abundant season could reduce the yield of the land so much that everybody ends up working more than before the adoption of agriculture. Also, if the tribesmen are too inclined to smooth their labor supply through time (ρ is high), they will refuse to work much harder during the abundant season than during the scarce season. If that is the case, working time will increase even if storage is feasible.

In sum, each of the four technological changes is enough to explain the consequences of shifting from hunting and gathering to agriculture: The increased population and working time, while consumption remains at subsistence level. Thus, from an economist's perspective, not only do the facts of the Neolithic Revolution make perfect sense: They were inevitable.

Figure 3-1 (page 37) illustrates the result of the four changes of agriculture happening together. The figure summarizes 20 periods in the (simulated) history of a tribe. During the first ten periods, the tribesmen make a living out of hunting and gathering. Population stays at its long-run equilibrium level; working time and utility are also constant. At the beginning of period 11, the tribe discovers agriculture. Population increases at first, but after a few generations it stabilizes at a new, higher equilibrium. Working time and utility both soar in period 11. After that, they decline over time. Working time stabilizes above its pre-agriculture level; the utility of the last generations falls below the utility of their hunter-gatherer ancestors. All the while, consumption remains at the subsistence level. Yet the tribesmen of periods 12 and after will not revert to hunting and gathering, as Figure 3-1B evidences. The "shadow" utility of hunting and gathering runs beneath the utility of agriculture. Things get bad for farmers, but their alternative gets even worse.

3.2 Conclusion

> "What needs explanation is why in contemporary contexts hunter-gatherers often demonstrate unlimited, rather than limited, material wants. Why is it that at Momega and, according to the literature, elsewhere modern hunter-gatherers have apparently insatiable demands for shotguns, rifles, motor vehicles, cassette recorders, CD players, televisions, and VCRs?" Jon Altman (1992)

As essential as the principle of scarcity is to the economist's way of thinking, it is strongly rejected by other social scientists. Émile Durkheim, a founding father of both sociology and anthropology, believed people learn from their social world what and how much to desire (1953, 95). To Durkheim, the unlimitedness of wants is not part of human nature, but a product of modern Western society: An evil product that fuels the war of all against all (Durkheim 1961, p. 45; 1969). Max Weber, the famous sociologist and "political economist," also deemed unlimited wants extrinsic, a capitalistic creation. He provided as evidence the behavior of traditional peasants. According to Weber, peasants do not crave for more and more, but are content to live the way they are accustomed. As soon as they satisfy their very limited wants, they stop working. It follows, Weber reasons, that an employer who wants to extract more effort from peasants should lower their wages instead of raising them (Weber,1958, pp. 59–62). Although Weber's characterization of peasant mentality has been debunked countless times [see, for example, James Scott (1985)], many of those who reject his evidence as false still embrace his ideas about the cultural origin of our greediness.

When in the 1960s it was established that hunter-gatherers' work very little compared to modern standards, anthropologists thought they had found indisputable proof for Durkheim and Weber's most radical ideas. Professor Emeritus Marshall Sahlins, the dominant voice of contemporary economic anthropology, declared hunter-gatherers the "original affluent society." They are affluent, he argued, not because their means are abundant, but because their wants are few. If the behavior of hunter-gatherers obeys any laws at all, it is the laws of Zen economics (Sahlins 1968, 1998). The principles of neoclassical economics, and in particular the idea of unlimited wants, are nothing but the "origin myth of capitalist society." Economic theory, Sahlins denounced, is merely the rhetoric used by capitalism to justify and perpetuate itself (Sahlins, 1976, pp. 53, 205–207).

The affluence of hunter-gatherers turns the adoption of agriculture into a conundrum (if a parent, forced to kill the children he can't feed, can be seriously called affluent). As Hardy (1992) famously put it: "Why farm? Why give up the 20-hour work week and the fun of hunting in order to toil in the sun?" The decision of our ancestors supplied non-economists with ammunition to attack another favorite of economic principles: Rationality.

In these pages I have argued that, if read properly, the facts of the Neolithic Revolution bear no evidence against the principles of unlimited wants and rationality. At least from that trench, nothing emerges that obliges us to delete the word *max* from our microeconomic textbooks, or demote nonsatiation from its rank of axiom. Neoclassical economics is perfectly able to explain the behavior of hunter-gatherers: Why they work so few hours, why given the chance they become farmers, and why, when exposed to modern life, they demand DVD players, televisions, and iPods.

TABLE 3.1

NOTATION SUMMARY

Variable	Sym.	Parameter	Sym.
Population size	N	Subsistence consumption	$\bar{c}$
Season j labor productivity	A_j	Cost of children interference	κ
Season j consumption per tribesman	c_j	Aversion to workload instability	ρ
Season j working time per tribesman	w_j	Weight of work in utility	$-\gamma$
Average working time	$\bar{w}$	Weight of children in utility	β
Number of children per tribesman	n	Season j total factor productivity	a_j
Utility function	u	Average total factor productivity	μ
		Instability of total factor productivity	δ
		Degree of decreasing returns to labor	θ
		Food storage is unfeasible (the tribe is nomadic)	$\sigma = \mathrm{N}$
		Food storage is feasible (the tribe is sedentary)	$\sigma = \mathrm{S}$

TABLE 3.2

SOLUTION TO THE TRIBESMAN PROBLEM

Var.	Without storage	With storage
c_j	$\bar{c}$	$\bar{c}$
w_j	$\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\frac{1}{A_1^{-(\rho+1)}+A_2^{-(\rho+1)}}\right]^{\frac{1}{\rho}} A_j^{-1}$	$\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\frac{A_j}{2}\right]^{\frac{1}{\rho}}$
n	$\left[\frac{\beta/\gamma}{(\bar{c}+\kappa)^{\rho+1}}\frac{1}{A_1^{-(\rho+1)}+A_2^{-(\rho+1)}}\right]^{\frac{1}{\rho}} - \frac{\bar{c}}{\bar{c}+\kappa}$	$\left[\frac{\beta/\gamma}{(\bar{c}+\kappa)^{\rho+1}}\right]^{\frac{1}{\rho}} \left\{\left[\frac{A_1}{2}\right]^{\frac{\rho+1}{\rho}} + \left[\frac{A_2}{2}\right]^{\frac{\rho+1}{\rho}}\right\} - \frac{\bar{c}}{\bar{c}+\kappa}$
s	0	$\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{\frac{1}{\rho}} \left\{\left[\frac{A_1}{2}\right]^{\frac{\rho+1}{\rho}} + \left[\frac{A_2}{2}\right]^{\frac{\rho+1}{\rho}}\right\}$

TABLE 3.3

SHORT-RUN EQUILIBRIUM

Var.	Without storage	With storage
A_j°	$\left\{\frac{\bar{c}+\kappa}{(N^\circ)^\rho\beta/\gamma}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]\right\}^{\frac{\theta}{\theta+\rho}} a_j^{\frac{1}{1-\theta}}$	$\left[2\frac{\bar{c}+\kappa}{(N^\circ)^\rho\beta/\gamma}\right]^{\frac{\theta}{\theta+\rho}} a_j^{\frac{\rho}{\theta+\rho}}$
c_j°	$\bar{c}$	$\bar{c}$
w_j°	$\left\{\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-1}\right\}^{\frac{1}{\theta+\rho}} a_j^{-\frac{1}{1-\theta}}$	$\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\frac{a_j}{2}\right]^{\frac{1}{\theta+\rho}}$
n°	$\left\{\frac{(\beta/\gamma)^{1-\theta}}{\left[(N^\circ)^\theta(\bar{c}+\kappa)\right]^{\rho+1}}\right\}^{\frac{1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta+\rho}}-\frac{\bar{c}}{\bar{c}+\kappa}$	$\left\{\frac{(\beta/\gamma)^{1-\theta}}{\left[(N^\circ)^\theta(\bar{c}+\kappa)\right]^{\rho+1}}\right\}^{\frac{1}{\theta+\rho}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}-\frac{\bar{c}}{\bar{c}+\kappa}$
s°	0	$\left\{\frac{1}{(N^\circ)^{\theta(\rho+1)}}\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{1-\theta}\right\}^{\frac{1}{\theta+\rho}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}-\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}$
U°	$2v\left(\bar{c}\right)-\frac{\bar{c}\beta/\gamma}{\bar{c}+\kappa}+\frac{\rho}{\rho+1}\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\right]^{\frac{\rho+1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta+\rho}}$	$2v\left(\bar{c}\right)-\frac{\bar{c}\beta/\gamma}{(\bar{c}+\kappa)}+\frac{\rho}{1+\rho}\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\right]^{\frac{\rho+1}{\theta+\rho}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}$

TABLE 3.4

LONG-RUN EQUILIBRIUM

Var.	Without storage	With storage
$N^\bullet$	$\left\{\frac{1}{(2\bar{c}+\kappa)^{\theta+\rho}}\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{1-\theta}\right\}^{\frac{1}{\theta(\rho+1)}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta(\rho+1)}}$	$\left\{\frac{1}{(2\bar{c}+\kappa)^{\theta+\rho}}\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{1-\theta}\right\}^{\frac{1}{\theta(\rho+1)}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}^{\frac{\theta+\rho}{\theta(\rho+1)}}$
$A_j^\bullet$	$\left[\frac{(\bar{c}+\kappa)(2\bar{c}+\kappa)^{\rho}}{\beta/\gamma}\right]^{\frac{1}{\rho+1}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{\frac{1}{\rho+1}}a_j^{\frac{1}{1-\theta}}$	$\left[\frac{(\bar{c}+\kappa)(2\bar{c}+\kappa)^{\rho}}{\beta/\gamma}\right]^{\frac{1}{\rho+1}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}^{-\frac{\rho}{\rho+1}}\left(2^{\theta}a_j^{\rho}\right)^{\frac{1}{\theta+\rho}}$
$c_j^\bullet$	$\bar{c}$	$\bar{c}$
$w_j^\bullet$	$\left[\frac{(2\bar{c}+\kappa)\beta/\gamma}{\bar{c}+\kappa}\right]^{\frac{1}{\rho+1}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1}{\rho+1}}a_j^{-\frac{1}{1-\theta}}$	$\left[\frac{(2\bar{c}+\kappa)\beta/\gamma}{\bar{c}+\kappa}\right]^{\frac{1}{\rho+1}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}^{-\frac{1}{\rho+1}}\left[\frac{a_j}{2}\right]^{\frac{1}{\theta+\rho}}$
$n^\bullet$	1	1
$s^\bullet$	0	$(2\bar{c}+\kappa)\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}^{-1}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}-\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}$
$U^\bullet$	$2v(\bar{c})+\frac{\beta/\gamma}{(\rho+1)}\left[\rho-\frac{\bar{c}}{\bar{c}+\kappa}\right]$	$2v(\bar{c})+\frac{\beta/\gamma}{(\rho+1)}\left[\rho-\frac{\bar{c}}{\bar{c}+\kappa}\right]$

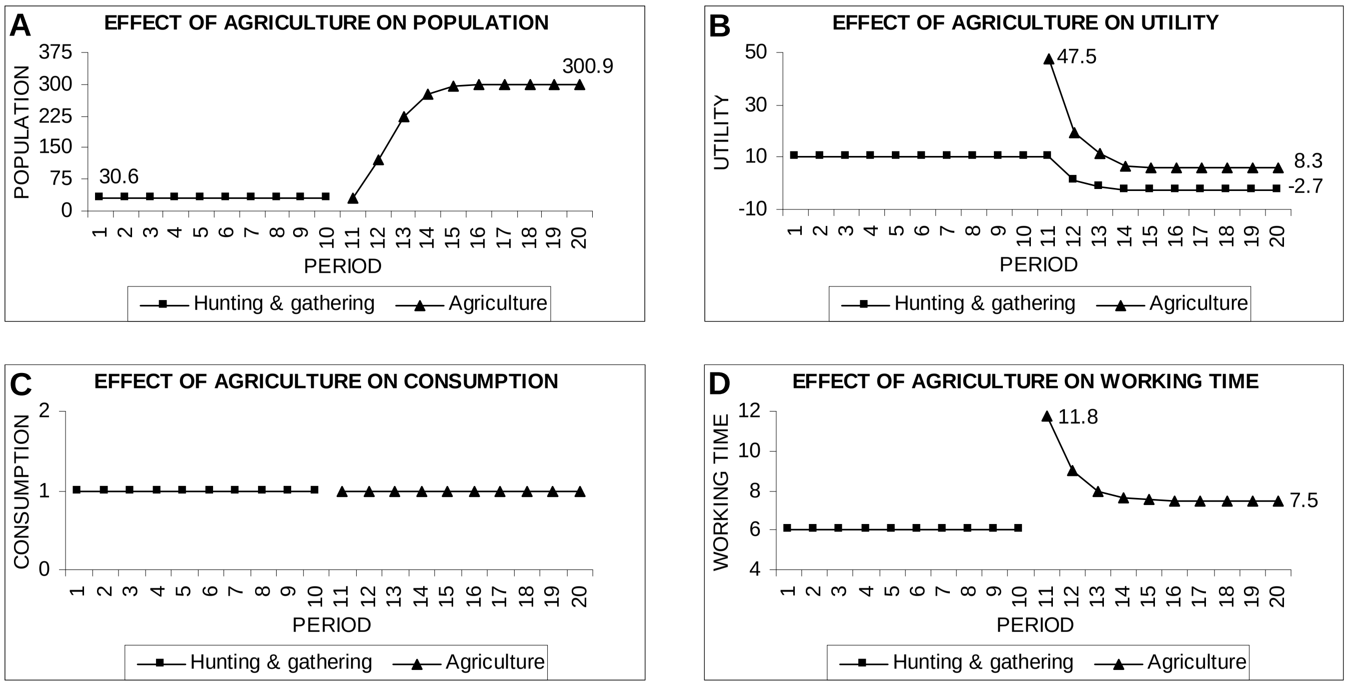

Figure 3-1: From periods 1 to 10 the tribesmen hunt and gather ($\mu = 5.2$, $\delta = 2.25$, $\kappa = 1$, $\sigma = \mathrm{N}$). At the beginning of period 11 they adopt agriculture ($\mu = 5.89$, $\delta = 0$, $\kappa = 0.5$, $\sigma = \mathrm{S}$). Simulation parameters: $\bar{c} = 1$, $\beta = 10$, $\gamma = 0.42$, $\rho = 1.26$, $\theta = 0.31$, $N_1 = 30.6$.

3.3 Appendix: Proofs of propositions

3.3.1 Preliminary results

Three functions that will be useful later:

$$\begin{aligned}
\mathrm{K}_p(x_1,x_2) &= \frac{x_1^p + x_2^p}{x_1^{p-1} - x_2^{p-1}}, \\
\mathrm{L}_p(x_1,x_2) &= \frac{x_1^p + x_2^p}{x_1^{p-1} + x_2^{p-1}}, && \text{(Lehmer mean)} \\
\mathrm{M}_p(x_1,x_2) &= \left[\frac{1}{2}x_1^p + \frac{1}{2}x_2^p\right]^{\frac{1}{p}}. && \text{(Generalized mean)}
\end{aligned}$$

Lemma 5 *If $p < q$ and $x_1 > x_2$, then $\mathrm{K}_p(x_1,x_2) > \mathrm{K}_q(x_1,x_2)$.*

Proof. From $x_1 > x_2$, it follows that

$$\frac{\partial K_p(x_1,x_2)}{\partial p} = -(\ln x_1 - \ln x_2)\frac{x_1^p x_2^{p-1} + x_1^{p-1} x_2^p}{\left[x_1^{p-1} - x_2^{p-1}\right]^2} < 0.$$

■

Lemma 6 (Lehmer mean inequality) *If $p < q$ and $x_1 \neq x_2$, then $L_p(x_1,x_2) < L_q(x_1,x_2)$.*

Lemma 7 (Generalized mean inequality) *If $p < q$ and $x_1 \neq x_2$, then $M_p(x_1,x_2) < M_q(x_1,x_2)$.*

3.3.2 Proof of proposition 1

For the dynamic system $N_{t+1} = n_t N_t$ to be stable, the following condition is sufficient:

$$-2 < N^{\bullet} \left.\frac{\partial n^{\circ}}{\partial N^{\circ}}\right|_{N^{\circ}=N^{\bullet}} < 0. \tag{3.3}$$

Condition 3.3 guarantees that if N_t is close to $N^{\bullet}$, then N_{t+1} will be even closer.

Case 1: Storage is unfeasible

If storage is unfeasible, we have that

$$N^{\circ}\frac{\partial n^{\circ}}{\partial N^{\circ}}=-\frac{\theta\left(\rho+1\right)}{\theta+\rho}\left(N^{\circ}\right)^{-\frac{\theta(\rho+1)}{\theta+\rho}}\left[\frac{\left(\beta/\gamma\right)^{1-\theta}}{\left(\bar{c}+\kappa\right)^{\rho+1}}\right]^{\frac{1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta+\rho}}.$$

Plugging $N^{\bullet}$ into the previous expression we get

$$N^{\bullet}\frac{\partial n^{\circ}}{\partial N^{\circ}}\bigg|_{N^{\circ}=N^{\bullet}}=-\underbrace{\frac{\theta\left(\rho+1\right)}{\theta+\rho}}_{\tau_1}\underbrace{\left[2-\frac{\kappa}{\bar{c}+\kappa}\right]}_{\tau_2}.$$

From $0<\theta<1$ and $\rho>1$, it follows that $0<\tau_1<1$. From $\bar{c},\kappa>0$, it follows that $0<\tau_2<2$. As a result, $-2<(N^{\bullet}\partial n^{\circ}/\partial N^{\circ})|_{N^{\circ}=N^{\bullet}}<0$.

Case 2: Storage is feasible

If storage is feasible, we have that

$$N^{\circ}\frac{\partial n^{\circ}}{\partial N^{\circ}}=-\frac{\theta\left(\rho+1\right)}{\theta+\rho}\left(N^{\circ}\right)^{-\frac{\theta(\rho+1)}{\theta+\rho}}\left[\frac{\left(\beta/\gamma\right)^{1-\theta}}{\left(\bar{c}+\kappa\right)^{\rho+1}}\right]^{\frac{1}{\theta+\rho}}\left\{\left[\frac{a_1}{2}\right]^{\frac{\rho+1}{\theta+\rho}}+\left[\frac{a_2}{2}\right]^{\frac{\rho+1}{\theta+\rho}}\right\}.$$

Plugging $N^{\bullet}$ into the previous expression we get

$$N^{\bullet}\frac{\partial n^{\circ}}{\partial N^{\circ}}\bigg|_{N^{\circ}=N^{\bullet}}=-\frac{\theta\left(\rho+1\right)}{\theta+\rho}\left[2-\frac{\kappa}{\bar{c}+\kappa}\right].$$

So again $-2<N^{\bullet}\left(\partial n^{\circ}/\partial N^{\circ}\right)|_{N^{\circ}=N^{\bullet}}<0$. ■

3.3.3 Proof of proposition 2

The following proofs build on the short-run equilibrium results of Table 3.3. Recall that $a_1 > a_2 > 0$, $0 < \theta < 1$, and $\beta, \gamma, \rho, \bar{c}, \kappa, N > 0$.

- $\partial n^\circ / \partial \mu > 0$.

  Proof.

$$\frac{\partial n^\circ}{\partial \mu} = \frac{\rho + 1}{\theta + \rho} \left\{ \frac{(\beta/\gamma)^{1-\theta}}{\left[(N^\circ)^\theta (\bar{c} + \kappa) \right]^{\rho+1}} \right\}^{\frac{1}{\theta+\rho}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}} \right]^{-\frac{\rho+1}{\theta+\rho}} \left[a_1^{-\frac{\rho+1}{1-\theta}-1} + a_2^{-\frac{\rho+1}{1-\theta}-1} \right] > 0.$$

  ■

- $\partial n^\circ / \partial \delta < 0$.

  Proof.

$$\frac{\partial n^\circ}{\partial \delta} = \frac{\rho + 1}{\theta + \rho} \left\{ \frac{(\beta/\gamma)^{1-\theta}}{\left[(N^\circ)^\theta (\bar{c} + \kappa) \right]^{\rho+1}} \right\}^{\frac{1}{\theta+\rho}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}} \right]^{-\frac{\rho+1}{\theta+\rho}} \underbrace{\left[a_1^{-\frac{\rho+1}{1-\theta}-1} - a_2^{-\frac{\rho+1}{1-\theta}-1} \right]}_{\tau}.$$

  The sign of $\partial n^\circ / \partial \delta$ depends on τ. Since $a_1 > a_2$, term τ is negative. Hence, $\partial n^\circ / \partial \delta < 0$.

  ■

- $\partial n^\circ / \partial \kappa < 0$.

  Proof.

$$\frac{\partial n^\circ}{\partial \kappa} = -\frac{\rho + 1}{\theta + \rho} (\bar{c} + \kappa)^{-\frac{\rho+1}{\theta+\rho}-1} \left[\frac{(\beta/\gamma)^{1-\theta}}{(N^\circ)^{\theta(\rho+1)}} \right]^{\frac{1}{\theta+\rho}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}} \right] < 0.$$

  ■

- $n^\circ[\mathrm{N}] < n^\circ[\mathrm{S}]$.

  Proof.

$$n^\circ[\mathrm{S}] - n^\circ[\mathrm{N}] = \left\{ \frac{(\beta/\gamma)^{1-\theta}}{\left[(N^\circ)^\theta (\bar{c}+\kappa) \right]^{\rho+1}} \right\}^{\frac{1}{\theta+\rho}} 2^{-\frac{1-\theta}{\theta+\rho}} \underbrace{\left[\mathrm{M}_{-\frac{1}{1-\theta}} \left(a_1^{\rho+1}, a_2^{\rho+1} \right)^{\frac{1}{\rho+\theta}} - \mathrm{M}_{\frac{1}{\theta+\rho}} \left(a_1^{\rho+1}, a_2^{\rho+1} \right)^{\frac{1}{\rho+\theta}} \right]}_{\tau}.$$

  The sign of $n^\circ[\mathrm{S}] - n^\circ[\mathrm{N}]$ depends on τ, which will be positive if

$$\mathrm{M}_{-\frac{1}{1-\theta}} \left(a_1^{\rho+1}, a_2^{\rho+1} \right) < \mathrm{M}_{\frac{1}{\theta+\rho}} \left(a_1^{\rho+1}, a_2^{\rho+1} \right).$$

  But

$$-\frac{1}{1-\theta} < \frac{1}{\theta+\rho}.$$

  Thus, from the generalized mean inequality, we conclude $\tau > 0$, so $n^\circ[\mathrm{N}] < n^\circ[\mathrm{S}]$. ■

- $\partial \bar{w}^\circ / \partial \mu > 0$.

  Proof. Instead of $\partial \bar{w}^\circ / \partial \mu$, consider $\partial \ln \bar{w}^\circ / \partial \mu$, which has the same sign as $\partial \bar{w}^\circ / \partial \mu$.

$$\frac{\partial \ln \bar{w}^\circ}{\partial \mu} = \frac{1}{1-\theta} \underbrace{\left[\frac{\rho+1}{\theta+\rho} \mathrm{L}_{-\frac{\rho+1}{1-\theta}} (a_1, a_2)^{-1} - \mathrm{L}_{-\frac{1}{1-\theta}} (a_1, a_2)^{-1} \right]}_{\tau}.$$

  The sign of $\partial \ln \bar{w}^\circ / \partial \mu$ depends on τ. But

$$\begin{aligned} \frac{\rho+1}{\theta+\rho} &> 1, \\ \mathrm{L}_{-\frac{\rho+1}{1-\theta}} (a_1, a_2) &> 0, \\ \mathrm{L}_{-\frac{1}{1-\theta}} (a_1, a_2) &> 0. \end{aligned}$$

  Therefore,

$$\tau > \mathrm{L}_{-\frac{\rho+1}{1-\theta}} (a_1, a_2)^{-1} - \mathrm{L}_{-\frac{1}{1-\theta}} (a_1, a_2)^{-1}.$$

On the other hand,

$$-\frac{\rho+1}{1-\theta}<-\frac{1}{1-\theta}.$$

Thus, from the Lehmer mean inequality it follows that

$$\mathrm{L}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)<\mathrm{L}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right),$$

or equivalently

$$\mathrm{L}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{-1}-\mathrm{L}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right)^{-1}>0.$$

That implies $\tau>0$, so $\partial\ln\bar{w}^\circ/\partial\mu>0$ and $\partial\bar{w}^\circ/\partial\mu>0$. ■

- $\partial\bar{w}^\circ/\partial\delta<0$.

Proof. Instead of $\partial\bar{w}^\circ/\partial\delta$, consider $\partial\ln\bar{w}^\circ/\partial\delta$, which has the same sign as $\partial\bar{w}^\circ/\partial\delta$.

$$\frac{\partial\ln\bar{w}^\circ}{\partial\delta}=\frac{1}{1-\theta}\underbrace{\left[\frac{\rho+1}{\theta+\rho}\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{-1}-\mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right)^{-1}\right]}_{\tau}.$$

The sign of $\partial\ln\bar{w}^\circ/\partial\delta$ depends on τ. But

$$\begin{aligned}\frac{\rho+1}{\theta+\rho} &> 1,\\ \mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right) &< 0,\\ \mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right) &< 0.\end{aligned}$$

Therefore,

$$\tau<\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{-1}-\mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right)^{-1}.$$

On the other hand,

$$-\frac{\rho+1}{1-\theta}<-\frac{1}{1-\theta}.$$

Thus, from lemma 5 it follows that

$$\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)>\mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right),$$

or equivalently

$$\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{-1}-\mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1,a_2\right)^{-1}<0.$$

That implies $\tau<0$, so $\partial\ln\bar{w}^{\circ}/\partial\delta<0$ and $\partial\bar{w}^{\circ}/\partial\delta<0$. ■

- $\partial\bar{w}^{\circ}/\partial\kappa<0$.

  Proof.

$$\frac{\partial\bar{w}^{\circ}}{\partial\kappa}=-\frac{1}{\theta+\rho}\left(\bar{c}+\kappa\right)^{-\frac{1}{\theta+\rho}-1}\left\{\frac{\beta/\gamma}{\left(N^{\circ}\right)^{\theta}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-1}\right\}^{\frac{1}{\theta+\rho}}\left[a_1^{-\frac{1}{1-\theta}}+a_2^{-\frac{1}{1-\theta}}\right]<0.$$

■

- $\bar{w}^{\circ}[\mathrm{N}]<\bar{w}^{\circ}[\mathrm{S}]$.

  Proof.

$$\begin{aligned}\bar{w}^{\circ}[\mathrm{S}]-\bar{w}^{\circ}[\mathrm{N}] &= \left\{\frac{\beta/\gamma}{2\left(N^{\circ}\right)^{\theta}\left(\bar{c}+\kappa\right)}\right\}^{\frac{1}{\theta+\rho}}\\ &\quad \underbrace{\left\{\mathrm{M}_{\frac{1}{\theta+\rho}}\left(a_1,a_2\right)^{\frac{1}{\theta+\rho}}-\mathrm{M}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{\frac{1}{\theta+\rho}}\frac{\mathrm{M}_1\left(a_1^{-1/(1-\theta)},a_2^{-1/(1-\theta)}\right)}{\mathrm{M}_{\rho+1}\left(a_1^{-1/(1-\theta)},a_2^{-1/(1-\theta)}\right)}\right\}}_{\tau}.\end{aligned}$$

The sign of $\bar{w}^{\circ}[\mathrm{S}]-\bar{w}^{\circ}[\mathrm{N}]$ depends on τ. But

$$\frac{1}{\theta+\rho}>-\frac{\rho+1}{1-\theta},$$

and thus, from the generalized mean inequality,

$$\mathrm{M}_{\frac{1}{\theta+\rho}}\left(a_1,a_2\right)^{\frac{1}{\theta+\rho}}>\mathrm{M}_{-\frac{\rho+1}{1-\theta}}\left(a_1,a_2\right)^{\frac{1}{\theta+\rho}}>0.$$

Also, $1<\rho+1$. So again, from the generalized mean inequality,

$$0<\frac{\mathrm{M}_1\left(a_1^{-1/(1-\theta)},a_2^{-1/(1-\theta)}\right)}{\mathrm{M}_{\rho+1}\left(a_1^{-1/(1-\theta)},a_2^{-1/(1-\theta)}\right)}<1.$$

Therefore, $\tau>0$, and that implies $\bar{w}^{\circ}[\mathrm{S}]-\bar{w}^{\circ}[\mathrm{N}]>0$. ■

- $\partial u^\circ/\partial \mu > 0$.

  Proof.

$$\frac{\partial u^\circ}{\partial \mu} = \frac{\rho}{\theta+\rho}\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\right]^{\frac{\rho+1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{\rho+1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}-1}+a_2^{-\frac{\rho+1}{1-\theta}-1}\right] > 0.$$

  ■

- $\partial u^\circ/\partial \delta < 0$.

  Proof.

$$\frac{\partial u^\circ}{\partial \delta} = \frac{\rho}{\rho+1}\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\right]^{\frac{\rho+1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta+\rho}}\underbrace{\left[a_1^{-\frac{\rho+1}{1-\theta}-1}-a_2^{-\frac{\rho+1}{1-\theta}-1}\right]}_{\tau} < 0.$$

  The sign of $\partial u^\circ/\partial \delta$ depends on τ. Since $a_1 > a_2$, term τ is negative. Hence, $\partial u^\circ/\partial \delta < 0$.

  ■

- $\partial u^\circ/\partial \kappa < 0$.

  Proof.

$$\frac{\partial u^\circ}{\partial \kappa} = -\frac{\rho}{\theta+\rho}(\bar{c}+\kappa)^{-\frac{\rho+1}{\theta+\rho}-1}\left[\frac{\beta/\gamma}{(N^\circ)^\theta}\right]^{\frac{\rho+1}{\theta+\rho}}\left[a_1^{-\frac{\rho+1}{1-\theta}}+a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta+\rho}} < 0.$$

  ■

- *In the short run* $u^\circ[\mathrm{N}] < u^\circ[\mathrm{S}]$.

  Proof.

$$u^\circ[\mathrm{S}] - u^\circ[\mathrm{N}] = \frac{\rho}{1+\rho}\left[\frac{\beta/\gamma}{(N^\circ)^\theta(\bar{c}+\kappa)}\right]^{\frac{\rho}{\theta+\rho}}(n[\mathrm{S}]-n[\mathrm{N}]).$$

  But $n^\circ[\mathrm{N}] < n^\circ[\mathrm{S}]$, and thus, $u^\circ[\mathrm{N}] < u^\circ[\mathrm{S}]$. ■

3.3.4 Proof of proposition 3

The following proofs build on the long-run equilibrium results of Table 3.4. Recall that $a_1 > a_2 > 0$, $0 < \theta < 1$, and $\beta, \gamma, \rho, \bar{c}, \kappa > 0$.

- $\partial N^{\bullet}/\partial \mu > 0$.

  Proof.

$$\frac{\partial N^{\bullet}}{\partial \mu} = \frac{1}{\theta}\left\{\frac{1}{(2\bar{c}+\kappa)^{\theta+\rho}}\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{1-\theta}\right\}^{\frac{1}{\theta(\rho+1)}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{\theta\rho+1}{\theta(\rho+1)}} \left[a_1^{-\frac{\rho+1}{1-\theta}-1} + a_2^{-\frac{\rho+1}{1-\theta}-1}\right] > 0.$$

  ■

- $\partial N^{\bullet}/\partial \delta < 0$.

  Proof.

$$\frac{\partial N^{\bullet}}{\partial \delta} = \frac{1}{\theta}\left\{\frac{1}{(2\bar{c}+\kappa)^{\theta+\rho}}\left[\frac{\beta/\gamma}{\bar{c}+\kappa}\right]^{1-\theta}\right\}^{\frac{1}{\theta(\rho+1)}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{\theta\rho+1}{\theta(\rho+1)}} \underbrace{\left[a_1^{-\frac{\rho+1}{1-\theta}-1} - a_2^{-\frac{\rho+1}{1-\theta}-1}\right]}_{\tau}.$$

  The sign of $\partial N^{\bullet}/\partial \delta$ depends on τ. Since $a_1 > a_2$, term τ is negative. Hence, $\partial N^{\bullet}/\partial \delta < 0$.

  ■

- $\partial N^{\bullet}/\partial \kappa < 0$.

  Proof.

$$\frac{\partial N^{\bullet}}{\partial \kappa} = -\frac{1-\theta}{\theta\,(\rho+1)}\,(\bar{c}+\kappa)^{-\frac{1-\theta}{\theta(\rho+1)}-1}\left[\frac{(\beta/\gamma)^{1-\theta}}{(2\bar{c}+\kappa)^{\theta+\rho}}\right]^{\frac{1}{\theta(\rho+1)}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1-\theta}{\theta(\rho+1)}} < 0.$$

  ■

- $N^{\bullet}[\mathrm{N}] < N^{\bullet}[\mathrm{S}]$.

$$N^{\bullet}[\mathrm{S}] - N^{\bullet}[\mathrm{N}] = \left\{ \frac{1}{(2\bar{c}+\kappa)^{\theta+\rho}} \left[\frac{\beta/\gamma}{\bar{c}+\kappa} \right]^{1-\theta} \right\}^{\frac{1}{\theta(\rho+1)}} 2^{-\frac{1-\theta}{\theta(\rho+1)}} \underbrace{\left[\mathrm{M}_{\frac{\rho+1}{\theta+\rho}}(a_1,a_2)^{\frac{1}{\theta}} - \mathrm{M}_{-\frac{\rho+1}{1-\theta}}(a_1,a_2)^{\frac{1}{\theta}} \right]}_{\tau}.$$

The sign of $N^{\bullet}[\mathrm{S}] - N^{\bullet}[\mathrm{N}]$ depends on τ, and τ will be positive if

$$\mathrm{M}_{-\frac{\rho+1}{1-\theta}}(a_1,a_2) < \mathrm{M}_{\frac{\rho+1}{\theta+\rho}}(a_1,a_2).$$

But

$$-\frac{\rho+1}{1-\theta} < \frac{\rho+1}{\theta+\rho}.$$

Thus, from the generalized mean inequality, we conclude $\tau > 0$, so $N^{\bullet}[\mathrm{N}] < N^{\bullet}[\mathrm{S}]$.

- $\partial\bar{w}^{\bullet}/\partial\mu > 0$

Proof. Instead of $\partial\bar{w}^{\bullet}/\partial\mu$, consider $\partial\ln\bar{w}^{\bullet}/\partial\mu$, which has the same sign as $\partial\bar{w}^{\bullet}/\partial\mu$.

$$\frac{\partial\ln\bar{w}^{\bullet}}{\partial\mu} = \frac{1}{1-\theta} \underbrace{\left[\mathrm{L}_{-\frac{\rho+1}{1-\theta}}(a_1,a_2)^{-1} - \mathrm{L}_{-\frac{1}{1-\theta}}(a_1,a_2)^{-1} \right]}_{\tau}.$$

The sign of $\partial\ln\bar{w}^{\bullet}/\partial\mu$ depends on τ. But

$$-\frac{\rho+1}{1-\theta} < -\frac{1}{1-\theta}.$$

Thus, from the Lehmer mean inequality it follows that

$$\mathrm{L}_{-\frac{\rho+1}{1-\theta}}(a_1,a_2) < \mathrm{L}_{-\frac{1}{1-\theta}}(a_1,a_2),$$

or equivalently

$$\mathrm{L}_{-\frac{\rho+1}{1-\theta}}(a_1,a_2)^{-1} - \mathrm{L}_{-\frac{1}{1-\theta}}(a_1,a_2)^{-1} > 0.$$

That implies $\tau > 0$, so $\partial\ln\bar{w}^{\bullet}/\partial\mu > 0$ and $\partial\bar{w}^{\bullet}/\partial\mu > 0$. ■

- $\partial \bar{w}^{\bullet}/\partial \delta > 0$

  Proof. Instead of $\partial \bar{w}^{\bullet}/\partial \delta$, consider $\partial \ln \bar{w}^{\bullet}/\partial \delta$, which has the same sign as $\partial \bar{w}^{\bullet}/\partial \delta$.

$$\frac{\partial \ln \bar{w}^{\bullet}}{\partial \delta} = \frac{1}{1-\theta} \underbrace{\left[\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1, a_2\right)^{-1} - \mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1, a_2\right)^{-1} \right]}_{\tau}.$$

  The sign of $\partial \ln \bar{w}^{\bullet}/\partial \delta$ depends on τ. But

$$-\frac{\rho+1}{1-\theta} < -\frac{1}{1-\theta}.$$

  Thus, from lemma 5 it follows that

$$\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1, a_2\right) > \mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1, a_2\right),$$

  or equivalently

$$\mathrm{K}_{-\frac{\rho+1}{1-\theta}}\left(a_1, a_2\right)^{-1} - \mathrm{K}_{-\frac{1}{1-\theta}}\left(a_1, a_2\right)^{-1} < 0.$$

  That implies $\tau < 0$, so $\partial \ln \bar{w}^{\bullet}/\partial \delta < 0$ and $\partial \bar{w}^{\bullet}/\partial \delta < 0$. ■

- $\partial \bar{w}^{\bullet}/\partial \kappa > 0$

  Proof.

$$\frac{\partial \bar{w}^{\bullet}}{\partial \kappa} = -\frac{1}{\rho+1} \frac{c}{(2c+\kappa)^{\frac{\rho}{\rho+1}} (c+\kappa)^{\frac{\rho+2}{\rho+1}}} (\beta/\gamma)^{\frac{1}{\rho+1}} \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}} \right]^{-\frac{1}{\rho+1}} \left[a_1^{-\frac{1}{1-\theta}} + a_2^{-\frac{1}{1-\theta}} \right] < 0.$$

  ■

- $\partial u^{\bullet}/\partial \kappa > 0$

  Proof.

$$\frac{\partial \bar{w}^{\bullet}}{\partial \kappa} = \frac{c\beta/\gamma}{(\rho+1)(c+\kappa)^2} > 0.$$

  ■

3.3.5 Proof of proposition 4

$\bar{w}^{\bullet}[\mathrm{S}] > \bar{w}^{\bullet}[\mathrm{N}]$ if and only if

$$\Delta\bar{w}^{\bullet}(\rho,\theta) \equiv \frac{1}{2}\left[\frac{(2\bar{c}+\kappa)\beta/\gamma}{\bar{c}+\kappa}\right]^{\frac{1}{1+\rho}}$$
$$\left\{\left[a_1^{\frac{\rho+1}{\theta+\rho}} + a_2^{\frac{\rho+1}{\theta+\rho}}\right]^{-\frac{1}{\rho+1}}\left[a_1^{\frac{1}{\theta+\rho}} + a_2^{\frac{1}{\theta+\rho}}\right] - \left[a_1^{-\frac{\rho+1}{1-\theta}} + a_2^{-\frac{\rho+1}{1-\theta}}\right]^{-\frac{1}{\rho+1}}\left[a_1^{-\frac{1}{1-\theta}} + a_2^{-\frac{1}{1-\theta}}\right]\right\} \geq 0.$$

Function $\Delta\bar{w}^{\bullet}$ is continuous in $\rho > 0$ and $0 < \theta < 1$. Also, provided that $a_1 > a_2 > 0$, it is straightforward that $\Delta\bar{w}^{\bullet}$ takes value 0 if and only if $\rho + 2\theta = 1$.

From continuity it follows that $\Delta\bar{w}^{\bullet}$ will have the same sign for all ρ and θ in the set

$$\mathcal{A}_+ \equiv \{(\rho,\theta) : \rho > 0,\ 0 < \theta < 1, \text{ and } \rho + 2\theta > 1\}.$$

One point in set $\mathcal{A}_+$ is $(1, 1/2)$. Evaluating $\Delta\bar{w}^{\bullet}$ at that point we get.

$$\Delta\bar{w}^{\bullet}(1,1/2) = \frac{1}{2}\left[\frac{(2\bar{c}+\kappa)\beta/\gamma}{\bar{c}+\kappa}\right]^{\frac{1}{2}}\underbrace{\left\{\mathrm{H}_{2/3}(a_1,a_2) - \mathrm{H}_2(a_1,a_2)\right\}}_{\tau},$$

where

$$\mathrm{H}_p(a_1,a_2) = \frac{a_1^p + a_2^p}{\left(a_1^{2p} + a_2^{2p}\right)^{1/2}}.$$

But, for all $p > 0$ and $a_1 \neq a_2$,

$$\frac{\partial\,\mathrm{H}_p(a_1,a_2)}{\partial p} = -a_1^p a_2^p(\ln a_1 - \ln a_2)\frac{a_1^p - a_2^p}{\left(a_1^{2p} + a_2^{2p}\right)^{3/2}} < 0.$$

Hence $\mathrm{H}_{2/3}(a_1,a_2) > \mathrm{H}_2(a_1,a_2)$, term $\tau > 0$, function $\Delta\bar{w}^{\bullet}(1,1/2) > 0$, and finally $\Delta\bar{w}^{\bullet}(\rho,\theta) \geq 0$ for all $(\rho,\theta) \in \mathcal{A}_+$.

The proof that $\Delta\bar{w}^{\bullet}(\rho,\theta) \leq 0$ for all $(\rho,\theta) \in \mathcal{A}_- \equiv \{(\rho,\theta) : \rho > 0,\ 0 < \theta < 1, \text{ and } \rho + 2\theta < 1\}$ is analogous, so I omit it. ■

Chapter 4

Institutions influence preferences: Evidence from a common pool resource experiment

This chapter was written with Carlos Rodríguez and Juan Camilo Cárdenas. It is forthcoming in the Journal of Economic Behavior and Organization.

It is now widely agreed that social preferences such as altruism, reciprocity, and guilt are strong motives for behavior. Without a state to enforce property rights (or the disciplining hand of reputation), the selfish homo economicus engages in a war of all against all, but the homo sapiens does not: Social preferences help him avert chaos and cooperate. Economists usually assume away the influence institutions exert on social preferences. Often the assumption is harmless, but occasionally it may result in unexpected or even disastrous consequences. English health authorities learned this the hard way. When they decided to incentivize blood donations by paying donors, instead of increasing, blood donations plummeted (Titmuss, 1969).[1]

Experiments indicate institutions affect social preferences. For example, Gneezy and Rustichini (2000) studied daycare centers in Haifa, where a fine was imposed on parents who picked up their children late. Unexpectedly, tardiness more than doubled in those centers. A plausible explanation is that, by transforming a misdemeanor into a commodity that parents could buy

[1] See Bowles (1998, 2007) for an extensive discussion of endogenous preferences and their policy implications.

cheaply, the fine eroded their sense of duty. Another example appears in Falk and Kosfeld's (2006) experimental study of principal–agent relations. They gave principals the option to set a lower bound on the effort of agents. Falk and Kosfeld found that agents who were not restricted by their principals worked harder than those who were. Agents seemed to punish distrust.

In this paper we explore the dynamic effects of external enforcement on the exploitation of a common pool resource (CPR).[2] As the previous evidence suggests, external enforcement may change the preferences of players, so we begin by developing a model of CPR games that captures that possibility. The ingredients of the model are

1. *Heterogeneous preferences.* We distinguish three types of players: (*i*) Selfish, who only care about their own material payoffs; (*ii*) unconditional cooperators, who feel guilty when they violate a social norm; (*iii*) conditional cooperators, who experience guilt with an intensity that declines when others violate the norm.

2. *State-dependent preferences.* When institutions change, player types may change as well. Institutions comprise such things as the enforcement of a norm by an external authority.

3. *Stochastic behavior.* A player will choose with higher probability those actions that give her a higher expected utility.

4. *Adaptive expectations.* Each player has an estimate of how many tokens her peers will extract from the common pool and updates that estimate as she observes what they actually do.

Next, we fit our model to experimental data. In our experiment, groups of five persons played a CPR game 20 times. In some treatments the experimenter fined players he caught extracting more than one token (he applied the fines in private to prevent shame from affecting behavior). Some groups were treated with a high fine, other groups with a low one. Both fines induced high levels of cooperation. The effect of the high fine accorded with our expectations. The deterrence power of the low fine, by contrast, could not be justified by any reasonable parameterization of

[2] In a CPR game each player chooses privately how many tokens she will extract from a common pool. A player's material payoff depends positively on the number of tokens she extracts and negatively on the aggregate level of extraction. Thus, individual and social interest conflict.

selfish preferences. Even more surprising was what happened when the experimenter proposed the sanction mechanism to the players but they voted against it; extraction fell sharply at first, and then cooperation slowly unraveled back to its original low level.[3] One may infer the norm was internalized by some players even when it was not enforced. Without enforcement, moralization seemed to vanish over time.

Fitting our model to the experimental data we find that most selfish players adopt a cooperative type when the experimenter prescribes extracting one token. We also find that fewer people internalize the norm if the norm is enforced. We rationalize these findings as follows. Initially, there are very few cooperative players. When the experimenter prescribes the norm, the number of cooperators rises: We term this a "prescriptive effect". If the players learn that the norm will be enforced, the number of cooperators immediately falls, although it still remains higher than its initial level. Enforcement seems to relieve some players from the guilt of infringement: We call this a "guilt relief effect." The existence of a prescriptive and a guilt relief effect also reconcile our findings with Gneezy and Rustichini's. In their experiment, the imposition of a fine alleviated the parent's guilty feelings, but as parents knew beforehand that it was their duty to pick up their children on time, the prescriptive effect was absent. The result was a crowding out of cooperation. In our experiment, both effects act together. The prescriptive effect dominates the guilt relief effect, so cooperation crowds in.

Finally, our study reveals that a player who cooperates conditionally under no fine is likely to cooperate unconditionally when a fine is in force. This is probably because the fine relieves her of the desire to retaliate against uncooperative players in the only way she can: By ceasing to cooperate herself.[4]

Our findings solve the two puzzles in the experimental results: The increase and later erosion of cooperation when commoners vote against the imposition of a fine, and the high deterrence power of low fines. When fines are rejected, moralization explains the increased cooperation; violations (accidental or not), coupled with reciprocal preferences, account for the erosion. Low

[3] Ostrom et al. (1994) and Cárdenas et al. (2000) also find unraveling in CPR games. The unraveling of cooperation has been reported in public good experiments as well. The earliest reports are in Kim and Walker (1984) and in Isaac et al. (1985). See Fehr and Gaechter (2000) for a more recent treatment of the subject.

[4] Andreoni (1995) advanced a similar hypothesis in the context of public good games.

fines, on the other hand, induce players to cooperate irrespective of the behavior of their peers. A spiral of negative reciprocation is prevented and, as a result, cooperation becomes stable.

4.1 A model of common pool resource games

N persons play a finitely repeated common pool resource (CPR) game. The game is repeated T times. At the beginning of each round, every player decides privately how many tokens to extract from a common pool, the minimum being one token, and the maximum x_{max} tokens. Let $x_{it} \in \{1, ..., x_{max}\}$ be the number of tokens that player $i \in \{1, ..., N\}$ takes from the common pool in round $t \in \{1, ..., T\}$.

A player's payoff from extraction depends positively on the number of tokens she extracts and negatively on the aggregate level of extraction. Denote by $\pi(x_{it}, \bar{x}_{-it})$ player i's payoff from extraction in round t, where $\bar{x}_{-it} = (N-1)^{-1} \sum_{j \neq i} x_{jt}$. Function $\pi(x_{it}, \bar{x}_{-it})$ is increasing in x_{it} and decreasing in $\bar{x}_{-it}$. The sum of the payoffs of all players is maximized when they all extract the minimum amount (one token).

Assume that the social norm is to extract one token. At the end of each round, an external authority inspects each player with probability $p_t \in [0, 1)$. If the authority discovers that a player violated the social norm, he fines that player with an amount $f_t \geq 0$ for every token she extracted in excess of one (the authority then casts the collected fine into the sea). Thus, the expected material payoff of player i in round t is $\pi(x_{it}, \bar{x}_{-it}) - p_t f_t (x_{it} - 1)$.

There are three types of players: Selfish (S), unconditional cooperators (UC), and conditional cooperators (CC). A selfish player derives utility only from her own consumption. An unconditional cooperator also enjoys consumption, but feels guilty when she extracts more than the amount prescribed by the norm, an idea we borrow from Bowles and Gintis (2002). Finally, a conditional cooperator enjoys consumption and feels guilty when she infringes the norm, though her guilt diminishes as group extraction increases. Conditional cooperators relate our model to those of reciprocal preferences such as Rabin's (1993) and Dufwenberg and Kirchsteiger's (2004). Fischbacher et al. (2004) report conditional cooperation is the most common behavior in one-shot public goods games, and that suggests it may also be common in CPR games. The effect of diminishing guilt on norm compliance was recently explored by Lin and Yang (2005).

Let $u(x_{it}, \bar{x}_{-it}, \theta_{it})$ be the utility function of player i in round t when she is of type $\theta_{it} \in \{\text{S},\text{UC},\text{CC}\}$. We define $u(x_{it}, \bar{x}_{-it}, \theta_{it})$ as follows:

$$u(x_{it}, \bar{x}_{-it}, \theta_{it}) = \pi(x_{it}, \bar{x}_{-it}) - p_t f_t(x_{it} - 1) - 1(\theta_{it} \neq \text{S})\beta_1 \pi_{max} \frac{x_{it} - 1}{x_{max} - 1} \left\{ 1 - 1(\theta_{it} \neq \text{CC})\beta_2 \frac{\bar{x}_{-it} - 1}{x_{max} - 1} \right\},$$

where $\pi_{max} = 880$ is the maximum material payoff a player may obtain in one round, β_1 and β_2 the positive constants, and function $1(s)$ is 1 if statement s is true and 0 otherwise. This means that an unconditional cooperator who extracts x_{max} tokens experiences guilt equivalent to β_1 times π_{max}. A conditional cooperator feels as guilty as an unconditional one, provided everybody else abides by the norm and extracts one token. If $\beta_2 > 1$ and aggregate extraction is high, a conditional cooperator will enjoy violating the norm.

We allow a player's type to depend on institutions. We shall postpone the definition of institutions until the next section. For the time being, bear in mind that institutions may comprise such things as the enforcement of a norm by an external authority, and that institutions may change over time. Each player is born a certain type (S, UC, or CC), and she may only switch types when institutions change. If we denote the institution in force during round t as ω_t, that means that $\theta_{it} = \theta_{i(t-1)}$ unless $\omega_t = \omega_{t-1}$. Denote as $q(\theta \,|\, \omega)$ the probability that a player will become type θ at the beginning of institutional regime ω.

Player i will choose with higher probability those actions that give her a higher expected utility. Let ε_{it} be her expectation of how much other players will extract in round t. The probability that player i will extract x tokens on round t is a logistic function of her expected utilities:

$$P_{it}(x) = \frac{\exp\left[\lambda \cdot u(x_{it}, \varepsilon_{it}, \theta_{it})\right]}{\sum_{y=1}^{x_{max}} \exp\left[\lambda \cdot u(y, \varepsilon_{it}, \theta_{it})\right]},$$

where $\lambda \geq 0$ represents her tendency to maximize. If $\lambda = 0$, the player will choose all extraction levels with equal probability. As λ approaches infinity, the player will tend to extract with probability one the number of tokens that maximizes her utility.

Finally, player i updates her estimate of how much others will extract as she observes what they actually do. Player i's expectations are adaptive:

$$\varepsilon_{it} = \begin{cases} \varepsilon(\omega_t) & \text{if } t = 1 \text{ or } \omega_t = \omega_{t-1}, \\ \phi\varepsilon_{i(t-1)} + (1-\phi)\,\bar{x}_{-it} & \text{otherwise.} \end{cases}$$

where $\phi \in [0,1]$ measures the persistence of expectations, and $\varepsilon(\omega)$ is an exogenous initial expectation. Initial expectations depend on ω because a change in institutions may induce a change in what players expect. Stochastic choice combined with adaptive learning make our model a close cousin of Camerer and Ho's (1999) EWA learning model. Our work is also linked to Janssen and Ahn's (2006), that fits an EWA learning model to the results of two public good experiments. They find that heterogeneous preferences are essential to account for their experimental evidence.

The steady state of $\bar{x}_t$, the mean extraction level of the group in round t, has one important property. If there are no conditional cooperators in a group, $\bar{x}_t$ has a unique stable steady state, but if enough conditional cooperators are added to the mix, the reciprocal nature of their preferences may cause a second steady state to emerge [a feature shared by other models of reciprocal preferences such as Rabin's (1993) and Lin and Yang's (2005)]. The intuition is simple: If conditional cooperators expect group extraction to be low, they will be inclined to extract few tokens. On the other hand, if they expect a high group extraction, conditional cooperators will tend to extract many tokens. Hence, there will be two attracting poles of self-fulfilling expectations: One where players cooperate a lot, and another with little cooperation.

4.2 A common pool resource experiment

In our common pool resource (CPR) experiment all subjects were adult villagers from five communities in Colombia. The communities exploited a common resource such as fish or water. To control for the effect of kin altruism, no two members of the same household were admitted into the same experimental group.

Here we briefly describe the experiment and discuss its results.[5]

[5] See Cárdenas (2005) for a detailed description of the experiment.

4.2.1 Experimental design

Groups of five persons ($N = 5$) play the CPR game of the previous section. The game is repeated 20 times ($T = 20$), and the players know the number of repetitions beforehand. In each round every player decides privately how many tokens to extract from a common pool, the minimum being one token and the maximum, eight ($x_{max} = 8$). The experimenter then informs players of the aggregate level of extraction, but does not reveal individual levels. Player i's payoff from extraction in round t is given by

$$\pi(x_{it}, \bar{x}_{-it}) = 800 + 40x_{it} - \frac{5}{2}x_{it}^2 - 80\bar{x}_{-it}.$$

A simple calculation shows that a player maximizes her material payoff by extracting eight tokens. The aggregate payoff, on the other hand, is maximized when each player extracts only one. After the final round, players cash their tokens. Prizes range between 1 and 2 days' wages.

At the end of round 10 the experimenter may introduce the following sanction mechanism: After each round he will randomly inspect one player; if he discovers that the player took more than one token, he will fine her in private. The experimenter may force the sanction mechanism on the players or let them vote on it. In either case, he first explains to the players that having a fine is in their best interests because it discourages extracting more than one token and because when everybody extracts only one token the material welfare of each player is maximized.

We identify four institutions:

- NF: No fine has ever been imposed on or approved by the players.
- HF: A high fine regime is in force.
- LF: A low fine regime is in force.
- RF: A fine regime was proposed to and rejected by the players.

We do not distinguish between fines imposed by the experimenter and fines approved by player vote because the distinction made no difference to the behavior of the players.[6] Since

[6] We performed a Kruskall–Wallis test on the hypothesis that mean extraction levels are the same under voted and externally imposed fine regimes. The test for high fines produced a p-value of 0.78. The test for low fines produced a p-value of 0.80.

the experimenter may affect the preferences of players when he proposes a fine and they vote against it, we do distinguish between the no fine (NF) and the rejected fine (RF) regimes.

Let be the fine in force when the institution is ω:

$$f(\omega) = \begin{cases} 0 & \text{if } \omega = \{\text{NF}, \text{RF}\}, \\ 175 & \text{if } \omega = \text{HF}, \\ 50 & \text{if } \omega = \text{LF}. \end{cases}$$

The expected material payoff of player i in round t is therefore $\pi(x_{it}, \bar{x}_{-it}) - (1/5)f(\omega)(x_{it} - 1)$, where $1/5$ is the probability she will be inspected.

Sixty-four groups of players received one of four different treatments:

- *Control* (8 groups). The institution is NF for all 20 rounds.
- *High fine* (14 groups). The institution is NF for the first 10 rounds and HF for the last 10 rounds.
- *Low fine* (26 groups). The institution is NF for the first 10 rounds and LF for the last 10 rounds.
- *Rejected fine* (16 groups). The institution is NF during the first 10 rounds and RF for the last 10 rounds.

The standard prediction for this version of the CPR game is its subgame perfect equilibrium. Table 4.2.1 summarizes the predictions for each institution. According to the predictions, only a high fine should have enough deterrence power to reduce individual extraction to its socially optimal level. Also, in the case of the low fine and the rejected fine institutions, the equilibrium extraction levels are far above the socially optimal level (one token). Thus, if one observes players complying with the social norm, one should feel less inclined to deem their compliance a mistake. Note that the equilibrium levels of extraction are close to or coincide with either the minimum or the maximum number of tokens that players are allowed to extract. This is intended to avoid the confusion that may arise among players if the equilibria were interior.

TABLE 4.2.1

PREDICTED LEVELS OF EXTRACTION

Institution	Predicted extraction
No fine	8
High fine	1
Low fine	6
Rejected fine	8

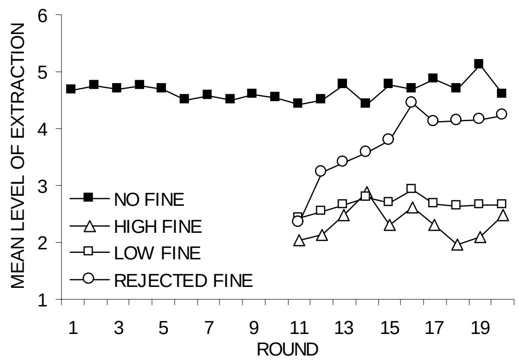

Figure 4-1: Experimental results: Aggregate behavior.

4.2.2 Results of the CPR experiment

Figure 4-1 displays the aggregate behavior of players under each institutional regime. Note that

1. Groups start at low levels of cooperation, extracting about 4.5 tokens on average. The mean level of extraction remains fairly constant during the first 10 rounds. In the control treatment, extraction stays around 4.5 tokens until the end of the game.

2. Under all treatments other than the control, cooperation increases on round 11. The social optimum, however, is never reached. Nonetheless, extraction falls even when the players vote against the fine.

3. Cooperation remains high after round 11 only when a fine, be it high or low, is in force. If the players reject the fine, cooperation slowly unravels.

TABLE 4.2.2

SUMMARY STATISTICS FROM THE CPR EXPERIMENT

	Institution			
	No fine	High fine	Low fine	Rejected fine
Mean extraction	4.6	2.3	2.7	3.7
Group deviation	2.3	1.9	2.1	2.3
Average individual deviation	1.8	1.0	1.2	1.8

Compare the results of the experiment with the predictions of Table 4.2.1. According to the predictions, initial extraction levels should be 60 percent higher than they actually are. Under the high fine, extraction should drop to one, instead it stays over two. We expected a low fine to exert little deterrence. However, the low fine and the high fine work almost as well. A rejected fine should have no effect whatsoever, but it has one.

Table 4.2.2 shows mean extraction levels under each institution, along with group and individual deviations from the mean. The high individual deviations suggest that players randomize or experiment.

Figure 4-2 shows histograms of individual extraction levels under different treatments. Under both fine treatments extraction is concentrated in the vicinity of one token. The histogram representing the no fine treatment is almost flat. If all players were identical, thatwould imply that they choose strategies completely at random, as if indifferent to material payoffs. A complementary explanation for the flatness is that players are heterogeneous along the moral dimension; some feel strongly that they should not take more than one token, while others have no qualms and maximize their material payoff by taking eight. Also note how the histograms that represent the rejected fine treatment get flatter on rounds 15 and 20, as cooperation deteriorates.

The unraveling process is better understood by examining, one by one, the groups that rejected a fine. Figure 4-3 shows four such groups. Group 1 extracts a high amount from the first period until the end. Groups 2–4 initially extract a low amount, but only group 4 cooperates until the last round. The most common pattern of behavior is represented by groups 2 and 3: both start by cooperating, but somewhere along the way they abruptly cease to cooperate (first

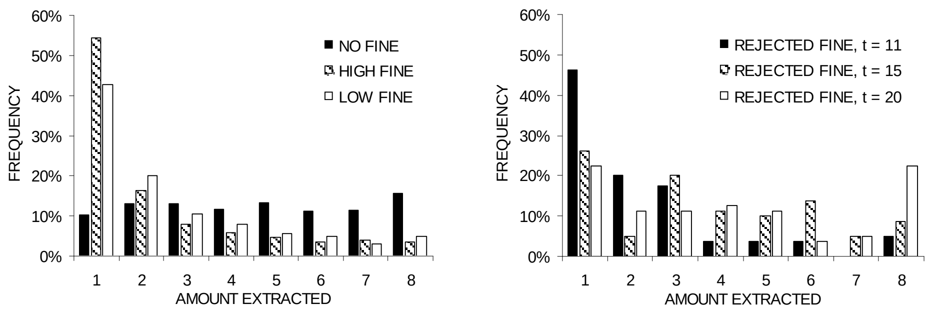

Figure 4-2: Experimental results: Distribution of individual extraction levels.

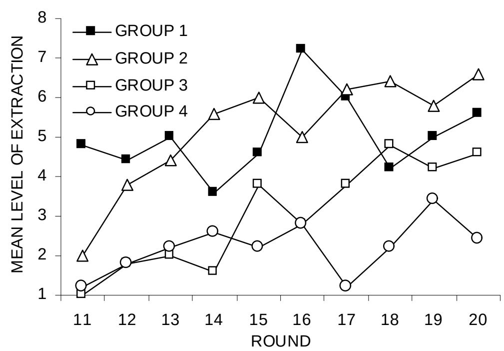

Figure 4-3: Experimental results: groups that voted against a fine.

group 2 and later group 3). The smooth, concave line representing the rejected fine treatment in Figure 4-1 results from averaging many groups like 2 and 3.

4.3 Model estimation and simulation

We used maximum-likelihood to estimate the parameters of our model: λ, β_1, β_2, ϕ, $\varepsilon(\cdot)$, and $q(\cdot\,|\,\cdot)$. Recall that λ is the players' tendency to maximize, β_1 and β_2 determine the social preferences of cooperators, $\varepsilon(\omega)$ is the initial expectation of players under institution ω, constant ϕ measures the persistence of expectations, and $q\,(\theta\,|\,\omega)$ is the probability that a player will become type θ at the beginning of institutional regime ω.We based our estimations on the

TABLE 4.3.1

ESTIMATED PARAMETERS

Parameter	Estimate	
λ	0.0030	(0.0007)
ϕ	0.50	(0.03)
β_1	4.00	(2.45)
β_2	4.00	(0.00)

outcomes of the first 19 rounds of play and left the final round to test the predictive accuracy of our model.

To simplify estimation, we made two assumptions regarding initial expectations:

1. If $\omega \in \{\text{NF,HF,LF}\}$, $\varepsilon(\omega)$ coincides with a stable steady state of $\bar{x}_t = N^{-1}\sum_{i=1}^{N} x_{it}$ under institution ω. Two conditions must hold for $\varepsilon(\omega)$ to be a stable steady state. First, the average level of player extraction when they expect others to extract $\varepsilon(\omega)$ must coincide with $\varepsilon(\omega)$. That is, the following condition must hold:

$$\sum_{\theta}\left\{q\left(\theta\,|\,\omega\right)\sum_{x=1}^{x=x_{max}}\frac{\exp\left\{\lambda\cdot u(x,,\theta)\right\}}{\sum_{y=1}^{x_{max}}\exp\left\{\lambda\cdot u(y,\varepsilon[\omega],\theta)\right\}}\right\}-\varepsilon[\omega]=0$$

   Second, the derivative of the left hand side of the equation with respect to $\varepsilon(\omega)$ must be negative.

2. If $\omega = \text{RF}$, $\varepsilon(\omega)$ is a convex combination of the stable steady states of $\bar{x}_t$.

The first assumption is justified by the fact that mean extraction levels remain fairly constant through all rounds under the no fine, high fine and low fine institutions (see Figure 4-1). With assumption number 2 we intend to capture the confusion that may arise among players when there is more than one steady state (as 4-3 suggests).

Table 4.3.1 displays the estimated values of λ, β_1, β_2, and ϕ. Table 4.3.2 displays the estimated distribution of types, $q(\cdot\,|\,\cdot)$, under each institution. Finally, Table 4.3.3 displays the estimated initial expectations.

Perhaps the most striking result is the effect that the institutional environment has on the distribution of types (Table 4.3). Under the no fine institution, only 12 percent of the

TABLE 4.3.2

ESTIMATED DISTRIBUTION OF TYPES, $q(\theta \mid \omega)$

	Institution (ω)			
Player types (θ)	No fine	High fine	Low fine	Rejected fine
Selfish	88% (2%)	20% (2%)	21% (5%)	2% (2%)
Unconditional cooperators	7% (2%)	63% (7%)	57% (2%)	30% (6%)
Conditional cooperators	5% (1%)	17% (9%)	22% (8%)	67% (4%)

TABLE 4.3.3

ESTIMATED INITIAL EXPECTATIONS AND IMPLIED STABLE STEADY STATES

	Institution (ω)			
Player types (θ)	No fine	High fine	Low fine	Rejected fine
$\varepsilon(\omega)$	4.7	2.0	2.4	2.2
Stable steady states	4.7	2.0	2.2	1.7; 5.8

players are cooperative. When a fine (high or low) is in force, the percentage rises to about 80 percent, and to 98 percent when the players reject a fine regime. Also, our results reveal that the enforcement of the norm induces more players to cooperate unconditionally: Unconditional cooperators are 30 percent when a fine is rejected, and approximately 60 percent when a fine (high or low) is in force.[7] Why? We hypothesize that fines relieve the cooperative player of the desire to retaliate against uncooperative ones in the only way she can: by ceasing to cooperate herself.

Table 4.3.3 also shows the stable steady states of $\bar{x}_{it}$ implied by the estimated parameters under each institutional environment. There is a unique stable steady state under the no fine, high fine and low fine institutions. That explains why players subject to those institutions rapidly cluster around the long run value of $\bar{x}_{it}$: Where equilibria are unique, there is little scope for confusion. On the other hand, $\bar{x}_t$ has two stable steady states when players vote against the imposition of a fine. In that scenario, the intervention of the experimenter at the end of round 10 plays two complementary roles: moralizing players and coordinating expectations. In

[7] These results are robust. We made 100 bootstrap estimations of the model, taking each group history as an independent observation. In all estimations we found that $q(\text{S} \mid \text{NF}) > q(\theta \mid \omega)$ for all $\omega \in \{\text{HF,LF,RF}\}$, $q(\text{S} \mid \text{RF}) < q(\theta \mid \omega)$ for all $\omega \in \{\text{NF,HF,LF}\}$, and $q(\text{CC} \mid \text{RF}) > q(\text{CC} \mid \omega)$ for all $\omega \in \{\text{HF, LF}\}$.

Schelling's (2006) terms, the experimenter makes the low extraction equilibrium a focal point.[8] The unraveling of cooperation is the transition from the high cooperation equilibrium to the low cooperation one.

In our model, fines affect behavior through two channels: Material deterrence and moralization (i.e., the externally induced change from selfish to cooperative type). To measure both channels separately, we simulated again the high and low fine regimes, but this time we kept preferences unaltered (i.e., using the NF distribution of types). In the new simulations, the low fine had no perceptible effect on extraction. The high fine, on the other hand, reduced the mean extraction level from 4.6 to 4.1 tokens. These results imply that, in our experiment, moralization accounted for the whole effect of low fines and for 78 percent of the effect of high fines. Material deterrence played only a minor role, and that explains why both fines work almost as well.

Our findings also explain the increase and later erosion of cooperation when commoners vote against the imposition of a fine. When players reject a fine, moralization explains the increased cooperation. Violations, coupled with a high share of conditional cooperators, account for the unraveling. A low fine is able to prevent the unraveling by changing the nature of cooperation from predominantly conditional to predominantly unconditional. The stabilizing role of unconditional cooperators becomes clear when one simulates what would happen if the experimenter imposed a low fine, but the distribution of types changed to that of the rejected fine institution (with most cooperators of the conditional kind). The triangle line in Figure 4-4a shows the result: Extraction falls in round 11 and then slowly unravels. To understand the mechanics of unraveling, look at Figure 4-4b. The figure displays two phase diagrams of mean extraction under a low fine, one with RF types and another one with LF types (see Table 4.3.2).With RF types the system has two steady states, one where extraction is low (L), and another one where extraction is high (H). The low extraction steady state has a small basin of attraction (to the left of point B), whereas the high extraction steady state has a large basin of attraction (to the right of point B). Since players randomize, the system will not stay close to L for a long time. Even a small shock will push the extraction level past B and into the basin of

[8] McAdams and Nadlery (2005) study coordination in a hawk–dove game. They find, as we do, that externally imposed norms signal focal points.

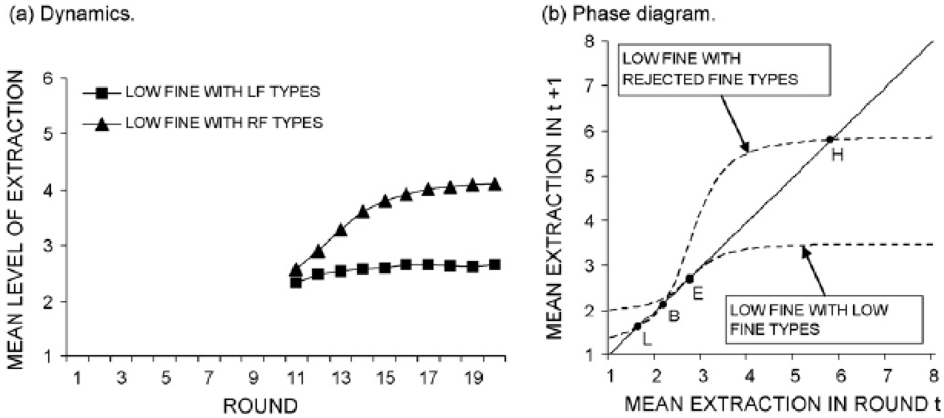

Figure 4-4: The stabilizing role of unconditional cooperators.

attraction of H. As a result, cooperation will unravel. On the other hand, with LF types there is only one stable steady state, so extraction remains low regardless of shocks.

We have seen how a low fine stabilizes cooperation by preventing a spiral of negative reciprocation: when the norm is enforced, cooperation tends to be unconditional, eliminating the high extraction steady state that arises when the norm is prescribed but not enforced. Because the imposition of a low fine may moralize selfish players and induce unconditional cooperation, the "fine enough or don't fine at all" policy prescription of Lin and Yang must be qualified.

To test the descriptive accuracy of our model, we simulated each treatment 500 times, using the estimated parameters as inputs. Figure 4-5 displays the aggregate behavior of players under each treatment, actual and simulated. Table 4.3.4 shows mean extraction levels under each institution, along with group and individual deviations from the mean. The table pairs actual and simulated values. Figure 6 compares the actual and simulated histograms of individual extractions. The results of the experiment and the output of the simulation are very similar. Our model provides a good account of the player's behavior at both the group and the individual level.

Next, we re-estimated our model subject to the restriction that preferences are not state-dependent (i.e., forcing $q(\theta\,|\,\text{NF}) = q(\theta\,|\,\text{HF}) = q(\theta\,|\,\text{LF}) = q(\theta\,|\,\text{RF})$, for all $\theta \in \{\text{S},\text{UC},\text{CC}\}$).[9]

[9] Estimated parameters for the restricted model: $\lambda = 0.003$, $\beta_1 = 4.5$, $\beta_2 = 4.25$, $\phi = 0.5$; $q(s\,|\,\theta) = 11\%$ and $q(\text{UC}\,|\,\theta) = 29\%$, for all θ; $\varepsilon(\text{NF}) = 5.7$, $\varepsilon(\text{HF}) = 1.7$, $\varepsilon(\text{LF}) = 1.8$, $\varepsilon(\text{RF}) = 2.2$.

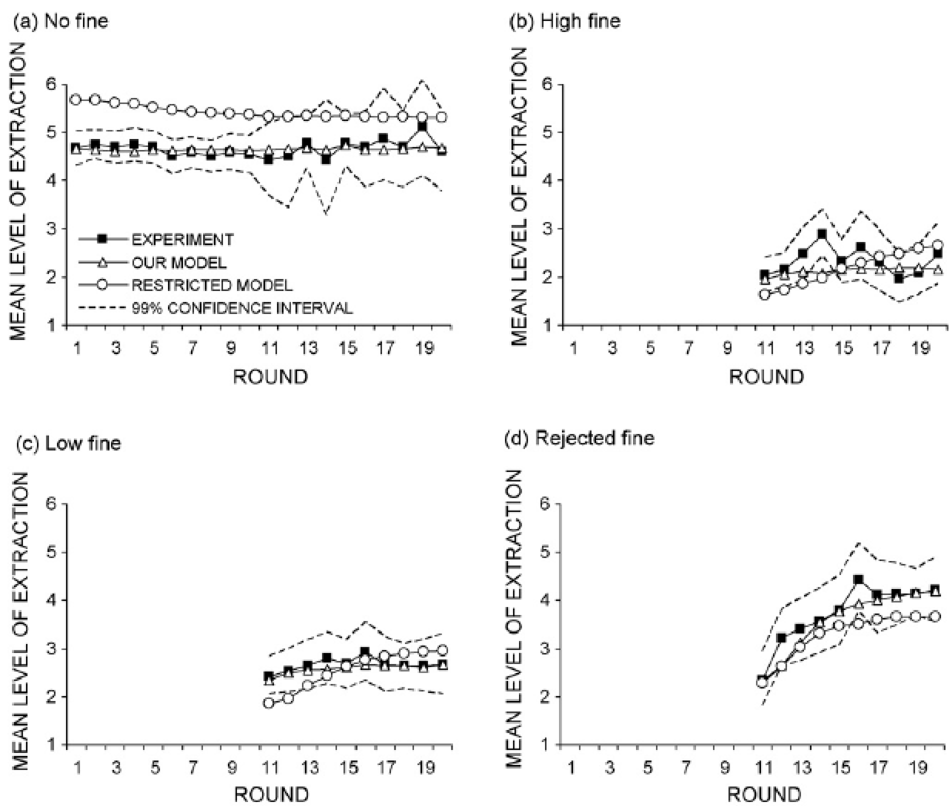

Figure 4-5: Mean levels of extraction, actual and simulated.

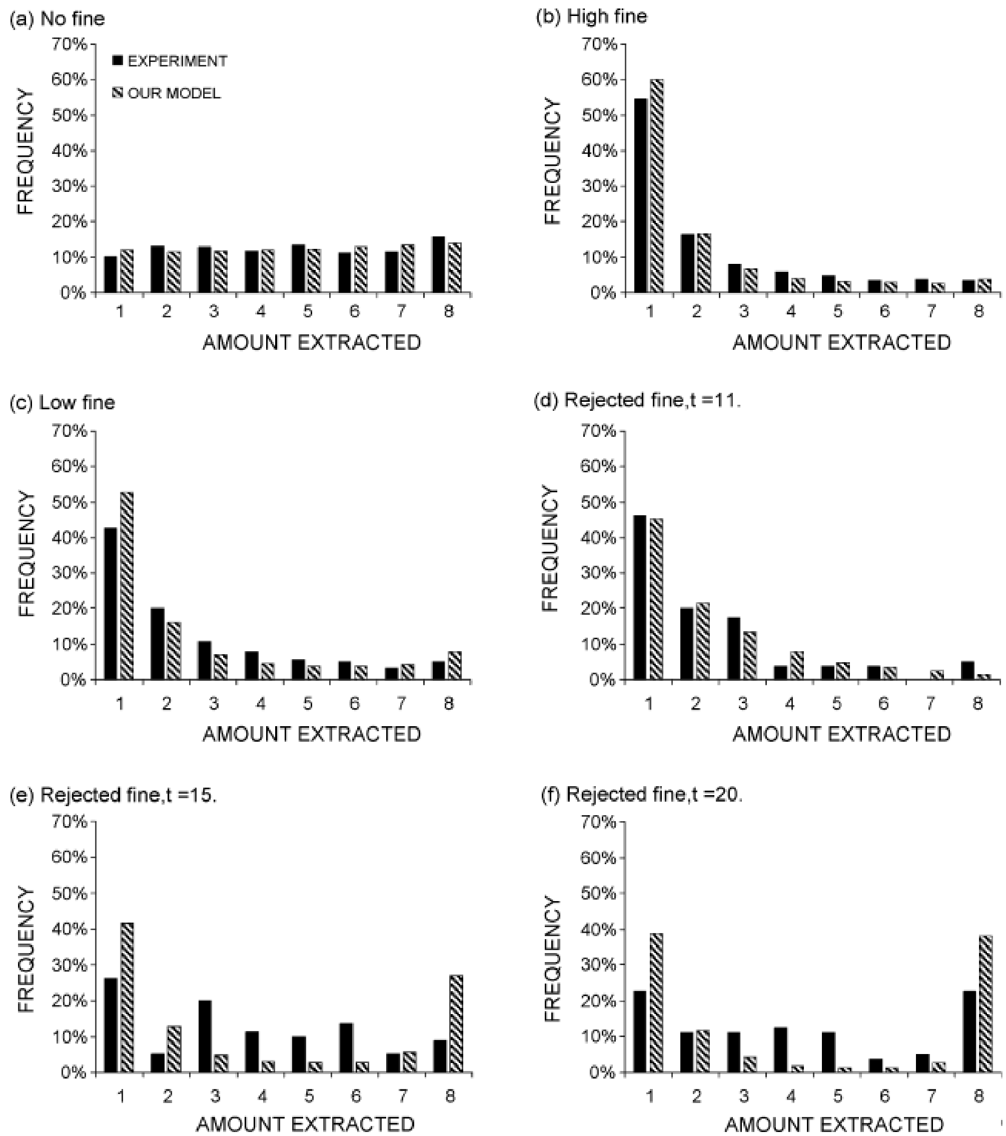

Figure 4-6: Distribution of individual levels of extraction, actual and simulated.

TABLE 4.3.4

Summary statistics, actual and simulated, from the CPR experiment

	Institution			
	No fine	High fine	Low fine	Rejected fine
Mean extraction				
Actual	4.6	2.3	2.7	3.7
Simulated	4.7	2.1	2.6	3.6
Group deviation				
Actual	2.3	1.9	2.1	2.3
Simulated	2.4	1.9	2.3	2.9
Average individual deviation				
Actual	1.8	1.0	1.2	1.8
Simulated	2.0	1.0	1.2	1.5

Using a likelihood ratio test we were able to reject, at a 99 percent confidence level, the hypothesis that the distribution of types does not change across treatments.[10] We also simulated the restricted model, using the estimated parameters as inputs, and it was unable to mimic the experimental evidence accurately (see Figure 4-5).

Finally, we used our model and the restricted model to predict the amount extracted by each of the 320 experimental subjects in the last round of play. To predict the extraction of a particular player, we used the posterior probability of that player being of type $\theta \in \{\text{S},\text{UC},\text{CC}\}$, given the priors in $q(\theta \,|\, \omega)$ and the behavior of the player and of the other members of his group during the first 19 rounds of play. Table 4.3.5 displays the mean prediction errors for both models under each institution. Our model outperformed the restricted model in all scenarios. We conclude that, in our CPR experiment, institutions influenced the social preferences of players.

[10] The log-likelihoods of the unrestricted and restricted models are $\mathcal{L}_U = -11467.14$ and $\mathcal{L}_R = -12202.57$. The likelihood ratio statistic is $2(\mathcal{L}_U - \mathcal{L}_R) = 1470.86 > \chi^2_6(0.99) = 16.81$, so we reject the hypothesis.

TABLE 4.3.5

MEAN ERRORS OF PREDICTION FOR OUR MODEL

AND FOR A MODEL WITHOUT STATE-DEPENDENT PREFERENCES

	Institution (ω)			
	No fine	High fine	Low fine	Rejected fine
Our model	0.75	0.71	0.68	0.86
Restricted model	0.81	0.88	0.79	0.92

4.4 Conclusion

Authorities may influence social preferences when they prescribe and enforce social norms. We found in a CPR experiment that the external imposition of a norm affected preferences in two ways.

First, it moralizes players. A speech by the experimenter sufficed to induce players to cooperate. How? By sowing in them the seed of guilt. Aristotle argued in his Nichomachean Ethics that effective laws worked by inculcating habits in citizens, that is, by moralizing them. Our results remind us that his argument is still relevant today.

Second, our model revealed that the enforcement of the norm affected the nature of moral sentiments. If the norm was enforced, players tended to comply with it irrespective of how others behaved, but if enforcement was absent, players conditioned their compliance on the good behavior of their peers.

Our results indicate that the extent of moralization is not the same when a norm is externally enforced as when it is not. In our experiment, more players became cooperative in the absence of enforcement. Why? We hypothesize that two effects operated simultaneously. First there is a prescriptive effect that always tends to increase cooperation. Second, a guilt relief effect appears when norms are enforced, and tends to decrease cooperation. Unfortunately, the guilt relief effect never appears alone in our experiment, so we can only infer its existence and measure it indirectly.

Our results also bring attention to the dynamic effects of enforcement. Conditional cooperation makes compliance fragile: a single rotten apple may spoil the whole bunch (and the addition of many good apples cannot restore it). In our experiment, a small fine sufficed to stabilize cooperation by making more players cooperate unconditionally, preventing the spread of moral degradation. Consider the implications for governmental corruption. Corrupt officers are hard to detect, so the expected punishment is often small compared to the potential gains from corruption. The occasional jailing of corrupt officers may nonetheless stabilize moral behavior if it prevents them from thinking: "everybody else is doing it, so why can't we?"

Further research is needed to determine when the enforcement of a norm will shield moral behavior from resentment or from "bad examples." For instance, sanctions were weakly enforced in our experiment, but they were fair. If some commoners were immune to punishment, punishment might cease to quench feelings of revenge; it would no longer serve to stabilize cooperation. Similarly, even if only a few people are beyond the reach of the law, the law may lose its effectiveness.

The way a low fine sustains cooperation may be analogous to the way the yellow card keeps the peace on a football field. Without the card, violence escalates after the first kick to the shin; it makes no difference whether the kick was intentional or accidental. Perhaps the card gives football players the sensation that bad behavior does not always go unpunished, suppressing their impulse to seek their own justice. Being close substitutes for reciprocation, low fines and yellow cards may sometimes stabilize norm compliance in a world of feeble social order.

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