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Samuel Bowles and Jung-Kyoo Choi*

We show that familiar explanations of the Neolithic agricultural revolution including superior labor productivity of farming, population pressure, or adverse climate change are inconsistent with the evidence now available. Our model along with archaeological evidence shows that a new system of property rights was a precondition that could have been sufficiently common in a few places to favor the independent take-up of farming. Thus farming could have emerged because it facilitated the application of private property to a wider domain of economic activities (which reduced conflict among group members) even though it was not initially a superior technology.

JEL Codes: N0 (Economic History), C78 (Evolutionary games), D23 (Organizational Behavior; Transaction Costs; Property Rights).

Keywords: pre-historic political economy, evolution of institutions, property rights, technical choice, evolutionary game theory, hunter-gatherer economics, strategic complementarity.

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1. INTRODUCTION

Like the steam engine, the computer, or the bow and arrow, cultivating plants and tending animals rather than foraging wild species is conventionally thought by archaeologists and anthropologists to have raised the productivity of labor, encouraging adoption of the new technology (Diamond 1997, Childe 1942, Cohen 1977). In these accounts, under pressure of growing populations, former foragers took up farming to raise their living standards (or attenuate a decline).

Economists, too, have posed the transition from foraging wild species to food production based on domesticated species as a change in the optimal allocation of labor across the two activities under increasing population pressure. They have explained the advent of farming by shifts in the marginal productivity of labor in the two activities, leading to an increase in the optimal distribution of labor devoted to subsistence on cultivated rather than wild species. Douglass North and Paul Thomas thus explained what they called "the first economic revolution" by some combination of "a decline in the productivity of labor in hunting, a rise in the productivity of labor in agriculture, or an … expansion in the size of the labor force" which, as Vernon Smith had earlier pointed out, would contribute to the relative scarcity of wild species and hence to the reduction in the marginal product of labor in hunting (North and Thomas 1977, Smith 1975.)

How do these accounts stand up in light of what is now known about the advent of farming? (Barker 2006, Bellwood 2005, Price and Bar-Yosef 2011, Richerson et al. 2001.) Beginning around 11,500 years ago, under more stable and warmer weather conditions favorable to plant growth and to a sedentary lifestyle, cultivation and eventually domestication spread as foragers converted to food production rather than gathering and hunting for their livelihood. Two facts are essential to our account.

First, while farming undoubtedly raised the productivity of *land*, we will see below that it is unlikely that the new technology raised *labor* productivity, at least not for many centuries following its introduction (Zvelebil and Rowley-Conwy 1986, Gregg 1988, Moore et al. 2000, Bettinger et al. 2010, Bowles 2011). In many parts of the world stature and health status declined with the introduction of cultivation (Cohen and Crane-Kramer 2007).

Second, early farming is associated with archaeological evidence of a novel set of property rights including private storage, ownership of fields by families or lineages and other indicators of individual property (Kuijt 2008, Kuijt and Finlayson 2009, Garfinkel et al. 2009, Bogaard et al. 2009, Bogaard et al. 2011, Bogaard et al. 2013, Earle 2000, Bogaard 2004, Byrd and Monahan 1995).

In Section 3 we show that explanations of this Neolithic agricultural revolution that are based on population pressure, plus greater (marginal or average) labor productivity of farming (relative to foraging) appear to be inconsistent with recent research on early farming. We provide evidence that the first farmers were unlikely to have been more productive than the foragers they replaced; that foragers took up farming under declining not increasing populations; and that the Neolithic agricultural revolution took place not as a result of climatic adversity but instead under increasingly farming-friendly climatic conditions facilitating sedentism.

The maximization of group well-being implicit in the economists' account of the transition yields a quite specific prediction: assuming that both foraging and farming outputs are increasing and concave in labor input, most groups would be mixed farming and foraging economies. And under the more farming-friendly Holocene climatic conditions and as both intentional and byproduct learning by doing made farming more productive, the interior optimal labor allocation would have gradually shifted in the direction of farming, leading most groups to take up substantial amounts of cultivation or animal tending, but few to go to a virtually complete reliance on farming. These predictions (we will see in Section 3) are not borne out by the data.

Further difficulties with the standard account arise from the rareness of the independent advent of farming (with perhaps a dozen cases at most), a fact that cannot be explained (as might be the rareness of the development of writing) by the difficulty of "inventing" farming. Hunter-gatherers are of necessity experts in plant and animal biology. We need to explain the adoption of food production, not its invention.[1]

Because land was abundant relative to labor right through the early Holocene it is difficult to explain why people would adopt a land-saving technology (namely, farming) that failed to raise labor productivity unless it had some other advantages. This is what our model seeks to explain.

2. OVERVIEW

Archaeologists, economists and others have long recognized the barriers to farming constituted by the collective decision making and common property rights of foraging groups (Sherratt 1997, Woodburn 1982, Demsetz 1967, Bowles 2004, North and Thomas 1977). These rights included open access to the resources of a group's conventional territory by any group member (and sometimes by outsiders as well) and sharing most food acquired in large amounts at a single time, for example, large prey or honey (Boehm 2000, Wiessner 2005, Bowles and Gintis 2012, Kaplan and Hill 1985). The long term stability of this forager norm-based social order is suggested by its prevalence in the ethnographic record of foragers, its persistence throughout the late Pleistocene, and results of evolutionary modeling and simulation (Boehm 2000, Boyd et al. 2010).

Applying these forager norms in a farming setting – to an animal slaughtered or a crop harvested – would greatly reduce the incentive to undertake the investments that farming required. Free riders' claims on would-be first farmers' crops and animals are found among the !Kung in Botswana, other groups in Southern Africa, the Batek in Malaysia (discussed in the penultimate section), and the Hiwi in Venezuela (Wiessner 1982, Hitchcock 1978, Endicott 1988). Even under environmentally favorable

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[1] Kent Flannery, who pioneered archaeological studies of the emergence of farming, wrote: "We know of no human group on earth so primitive that they are ignorant of the connection between plants and the seeds from which they grow" (Flannery 1968). Seeing that virtually all human groups (excluding Arctic populations and a few others) were free to experiment with cultivation and animal tending, and many did, but without taking it up, we can conclude that it cannot be foragers' ignorance of the possibilities of food production that explains why independent emergence of farming was so rare.

conditions, a transition to farming would encounter serious institutional obstacles if private property rights did not cover tended animals, crops and stores.

The fact that the vast majority of the tens of thousands of substantially autonomous human populations at the end of the Pleistocene did not take up farming independently, along with the bimodal distribution of small scale economies along the foraging-farming continuum (Section 3) suggests that the independent emergence of farming is better modeled as a process of selection among alternative equilibria than as an incremental displacement of a unique stable interior equilibrium allocation resulting in an ever larger fraction of the population's labor being devoted to farming.

Because we wish to explain the independent emergence of farming, not its subsequent spread, we model the dynamics of a single autonomous population. We need answers to two questions: First, under what conditions could both a foraging and a farming equilibrium exist for this population? And second, what would be a plausible dynamic accounting for a transition from the former to the latter?

The implied existence of more than one stable equilibrium would have to be based on positive feedbacks of some kind. These, we hypothesize, concern the institutions supporting the introduction of farming, not the process of food production itself. In many cases, the expected payoff to the choice of a particular technology (planting rice rather than digging for tubers for example) does not depend much on the number of others adopting the same technology. By contrast, a strategy of respecting the property rights of others and defending one's own possessions would be unlikely to work if few of their group mates adopted the same strategy.

The strategic complementarity among strategies which, if widely adopted, would represent a novel institution, motivates our representation of institutions prior to the formation of states as conventions (that is, symmetric equilibria of non-cooperative coordination games), transitions among which are impeded by a 'critical mass' problem.

The second complementarity in our alternative explanation is that farming as a technology enhances the payoffs to adopting private property as an institution, and conversely. This technical-institutional synergy arises from two characteristics of farming that distinguish it from foraging. First, both farming and its associated sedentary living required significant long-term investment in field preparation, animal raising, dwellings and storage; and a significant portion of these forms of wealth – animals and stored grains, for example – were subject to appropriation by others. Second, these forms of farming wealth were sufficiently valuable, long-lived, and limited in scope to make their delimitation and defense cost effective, so that individual possession would be less likely to be contested.

The livelihood of foragers, by contrast, depended on mobile, ephemeral, and dispersed resources for which unambiguous individual possession was virtually impossible to establish. Thus farmed wealth was more readily subjected to private property. And conversely private property rights were essential to providing the incentives necessary to justify the long-term production process and fixed investments that farming required.

In Sections 4 and 5 we formalize these complementarities using an extension of the biologist John Maynard Smith's Hawk-Dove-Bourgeois game, modified to take account of both the possible contestation of possession and the ethnographic evidence on the importance of social norms for the maintenance of social order in small stateless societies (Maynard Smith 1982). In this model, if possession is unambiguous and hence are not contested, a convention of mutual respect for the private ownership of an individual's wealth (which Maynard Smith called a "bourgeois" strategy) is evolutionarily stable, that is, not invadable by other strategies. Private property if widely adopted then could eliminate costly contestation among group members, raising individual payoffs (Sugden 1986).

But if possession is sufficiently contestable, either mistakenly or intentionally, this is not the case (Bowles 2004): the bourgeois strategy is no longer evolutionarily stable. This, we hypothesize, is among the reasons why in the economy and social system of mobile hunter-gatherers, possession-based private property played a limited role. The two strategic complementarities – the critical mass problem for the adoption of a system of private property rights and the mutual dependence of farming and private property –

are the basis of our answer to our first question, providing a reason why the distinct equilibria could coexist.

The two complementarities also explain why the transition to a private property regime was a necessary precondition for the agricultural revolution, and also why it was very improbable. This then brings up to the second question, namely how a transition from the foraging equilibrium to the farming equilibrium might have occurred. While imposition on erstwhile foragers of a private property with farming regime by an "extractive" elite (as conjectured by Acemoglu and Robinson (2012)) clearly cannot be ruled out, we provide empirical evidence in the next section that this is unlikely to have occurred. In any case it would be valuable to know if the novel institutions on which the Neolithic agricultural revolution was based could have emerged by a decentralized process. This is what our model is designed to explore.

By introducing idiosyncratic (non best response) play in the Section 6 we are able to explore the processes that could generate rare transitions from a stationary state with weak or nonexistent private property rights and the exploitation of wild species (the hunter-gatherer technology-institutional equilibrium) to a private property with farming state. In principle, there are two routes by which this could have occurred.

The first is that hunter-gatherer populations might have taken up farming prior to the advent of private property, and the lesser contestability of farming wealth then might have subsequently facilitated the transition to a private ownership regime. In this Marx-inspired scenario the exogenous emergence of a superior technology or other opportunity for increased income has the leading role. A prominent example is the account by Demsetz (1967) of the emergence of private property among native Americans engaged in the fur trade: new property rights, he wrote, "stem from the development of new technology and the opening of new markets, changes to which old property rights are poorly attuned."

But this scenario would have required a large enough productivity advantage of farming so that it would pay off even if the harvest were to be shared widely with one's entire group according to pre-existing social norms. The empirical evidence on the lack of an initial labor productivity advantage of farming cited in the next section would seem to rule out this scenario.

The second possibility, which constitutes our proposed contribution to the explanation of the Neolithic agricultural revolution, is the following. The amelioration of climatic volatility 11,500 or so years ago allowed a more sedentary livelihood, contributing to conditions for an evolutionarily stable private property regime (defensible wealth such as territory and dwellings) prior to farming. This could have occurred among groups of sedentary hunter-gatherers occupying sites with highly productive concentrated resources which could be delimited and defended. If some of these sites were suitable for food production, the emergence of farming would then have been possible even without a productivity advantage. This could occur if the private property with farming package limited the costs that farmers incurred in their conflicts with others. Farming could initially have emerged because it facilitated and stabilized an effective mechanism of conflict reduction (private property) not because it enhanced productivity. Four possible trajectories of institutional and technological transition are identified by the model – two of them resulting in the eventual take-up of farming. In Section 7 we use archaeological data to illustrate each. In the concluding section we ask if our model gives a plausible account of the Neolithic agricultural revolution; we suggest a variant of our model in which collective action by the first farmers plays a role. We also explain why farming, once established at the sites where it emerged independently, could spread to secondary sites despite an initial lack of a labor productivity advantage.

Our interpretation is consistent with the emphasis in the recent archaeological literature on cultural and institutional preconditions for farming (Watkins 2010, Willcox and Storedeur 2012, Kuijt and Finlayson 2009, Smith 2012). We contribute to this literature by suggesting a specific mechanism – the decentralized emergence of private property – whereby the institutional and cultural changes associated with sedentism might have proceeded and facilitated the emergence of farming.

3. EMPIRICAL DOUBTS ABOUT STANDARD EXPLANATIONS

Three facts are the basis of our conclusion that that farming did not emerge as a way to improve or sustain livelihoods under adverse climatic conditions or increasing population.

3. 1. *Labor productivity in farming was not initially greater than in foraging*

In the land-abundant late Pleistocene and early Holocene the productivity of labor (rather than total factor productivity or resource productivity) is the appropriate indicator of both the motivation for an individual forager to take up farming and the likely reproductive success of that individual or of groups that for whatever reason had taken up farming.

Physical measures of productivity – energetic output per hour of labor (including processing) – can be computed for a few forager populations and for some cultivars farmed under conditions and using technologies that appear to have characterized the first farming. Using data for 15 cultivars similar to the first cultivated crops and 5 hunting and gathering populations we find that the mean caloric return for the cultivars is 63 percent of the mean for wild species.[2] The data are shown in Figure 1. While lacking an initial labor productivity advantage, it appears that from the outset farming vastly increased the productivity of land and animals.[3]

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[2] The methods are described in Bowles (2011). Comparison of caloric returns for foraged wild species and cultivation requires that account be taken of the following differences. While both foragers and farmers practice delayed return production and storage, the extent of time delay is much greater for farmers. Moreover the much reduced geographical mobility and diversity of sources of nutrition among farmers gives rise to greater seasonal and annual risk (both idiosyncratic and systematic). Estimates must therefore take account of losses during storage, time delay, and risk exposure. When account is taken of risk and time delay the ratio of the mean productivity (cultivars divided by wild species) falls to 0.59 and 0.58 respectively (all of the farmer-forager differences in means are statistically significant at conventional levels).

[3] The archaeologist Amy Bogaard has estimated that under the wheat farming methods used during the early Neolithic in Europe, a single hectare of land could provide more than two thirds of the calories required annually for a family of five (Bogaard 2004, Table 2.2). By contrast, in a sample of ethnographic foragers thought to be similar to Late Pleistocene hunter-gatherers, the area exploited by a group, per family of five was 60 km^2 (Marlowe 2005) and among the Ache

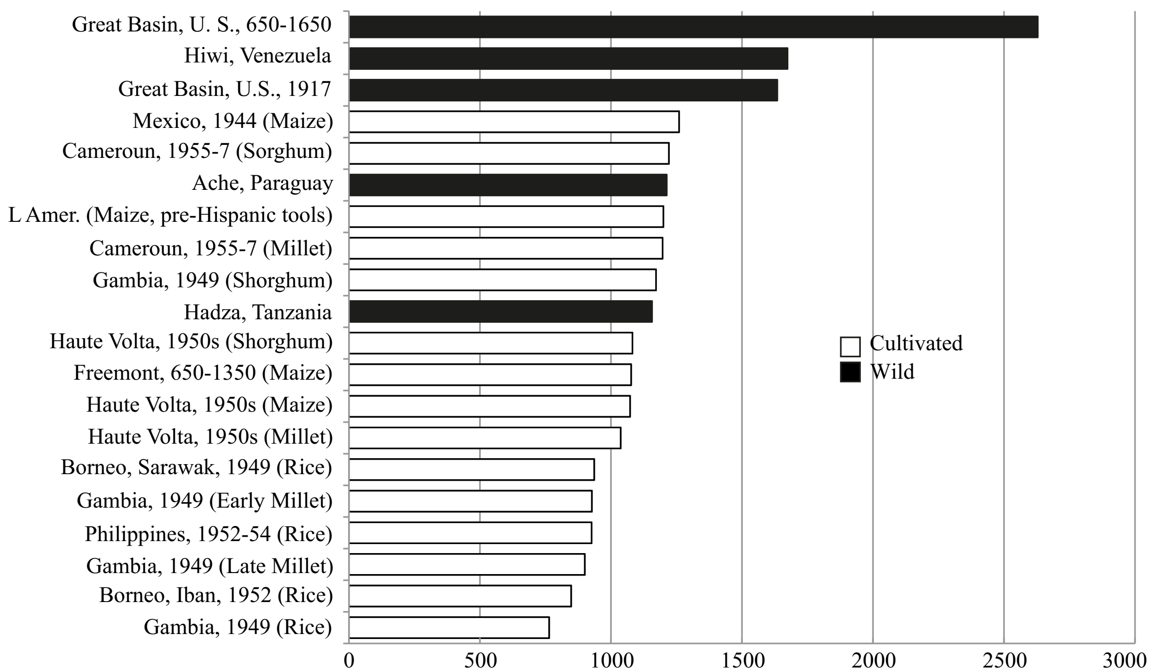

FIGURE 1. – Net Kilocalories per Hour of Direct and Indirect Labor: Wild and Cultivated Species. SOURCE. – Bowles (2011). NOTE. – Excluded are return rates for wild species in cases where atypically rich resource concentrations were encountered, or vehicles or firearms were used, or where data were available for one sex only or for a limited span of time. Cultivated data are for cereals only due to the lack of the comparable data on non-cereal cultivars of the first farmers (such as avocado, bottle gourd and squash).

3. 2. *Farming was initiated in declining not growing populations*

Using evidence on the age structure of the deceased in burials before and following the advent of farming, the archaeologist Jean-Pierre Bocquet-Appel and his co authors have documented what they term the Neolithic Demographic Transition from a roughly stationary population of foragers to a slowly growing population of farmers. The important fact for understanding the causes of the Neolithic agricultural revolution is that the first farming, in the Levant, followed almost eight centuries of stationary or even declining population. The initiation of farming at European and North American sites was preceded by even more prolonged periods of declining population (Guerrero et al.

foragers in lowland Paraguay most adult male hunters exploit 200 km^2 in a single year, and some cover five times that area (Kaplan et al. 2000).

2008, Bocquet-Appel 2006, Bocquet-Appel 2002).[4] These findings do not preclude resource scarcity as an impetus for the advent of farming as suggested by Smith (1975), but they do cast doubt on the conventional account in which growing population was the stimulus.

3. 3. *The Neolithic agricultural revolution took place under increasingly farming-friendly climatic conditions not under climatic adversity*

Archaeologists have long thought that foragers took up farming in response to the climatic adversity called the Younger Dryas (12,900 to 11,700 years before the present (Bar-Yosef and Meadow 1995). But recent improved dating of both temperature and growing conditions on the one hand and, on the other, the first independent adoptions of food production are inconsistent with this view. There were local variations, of course, but the amelioration of climate marking the beginning of the Holocene was a global phenomenon and, and, as is evident in Figure 2, it predated the advent of farming even at the earliest sites.[5] The top panel indicates an increase in temperature and reduction in its inter-annual volatility, which favored both sedentary living and farming. The remaining panels provide measures of conditions favorable for plant growth.

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[4] Moreover some of the earliest farming (at Abu Hureyra and Mureybet, for example) took place at sites of resource abundance and comparatively limited population pressure (Bar-Yosef and Belfer-Cohen 1992).

[5] The substantial reduction in inter-annual variation in temperature at the end of the Pleistocene shown in Figure 2 reduced the pressure for mobility which had constituted an obstacle to the investments in dwellings, stores, and land improvements associated with farming. Matranga (2016) provides evidence of a coincident increase in the within year seasonality of rainfall and temperature which would have also increased the returns to storage, providing a further impetus to sedentism. An interesting and internally consistent interpretation of the climate adversity hypothesis is provided by Dow et al. (2009) and Dow and Reed (2015). They make the case that a concentration of sedentary populations in sites well suited for food production resulting from climate adversity made it optimal for at least some to engage in farming, which then became more common as farming productivity increased due to learning by doing. The timing of the climate adversity and the first farming (see Figure 2) appears to cast some doubt on this sequence, but the key mechanism for Dow et al. – concentration of population at good sites – does not depend on climate adversity, as this could have come about for other reasons.

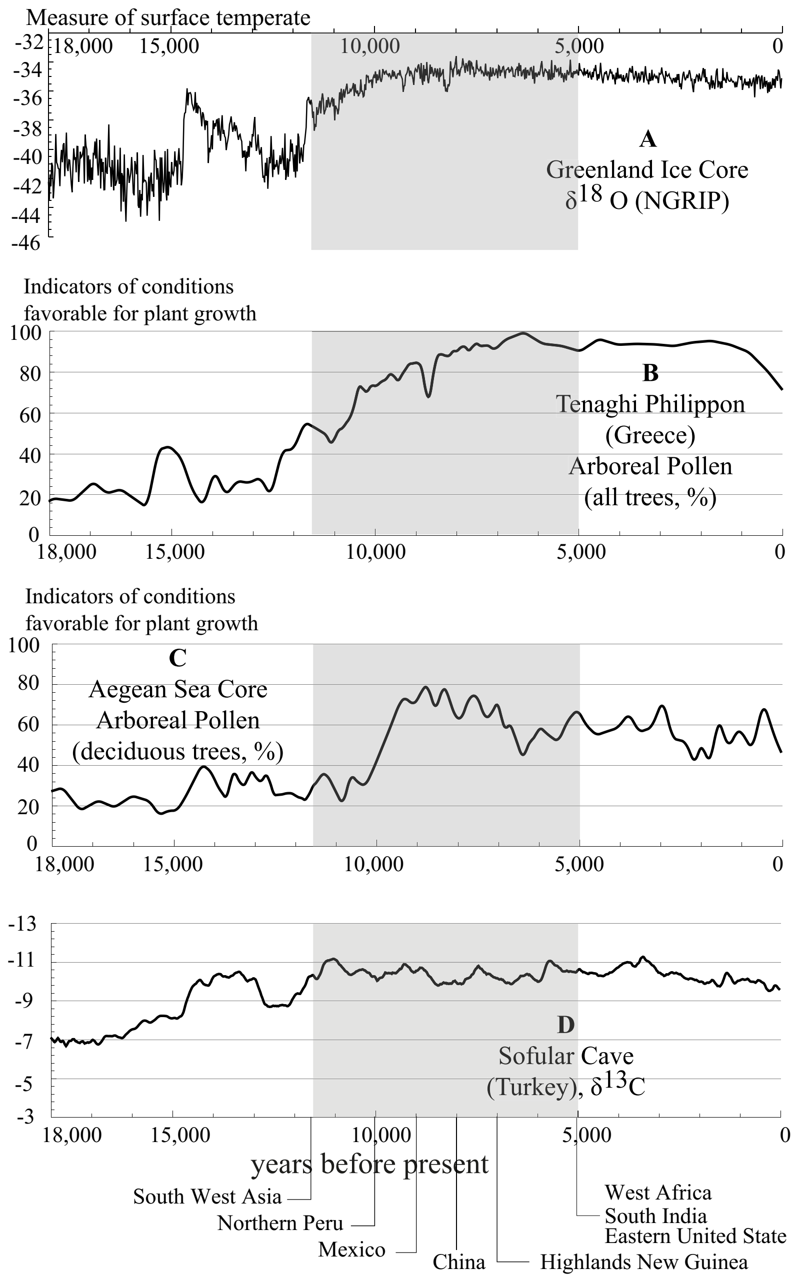

FIGURE 2. – Holocene climate amelioration and the advent of farming. Sources of the climate data: **A**. Greenland ice core data from GRIP 2005. **B.** Arboreal pollen from Tenaghi Pilippon (eastern Greece, all trees, from the supplementary materials of Muller et al. (2011); pre 7100 ya and 7100 to present (Lang and Wolff 2011), data described in Muller et al. (2011), Martrat et al. (2007), Martrat et al. (2004). **C.** Arboreal pollen (deciduous trees) from an Aegean sea core. (Fleitmann et al. 2009) **D.** $\delta^{13}C$ signal from Sofular Cave in Turkey (Fleitmann et al. 2009) for which larger negative (absolute) values are indicative of a warmer and wetter climate that would promote a higher proportion of C_3 plants (trees and shrubs). The farming dates are first domestications from Price and Bar Yosef (2011), except for India (Karnataka) which is from Fuller (2006a).

Three additional pieces of information introduced in the next sections suggest directions for a plausible alternative explanation.

3. 4. *Small scale economies are bimodally distributed between foraging and farming*

The data on calories per hour of labor just cited are for average not marginal labor productivity, and it is likely that in some locations the productivity of a limited amount of time devoted to farming (on the best or nearest land, for example) would have been considerably higher than the productivity of labor in hunting or gathering the lowest ranked species.[6] Then equating the marginal productivity of labor in farming and foraging as in the economic model underlying the standard account of the advent of farming would predict that most Late Pleistocene groups would have engaged in some amount of farming. The extent of farming would then have advanced under the more farming-favorable climate of the Holocene or gradually improving productivity of farming, but few populations would have converted to virtually complete reliance on food production. This is not what occurred. As we have just seen there is no convincing evidence of farming prior to 11,500 years before the present.

Another piece of evidence also tells against this account. Data on 870 small scale societies collected by ethnographers for the most part around the middle of the past century display a strikingly bimodal distribution along the forager to farmer continuum, measured by percentage of food produced by cultivation and herding (Bellwood 2005).[7]

[6] For example the lowest ranked species taken in the Great Basin data in Figure 1 yielded considerably fewer calories per hour of labor than the mean of the data on cultivated species. (Simms 1987)

[7] Almost half of the societies are at the extremes of the distribution, that is either foragers with 15 per cent or less of food derived from farming (23.1 percent of all populations), or instead farmers with 85 percent or more of their food produced rather than hunted and gathered (23.0 percent). Only 21.4 percent of the societies engage substantially in both, acquiring between 35 and 65 percent of their food from farming.

3. 5. *Even under farming friendly early Holocene climate conditions foraging persisted even in many locations well suited for food productio*n.

Given the global nature of the Holocene climate shift, the independent take up of farming was remarkably limited. Part of the explanation of the Neolithic agricultural revolution is suggested by where and why it did not happen. In much of the world foragers were displaced by farmers or assimilated into their populations. But Australia remained a "continent of hunter-gatherers" until the late 18th century, thus providing a kind of natural experiment for understanding why the advent of farming was a rare rather than a common event (Lourandos 1997).

Captain James Cook, sailing near Cape York at the northern tip of Australia in 1770, wondered why farming was not practiced there: "In this Extensive Country it can never be doubted that most sorts of Grain, Fruits, Roots &c of every kind would flourish were they once brought hither… When one considers the Proximity of the Country with New-Guiney, New Britain and several other islands which produce Cocoa-Nutts and many other fruits proper for the Support of Man, it seems strange that they should not long ago have been transplanted here." (Cook 1971)

It appears that Cook was right to be puzzled. Figure 3 shows that areas of Australia populated by hunter gatherers at the time of his visit are well suited for the cultivation of four crops which elsewhere played a major role in the Neolithic agricultural revolution. Some have proposed that Australia lacked species suitable for cultivation and could not acquire them from other regions (Diamond 1997); but neither claim is convincing, as is shown in Bowles (2015b).

Our model is consistent with the view that it was not geography that explains why the original Australians did not farm, but rather the lack of suitable institutions – in this case private property. As in Australia, in other areas of the world – parts of California and the Western Cape of South Africa for example – hunter-gatherers living on prime farmland persisted until European contact less than half a millennium ago (Kroeber 1953, Sadr 1998, Smith 2007, Bettinger 2015).

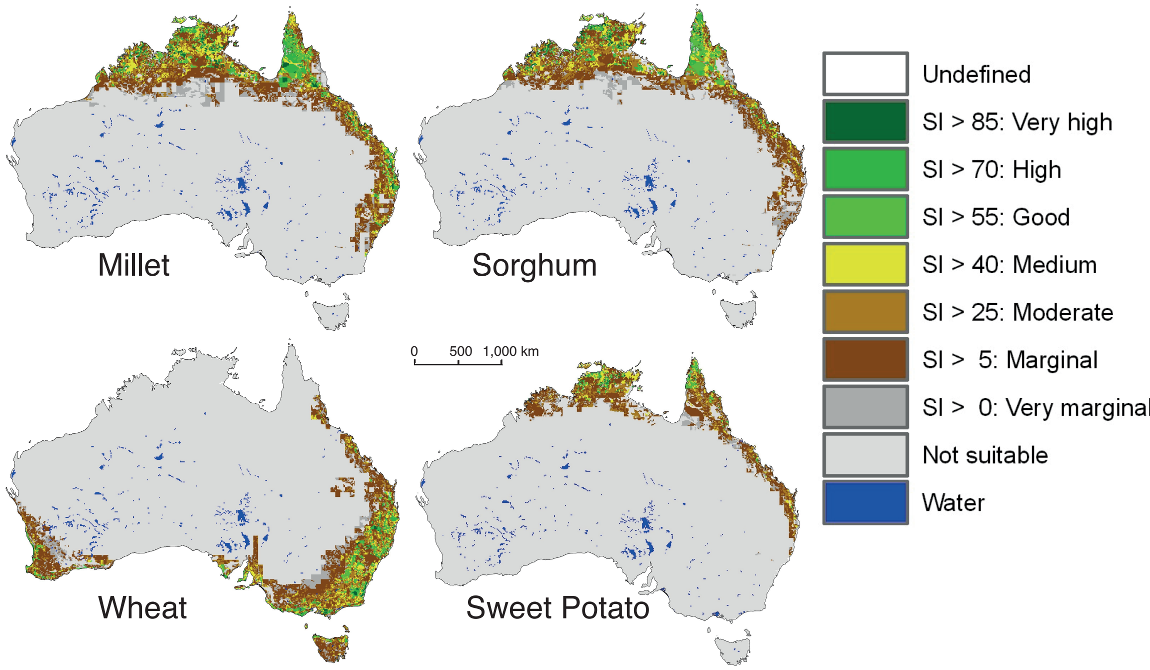

FIGURE 3. – Areas Suitable for Rain Fed Cultivation in Australia. SOURCE. – Fischer et al. (2002). Food and Agriculture Organization's Global Agro-Ecological Zones (GAEZ) 2002 database available from http://www.iiasa.ac.at/Research/LUC/SAEZ. NOTE. – The locations of the greatest concentration of hunter-gatherers prior to European contact include substantial areas of rich farmland, including what is now termed the wheat belt and the northern and eastern coastal regions suitable for yam and sweet potato (the latter of which came much later).

3.6 It appears unlikely that farming was imposed by centralized elite authority

An explanation of consistent with the data introduced up to this point is that proposed by Acemoglu and Robinson (2012, 2009). They suggest that erstwhile mobile foragers had been "forced to settle down" and that farming and the private property rights farming required emerged under politically and economically unequal "extractive institutions." This interpretation, like ours, stresses the importance of prior institutional change, and private property rights specifically, as a precursor or at least a concomitant of farming.

There is ample evidence from more recent epochs that to facilitate tax collection, states have sought to enforce both sedentism and cereal production on erstwhile mobile or root crop growing populations (Scott 2009). There is also evidence from ethnographic hunter-gatherers as well as archaeological evidence suggesting that political institutions for collective decision-making (e.g. about movements, defense and predation) and enforcement of norms (e.g. concerning food sharing and sexual mores) existed in early Holocene populations, including those that independently adopted the Holocene package of farming and private property.

But it remains a question whether any of the collective political processes that might have been extant at the time of the first farmers – "big men" systems or proto states, for example – could have supported a centralized authority sufficiently powerful to enforce sedentism on a heavily armed mobile population from whom surpluses were then extracted. Without exception the independent adoptions of farming long predate the first states, as we show in Table 1.

One of the best-studied cases of the Neolithic agricultural revolution is the Levant, and particularly the recent research on the village of Abu Hureyra. Evidence from mortuary practices there, dwelling size and other data give no indication of political hierarchy or that economic inequality increased during this period (Moore et al. 2000, pp. 505, 495). These substantial sedentary communities "could be formed and maintained without social hierarchies of power" as the archeologist Trevor Watkins put it, describing the Neolithic revolution throughout the Levant. "Ascribed status, social hierarchies and inequalities of power" would later follow, but did not precede the advent of farming and private property (Watkins, 2010).

While public, even monumental, constructions have been unearthed at the sites of southwestern Asian populations that first took up farming, there is no evidence of concentrations of political power in elite hands, as would be indicated by unusually large and well-made residences associated with public facilities.[8] Rather, these non residential "collective" spaces are believed by archaeologists to have been used for communal meetings and rituals (Bar-Yosef and Meadow 1995, Cauvin and Estevez 2008, Roux et al. 2000, Flannery and Marcus 2012). While in some communities (but not others) there

[8] We survey the evidence on political structures and economic inequality prior the advent of farming in southwestern Asia in Bowles (2015a). Flannery and Marcus (2012) refer to the impressive buildings at Göbekli Tepe and other Anatolian sites as "men's houses" (p.138) or "ritual houses" (p.136) not dwellings of members of a political elite.

is evidence of economic differentiation, in none does there appear to have been substantial and inherited inequalities in wealth, as would be indicated by the kinds of elaborate burials (including children) found at some late Pleistocene sites (Byrd and Monahan 1995, Kuijt 1996, Belfer-Cohen 1995).

TABLE 1.

REGIONS AND DATES OF EARLY DOMESTICATIONS AND EARLY STATES OR PROTO-STATES

Region (contemporary geographic designations)	*First domestications before the present, in years BP (crop)*	*First state BP(name of earliest state or proto state in region)*
Southwest Asia	11,500 (Einkorn, emmer, barley)	5,500 (Late Uruk)
China	8,000 (Millet, rice)	4,300 (Erlitou)
Mexico	9,000 (Pepo squash)	2,400 (Teotihuacan)
Northern Peru	10,000 Arrowroot	2,200 (Moche)
Highland New Guinea	>7,000 (Yam, banana, taro)	European (Aust.) colonization
West Africa (Sahel)	5,000 (Sorghum, animals 9000)	1,500 (Ghana, possibly Tichitt)
South India (Karnataka)	5,000 (Millet)	3,200 (evidence of elite burials)
Eastern United States	5,000 (Pepo squash, sunflower)	European colonization

NOTE. – Excepting those noted below, the approximate dates of the first named states are from Trigger (2003, p.32) with the defining characteristic that "central governments possessed ultimate control over justice and the use of force" (p. 47). The first domestications except Karnataka are from Price and Bar Yosef (2011) (cultivation probably predated domestication by many centuries, or possibly much more). Dates for Ghana are from Holl (1985) and Munson (1980). Evidence for India is from Fuller (2006a).

4. THE EVOLUTIONARY DYNAMICS OF POSSESSION-BASED PROPERTY

Because our model is designed to explain a rare event – the emergence of farming – the propositions that we demonstrate do not concern the parameter values under which a unique and globally stable farming-with-private-property equilibrium would emerge, so that a transition away from the forager equilibrium would occur with certainty. Rather we study conditions under which equilibria with and without farming exist, and then characterize the conditions affecting the probability of a transition from the forager to the farmer equilibrium.

In this section we introduce a new model the Civic-Bourgeois game to study the evolution of a property-respecting strategy. In the next section we extend the model to incorporate individuals' technology choice between farming and foraging, and show how the choice is affected by the complementarity between adoption of farming technology and the evolution of private property rights.

4. 1 The Civic-Bourgeois game and the evolution of private property rights.

Consider the following two-person simultaneous game with two conditional strategies (Civic and Bourgeois) that conditionally use actions Hawk (H) and Dove (D). Two individuals acquire goods (in a manner to be considered in the next section) and then play two sub-games which determine the distribution between the two players of the product that each has acquired.

Actions. For each sub-game, the action space ($A = A_1 \times A_2$) and the payoff function of actions for each player, $\pi : A \rightarrow R$ is defined as in the standard Hawk-Dove game where v is the value of the product in question (when we introduce the choice of technology we will distinguish between agriculture (v_a) and foraging (v_f)); c is the cost to the individual if he loses a contest over the distribution of the good, occurring with probability ½ should a contest take place; and $v < c$.

TABLE 2

THE ACTION SPACE AND ASSOCIATED ROW PAYOFFS

	H	D
H	$\frac{v-c}{2}$	v
D	0	$\frac{v}{2}$

Strategies. The two strategies –Bourgeois and Civic – dictate the conditions under which the individual will take action H or D.

A Civic conditions his action not on possession but instead on the reputation of the other player, who may bear a stigma if in the past he has refused to share with others. Civics play H when they detect a stigma in the other player, which occurs with probability δ; and they play D otherwise. Civics themselves are not stigmatized for playing H because it is pubic information that their playing H is a social sanction on someone who has refused to share. The parameter δ is thus a measure of the effectiveness of social norms that enforce sharing, and it is public information, common to all interactions and exogenously determined by the size of the group, its recent history, its network structure, and other details that do not enter into our account.[9]

A Bourgeois conditions his action on possession of the good, that is whether the good that is being distributed was acquired by him or not. As in the standard Hawk-Dove-Bourgeois Game, a Bourgeois plays H if the product to be distributed is the one that he acquired. In other words, he claims ownership, and if challenged fights to defend it. If the good was acquired of the other, the Bourgeois plays D.

We further assume that due to the possible ambiguity of ownership a Bourgeois will contest possession of a product that is in the possession of the other with probability μ. If $\mu = 1$ a Bourgeois will contest any claim of individual possession by another, and always play H, like the Hawk in the Maynard Smith's standard game, and if $\mu = 0$ a Bourgeois plays H only if it was he who acquired the product to be distributed and will play D otherwise.

Payoffs. To illustrate the resulting payoffs, suppose a Civic player meets a Bourgeois player (Figure 4). When they interact over the Civic player's product (the left panel), the Civic plays H with probability δ while the Bourgeois opponent plays H with probability μ. In the second subgame, when they interact over the Bourgeois player's product (the right panel), the Civic player again plays H with probability δ while the Bourgeois player always plays H because he always defends his own product.

[9] This reputation-based strategy could be modeled as the result of repeated interaction with sufficiently patient actors. But given that the behavior that results is commonly observed in small scale societies (Boehm 2000, Wiessner 2005, Mahdi 1986) and that we have modeled it elsewhere (Boyd et al. 2010), little would be gained by repeating the exercise here.

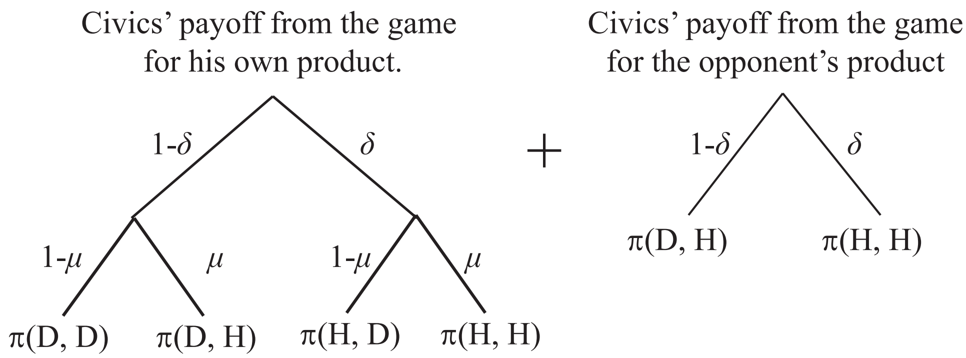

FIGURE 4. – Payoff to a Civic when paired with a Bourgeois

Generalizing, let $r(X,Y|\delta,\mu)$ represent the expected payoffs for the individual who plays strategy *X* in an interaction with another playing *Y* (where $X,Y \in \{C,B\}$), conditional on the values of δ and μ. (We use C and B respectively to indicate the Civic and Bourgeois strategies.) We write $r(X,Y|\delta,\mu)$ in two parts: the individual's payoff from the sub-game over his own product in the first square bracket (below) and the individual's payoff from the sub-game over his opponent's product in the second square bracket. Then the payoffs from the Civic-Bourgeois game are

$$r(C,C|\delta,\mu)=\left[\pi(D,D)\right]+\left[\pi(D,D)\right], \tag{1a}$$

$$\begin{aligned} r(C,B|\delta,\mu)=&\left[(1-\delta)\big((1-\mu)\pi(D,D)+\mu\pi(D,H)\big)+\delta\big((1-\mu)\pi(H,D)+\mu\pi(H,H)\big)\right] \\ &+\left[(1-\delta)\pi(D,H)+\delta\pi(H,H)\right], \end{aligned} \tag{1b}$$

$$\begin{aligned} r(B,C|\delta,\mu)=&\left[(1-\delta)\pi(H,D)+\delta\pi(H,H)\right] \\ &+\left[(1-\delta)\big((1-\mu)\pi(D,D)+\mu\pi(H,D)\big)+\delta\big((1-\mu)\pi(D,H)+\mu\pi(H,H)\big)\right], \end{aligned} \tag{1c}$$

$$r(B,B|\delta,\mu)=\left[(1-\mu)\pi(H,D)+\mu\pi(H,H)\right]+\left[(1-\mu)\pi(D,H)+\mu\pi(H,H)\right]. \tag{1d}$$

The payoffs in Figure 4, $r(C,B|\delta,\mu)$, are equation (1b).

4. 2. *Updating strategies and dynamics of behavioral strategies*

Equations (1a) to (1d) allow us to characterize the deterministic dynamics (that is abstracting from idiosyncratic play) of the population share of the individuals with the civic or the bourgeois strategies. We assume a finite population (sufficiently large to ignore integer problems) in which players use a payoff monotonic updating process whereby the behavioral strategy they adopt is a best response to population share of individuals using each strategy in the previous period.

Define the population fraction of Bourgeois and Civics in a group as β and 1-β, respectively. The expected payoffs to Civic and Bourgeois can be written as

$$Er(C \mid \beta,\delta,\mu) = (1-\beta)r(C,C \mid \delta,\mu) + \beta r(C,B \mid \delta,\mu) \qquad (2a)$$

$$Er(B \mid \beta,\delta,\mu) = (1-\beta)r(B,C \mid \delta,\mu) + \beta r(B,B \mid \delta,\mu) \qquad (2b)$$

Let $\Delta^B(\beta,\delta,\mu)$ be the expected payoff advantage of Bourgeois over Civic. Then we have

$$\begin{aligned}\Delta^B(\beta,\delta,\mu) &\equiv Er(B \mid \beta,\delta,\mu) - Er(C \mid \beta,\delta,\mu) \\ &= \frac{1}{2}\Big[(1+\mu)v - \delta\big((1-\mu)v + (1+\mu)(v+c)\big)\Big] + \beta\big[c(\delta+\delta\mu-\mu)\big]. \qquad (3)\end{aligned}$$

According to the payoff-monotonic best response learning process, β increases if $\Delta^B(\beta,\delta,\mu)$>0 in the previous period, and decreases if the inequality is reversed.

Proposition 1 allows us to characterize the parameter set (δ,μ) such that the evolutionarily stable stationary states are β=0 and β=1 representing the evolutionarily stable equilibrium of, respectively, a norm-based sharing economy and a possession-based private property economy.

PROPOSITION 1 (EVOLUTIONARY DYNAMICS OF THE FRACTION BOURGEOIS): *For* $\delta > \frac{v+\mu v}{2v+c+\mu c}$ *and* $\mu < \frac{(c-2v)\delta+v}{(2-\delta)c-v}$ *there exists*

$$\beta_B^* = \frac{\delta\big((1-\mu)v+(1+\mu)(v+c)\big)-(1+\mu)v}{2c(\delta+\delta\mu-\mu)},$$

in (0,1), such that under a deterministic payoff-monotonic updating process β *increases if* $\beta > \beta_B^*$ *and decreases if* $\beta < \beta_B^*$.

PROOF: See Appendix A.1.

Proposition 1 also formalizes our first strategic complementarity, namely that the payoff to Bourgeois is increasing in the fraction Bourgeois. Proposition 1 is equivalent to identifying the condition under which $\Delta^B(\beta,\delta,\mu)$ is negative when $\beta=0$ and positive when $\beta=1$, which implies that $\Delta^B(\beta,\delta,\mu)$ is increasing in β.

The intuition underlying the proposition is that where norms are sufficiently strong (that is, as δ approaches 1) virtually all interactions between individuals with different strategies will result in a conflict, so that each strategy would gain higher payoffs by interacting only with like strategies (this being true of bourgeois strategy only if ambiguity of possession is sufficiently low that conflicts among bourgeois types are rare). This is the basis of our first complementarity.

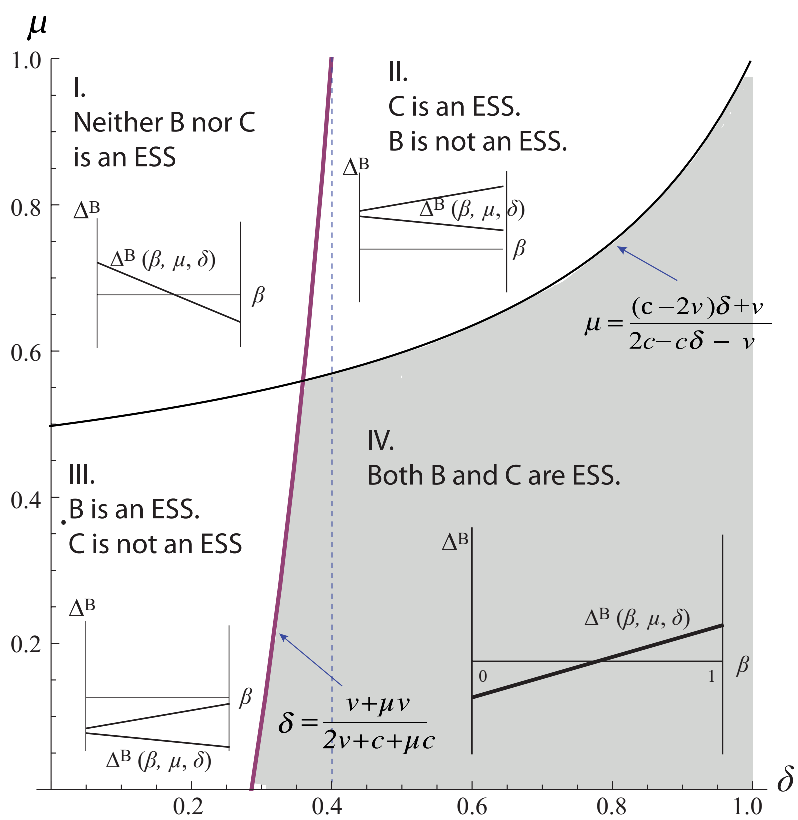

FIGURE 5 –. Social norms, property rights and multiple stable institutional equilibria.

In Figure 5 the gray area labeled IV indicates the set of (δ,μ) values – norms sufficiently strong and possession sufficiently secure – such that both conditions in Proposition 1 are satisfied, and as a result both Civic and Bourgeois are evolutionarily stable strategies. The small figure in the grey shaded region shows the how $\Delta^B(\beta,\delta,\mu)$ varies with the fraction Bourgeois. The small insert figures in the three other regions likewise show how the payoff advantage of the bourgeois types varies with the fraction Bourgeois. Because we are interested in the transition from one evolutionarily state to another and only in region IV are there two such states, we focus on region IV in the remainder of the paper.

5. TECHNOLOGY CHOICE BETWEEN FORAGING AND FARMING

Prior to playing the Civic-Bourgeois game just described, individuals choose a technology – farming or foraging – and this determines the nature of the product that each acquires and brings to the Civic-Bourgeois game at which the distribution of the product will be determined.

Individuals are either a forager or a farmer and acquire v_f and v_a^g, respectively, irrespective of their behavioral strategies. Unlike foraging, farming requires a prior investment of an amount *z*, resulting in a subsequent gross product of $v_a^g = \rho z$ and a net product of $v_a \equiv v_a^g - z = \rho z - z$ where $\rho - 1$ is the rate of return to the farmer's investment.

We will suppose the farmer uses a single product production process with inputs of labor and an amount *z* of the previous period's output (as seeds or food for draft animals). The farmer's gross output is the amount he harvests at the end of the growing period, while the net output is his feasible consumption after setting aside the necessary inputs to continue the process in the next period.[10]

[10] If the farmer's only investment were the seeds that are set aside for the next harvest then z / v_a is just the ratio of seed per unit of output (net of seed use), which in the early Holocene may have been something like a third (Bowles 2011). The investment cost for animal tending would have been much greater.

When there is a contest between individuals, what a farmer stands to lose in a contest is his gross output. Thus the payoff of the farmer in the Civic-Bourgeois game over his own product, is the product net of investment costs, v_a if the product is not taken by others, or $-z$ if it is taken by others. The forager by contrast has a payoff of v_f if his product is not taken, and zero otherwise. Thus farmers benefit more than foragers from the establishment of unambiguous rights of possession, which deter contestation.

5. 1. *Conditions for a transition to farming*

We now identify the empirically motivated conditions under which there will be a critical value of the fraction Bourgeois, β_a^*, which if exceeded makes farming rather than foraging a best response. Switching from forager to farmer could be expected-payoff enhancing as the result of two possible effects. First is the *productivity effect,* and this could make farming a best response if v_a (i.e., $v_a^g - z$) were greater than v_f so farming improves net output per unit of labor. We know on empirical grounds that this is unlikely: the productivity effect is likely to have been negative.

Second is the *property rights effect*. Because the nature of goods acquired by farming makes possession less ambiguous than is the case for foraged goods the likelihood that the goods that one has acquired will be contested is less for farmers than for foragers. Thus we have $\mu_a < \mu_f$ that is, farming reduces the contestability of his product, and hence if $\beta > 0$ this also reduces the likelihood that the farmer will be engaged in a contest in which, should he fail, he would both lose *z* and bear the cost *c*.

A positive *property rights effect* may more than compensate for a negative productivity effect and this is more likely to occur if β is sufficiently large. As a result there may exist some β such that farming yields a higher expected payoff than foraging even if it is not more productive. To study how farming could emerge as a result of this property rights effect even if had a productivity disadvantage, we assume

A1. $v_a - v_f < 0$.

and we explore the conditions under which farming could nonetheless have higher expected payoffs.

Let $\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)$ be the expected payoff advantage of farming over foraging under the conditions described by the arguments of the function. Letting $\delta=1$ in order to focus on the effect of μ, we have

$$\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)\equiv\frac{1}{2}\Big((v_a^g-z)-v_f\Big)-\frac{1}{2}z+\frac{1}{2}\beta\Big((v_a^g-v_f)+\mu_f(v_f+c)-\mu_a(v_a^g+c)\Big)\geq 0\,. \quad (4)$$

(See Appendix A.2 for the derivation of Equation (4) and for the general case where we may have $\delta<1$). Setting this expression equal to zero we find the frequency of Bourgeois, β_a^*, such that $\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)$ is positive when $\beta>\beta_a^*$ and not otherwise. A transition to and subsequent persistence of farming is possible if and only if there exists some $\beta_a^*<1$.

Proposition 2 shows that this depends on the relative productivity of the two technologies, the extent of investment required in farming, and the respective probabilities of contests for farmed and foraged goods.

PROPOSITION 2 (PAYOFF ADVANTAGE OF FARMERS): *Given* ***A1*** *there exists*

$$\beta_a^*=-\frac{\Big((v_a^g-z)-v_f\Big)-z}{(v_a^g-v_f)+\mu_f(v_f+c)-\mu_a(v_a^g+c)}=-\frac{v_a-v_f-z}{v_a-v_f+z+\mu_f(v_f+c)-\mu_a(v_a+z+c)}$$

in (0,1), if and only if

$$\mu_a\leq\frac{2(v_a-v_f)+\mu_f(v_f+c)}{v_a+z+c}\,.$$

PROOF: See Appendix A.2.

Proposition 2 expresses the tradeoff that determines the possibility of an evolutionarily stable bourgeois-farming equilibrium: the greater stakes that farmers may lose in a contest may be more than offset by the lesser probability that farmed (rather than foraged) produce will be contested, if the fraction of Bourgeois in the population is sufficiently great. To explore this critical tradeoff further in Figure 6, we identify the set of combinations of investment in farming and the reduced probability of contestation associated with farming that by Proposition 2 allows farming to be a best response to some distribution of behavioral strategies in the population.

This requires that $\beta_a^* < 1$ so setting $\beta_a^* = 1$ and holding μ_f constant, we have the solid curve in Figure 6, the locus of combinations of μ_a and z such that the expected payoffs to farming and foraging are identical when the two technologies are equally productive ($v_a = v_f$) and all members of the population are Bourgeois. For the evolution of farming to be possible we must have a (μ_a, z) pair below this locus. The dashed line shows a similar locus but for farming less productive than foraging, that is with $v_a = k \times v_f$ ($k < 1$) as might have been the case under the climatic conditions during the Pleistocene.)

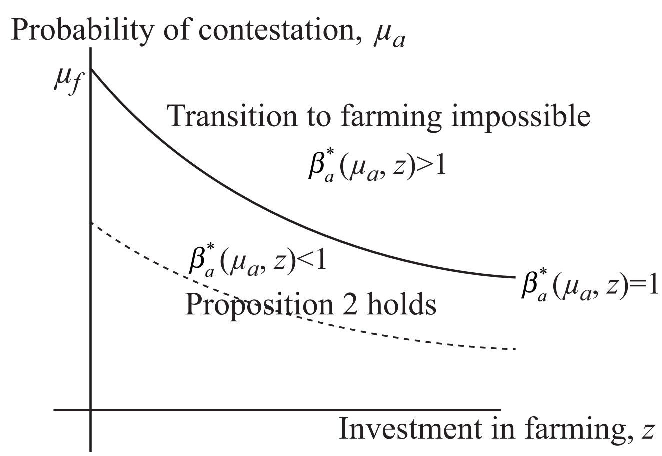

FIGURE 6 –. Contestability, farming investment and the possibility of a transition to farming when farming and foraging are equally productive. (The dashed line indicates the effect of a lesser level of farming productivity).

Note from Eq. (4), that $\partial \Delta^a(\beta, \mu_a, \mu_f, v_a^g, v_f) / \partial \beta > 0$ if and only if

$$\mu_a \leq \frac{v_a - v_f + z + \mu_f(v_f + c)}{v_a + z + c}, \quad (5)$$

which is satisfied if Proposition 2 holds. Thus a larger fraction of Bourgeois in the population raises the expected payoff advantage of farming given the conditions of empirical relevance, namely, that farming not more productive. As one would expect, the more investment-using farming is, the greater is this strategic complementarity between private property and farming: if we vary *z* while holding v_a constant we find that $\partial\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)/\partial\beta$ is increasing in *z* as long as $\mu_a<1$.[11] This confirms the intuition based on ethnographic and historical studies that the adoption of private property rights may have been especially important as a precondition for high investment arboreal and animal species as opposed to low investment cultivated species such as some root crops.

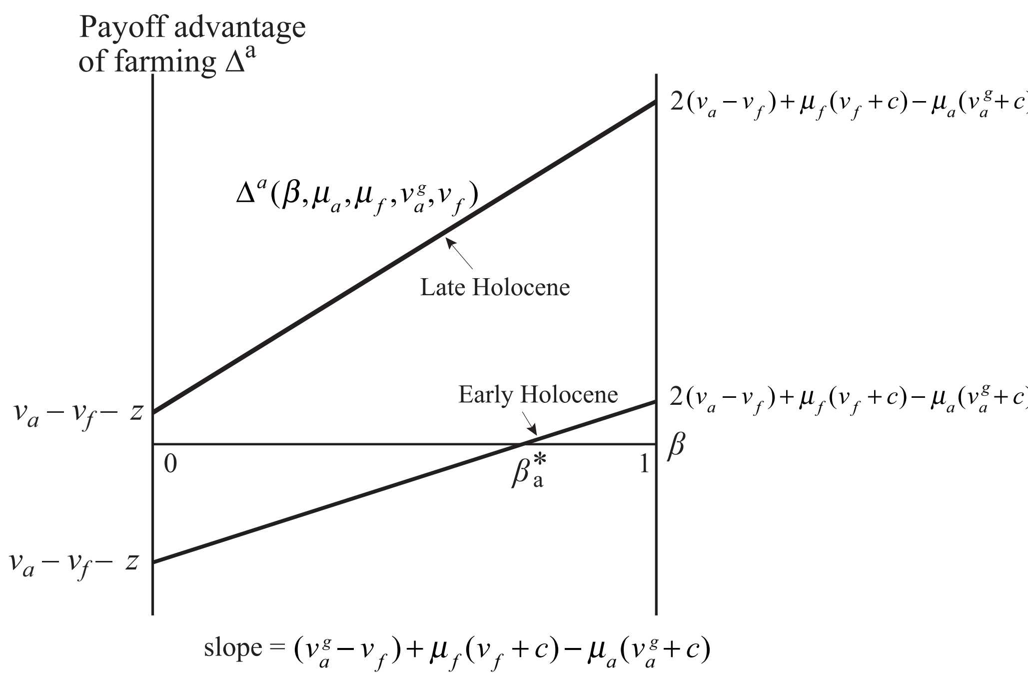

FIGURE 7 –. Why institutional innovation was a precondition for the Neolithic agricultural revolution.

Figure 7 presents alternative versions of Eq. (4). The top line represents the standard view that farming was introduced for its productivity advantages even in the absence of

[11] That is: holding v_a constant, $\partial(\partial\Delta^a/\partial\beta)/\partial z=1-\mu_a$.

private property. But as can be seen in the figure this route to the Neolithic agricultural revolution would have required an extraordinarily farming productivity (namely, $v_a - v_f > z$), in order to allow farming to be adopted without private property rights. We have labeled this line "Late Holocene" because it may be an accurate representation of the situation well into the Neolithic Agricultural Revolution, in those areas where the productivity of farming had substantially increased. The empirically relevant case for the initial emergence of farming is the bottom line in the figure where **A1** and Proposition 2 hold.

5. 2. *Strategic complementarity between farming and the Bourgeois strategy*.

Figure 7 illustrates first part of the second complementarity which exists between farming and private property, namely, that a greater fraction of Bourgeois increases the payoff associated with farming. The dual of this second complementarity is that the payoff advantage of being a Bourgeois increases as farming is more prevalent due to the lesser likelihood of possession ambiguity (because $\mu_a < \mu_f$) over the products of farming. The result is that for a Bourgeois, contests will be less frequent if farming is more prevalent. Using Eq. (3), this requires that:

$$\frac{\partial \Delta^B(\beta,\delta,\mu)}{\partial \mu} = v - \delta c + \beta\big(2c(\delta-1)\big) < 0 \qquad (6)$$

Because the last term cannot be positive, a sufficient condition for Eq (6) is that $\delta > v/c$, which we assume in what follows:

A2. $\delta > v/c$

By requiring that norms be sufficiently strong and or the costs of losing a conflict be sufficiently great relative to the value of the possession, **A2** simply precludes the degenerate case in which the Bourgeois in an all Civic population would do better by playing Hawk unconditionally.

Table 3 summarizes the relevant complementarities.

TABLE 3

STRATEGIC COMPLEMENTARITIES IMPEDING THE NEOLITHIC AGRICULTURAL REVOLUTION

Complementarity	*Economics*	*Result*
Bourgeois strategies are strategic complements	Payoffs to Bourgeois increasing in β	If Proposition 1 holds, then $\delta > \mu / (1+\mu)$ so from Eq. (3): $\partial\Delta^B(\beta,\delta,\mu)/\partial\beta > 0$
Farming and Bourgeois are strategic complements, I	Relative payoffs to farming increasing in β	If Proposition 2 holds: $\partial\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)/\partial\beta > 0$
Farming and Bourgeois are strategic complements, II	Relative payoffs to Bourgeois decreasing in μ	Given A2, from Eq (3) & (6): $\partial\Delta^B(\beta,\mu,\delta)/\partial\mu > 0$.

Proposition 2 thus explains why farming could be adopted despite its productivity disadvantage, as long as the offsetting reduction in conflict associated with adopting farming were sufficiently great. Because this offsetting conflict-reduction effect is only present in interactions of farmers with bourgeois types, Proposition 2 makes clear why the advent of farming (given its productivity disadvantage) required the adoption of a new set of property rights.

6. THE EMERGENCE OF FARMING-FAVORABLE INSTITUTIONS

The final step of our explanation, then, is to characterize the conditions under which (prior to farming) the adoption of private property rights could become sufficiently widespread not only to sustain farming as a payoff-advantageous technology (given by β_a^* in Proposition 2) but also to sustain itself (given by β_B^* in Proposition 1).

To do this we modify the updating stage of the game so that individuals are now boundedly rational and idiosyncratically choose the trait that is not a best response with some small probability ψ. We then model the stochastic process generating movements away from the neighborhood of the all-Civic state that represents the status quo prior to the Neolithic agricultural revolution. From this model we derive an expression for the probability in any given period of a transition to the basin of attraction of a farming-with –private-property state.

Because it is plausible that idiosyncratic play is more likely when the costs of deviating from a best response are smaller, we use the logit choice protocol (Blume 2003.) Thus we let the probability of non-best response play be decreasing in the cost of deviating from the best response (which in this case means playing Bourgeois, instead of Civic so the deviation cost is just $-\Delta^{B}(\beta,\delta,\mu)$) and also decreasing in ϕ, the (finite) degree of rationality of the agent, which is common to all members of the population. Thus we have the probability that the individual responds idiosyncratically:

$$\psi(\Delta^{B}(\beta,\delta,\mu),\phi)=\frac{1}{1+e^{\phi\Delta^{B}(\beta,\delta,\mu)}}.$$

Individuals play the best response strategy with probability $1-\psi$. We term ϕ the degree of rationality because when $\phi=0$ the individual selects a strategy randomly, while the rate of idiosyncratic play goes to zero as ϕ goes to infinity.

Let *n* be the population size and n_{B}^{*} be the smallest integer that exceeds $n\beta_{B}^{*}$ that is, the least number of Bourgeois players sufficient to induce a transition to the private property regime. Because the updating process is based only on the distribution of play in the previous period, for sufficiently rational agents, idiosyncratic movements away from the immediate neighborhood of β=0 that fall short of $n\beta_{B}^{*}$ are returned in the next period almost certainly to neighborhood of β=0.

For this reason, we focus on transitions in a single period from a state with only Civics in a foraging economy to a state such that the number of those playing Bourgeois exceeds $n\beta_{B}^{*}$ as in Kandori et al. (1993), where "an equilibrium is upset by large jumps (from the equilibrium to the basin of attraction of the other equilibrium)" (p. 52) or as in Binmore et al. (2003), where a "single burst of mutations" (p. 309) is considered.

Let $n_{B,t}$ be the number of Bourgeois in the population at time *t*. Define the state as the number of Bourgeois in the population and the set of states as $S=\{1,2,\cdots,n\}$. Then following Kandori et al. (1993), Lemma 2, we have the transition probability that in any period in the all Civic state n_{B}^{*} or more individuals idiosyncratically adopt the bourgeois trait:

$$\Pr\left[n_{B,t+1} \geq n_B^* \mid n_{B,t} = 0, \delta, \mu, n\right] = \sum_{n_B = n_B^*(\delta,\mu)}^{n} \binom{n}{n_B} \psi(\Delta^B(\beta = 0, \delta, \mu), \phi)^{n_B} (1 - \psi(\Delta^B(\beta = 0, \delta, \mu), \phi))^{n - n_B} \tag{7}$$

Recall that our proposed resolution of the puzzle of the independent emergence of farming is that the reduction in inter-annual climate volatility at the end of the Pleistocene reduced pressures for forager mobility and allowed some groups to settle more or less permanently, acquiring fixed assets such as dwelling and stores. The effect would have been to make possession of goods less ambiguous and contestable.

To explore this hypothesis, we use Eq. (7) to determine the effect that a reduction in contestability (μ) would have on the probability of a transition to a private property regime. In Eq. (7), μ appears twice: first, as a determinant of n_B^*, the critical number of Bourgeois to induce a transition to the new property rights regime, and second, as a determinant of the cost of deviating from the best response and hence (inversely) of the likelihood of idiosyncratic play. We now show that the two effects of a reduction in μ work in the same direction: first, it raises ψ and second, it lowers n_B^*, thus raising the probability of a transition.

The first is true because from Eq. (6) we know that $\partial\Delta^B(\beta = 0, \delta, \mu) / \partial\mu < 0$ so a reduction in μ lowers the cost of deviating from the best response and idiosyncratically playing Bourgeois. To show the second we differentiate β_B^* (given in Proposition1) with respect to μ, and find that **A2** guarantees that $\partial\beta_B^* / \partial\mu > 0$. Since n_B^* is the smallest integer that exceeds $n\beta_B^*$, n_B^* will be non-decreasing in μ. These two results give us:

PROPOSITION 3. (THE TRANSITION OF A PRIVATE PROPERTY REGIME): *Conditional on **A2**, a fall in the contestability of possession, μ, induces a greater probability of a transition from an all-Civic-forager to an all-Bourgeois-forager population.*

PROOF: See Appendix A.3.

7. THE NEOLITHIC AGRICULTURAL REVOLUTION

We have just seen that the minimum fraction of Bourgeois types required for the deterministic dynamic to carry the population to universal adoption of private property is increasing in μ, and hence is lesser in a farming economy than in a foraging economy which we express as $\beta_B^*(\mu_a, v_a) < \beta_B^*(\mu_f, v_f)$. Also recall that β_a^* is the threshold of β such that when $\beta > \beta_a^*$ the expected farming payoff exceeds the expected forager payoffs and the farming transition will occur.

Combining these results, we see that a transition to farming is possible under three scenarios (cases I, II and IV below) that are summarized in Figure 8. Cases II and IV represent the Neolithic agricultural revolution.

Case I. False Start: No institutional transition, $\beta_a^* < \beta < \beta_B^*(\mu_a, v_a)$.

In this case, farming is adopted because as a result of idiosyncratic play $\beta > \beta_a^*$, but the reduction in μ resulting from the introduction of farming is not sufficient and the fraction Bourgeois still falls short of the critical value for a property rights transition, i.e., $\beta < \beta_B^*(\mu_a, v_a)$. As a result, the fraction Bourgeois declines, reaching a level below β_a^*, at which point the erstwhile farmers return to foraging.

This path may represent a number of cases in the archaeological record in which intensive management or even cultivation of wild species was initially taken up only to be abandoned subsequently. Examples include the short-lived domestication of Barbary sheep in the Libyan Sahara and the proto-farming briefly practiced by the Levantine Natufians during the brief warming around 15-13 thousand years ago.[12] The Batek

[12] On Barbary sheep see Barker (2006). Ofer Bar-Yosef refers to Natufians as "perhaps the earliest farmers" (Bar-Yosef 1998), while Unger-Hamilton concludes that "the evidence favors the notion that cereals were being cultivated in the Early Natufian." Additional evidence is found in Bellwood (2005), Barker (2006), Unger-Hamilton (1991), and Anderson (1991).

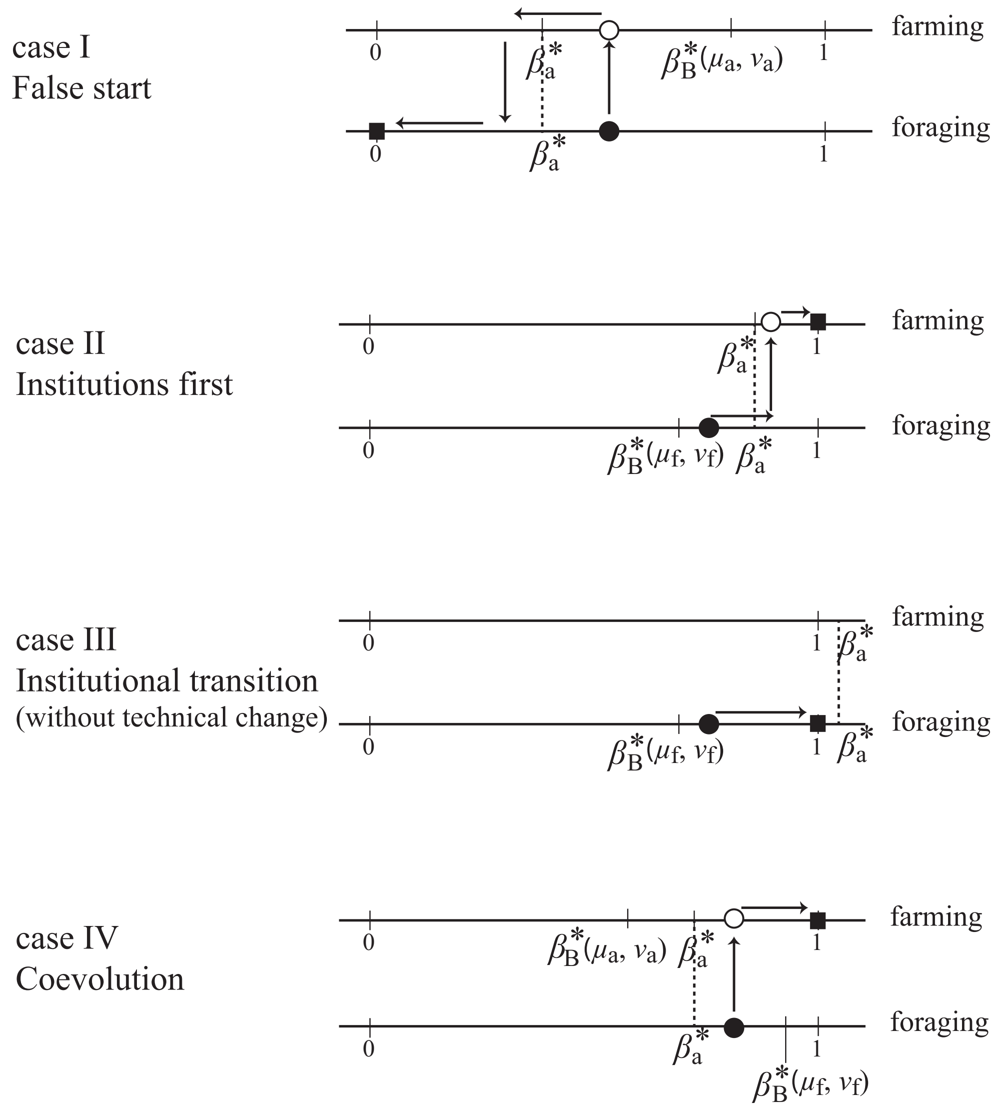

FIGURE 8 –. Technological and institutional transitions in the Neolithic revolution.
Note: a closed circle indicates the realization a frequency of Bourgeois in the population that exceeds the critical value $\beta > \beta_B^*$ or $\beta > \beta_a^*$; open circles indicate a transition to farming, closed squares indicate the endpoint of this transition process.

people, foragers in Malaysia half a century ago, provide another example (Endicott 1988). Two Batek men had discovered cultivated rice nearby and tried planting some in their group's territory. But their fellow Batek simply harvested it and, given their norms governing any food acquired in large quantities, felt obliged to share the harvest with the entire group. The two gave up their attempt at farming.

Case II. Institutions first, then technology, $\beta_B^*(\mu_f, v_f) < \beta < \beta_a^* < 1$.

The fraction Bourgeois exceeds β_B^*, so that private property proliferates in a hunting-gathering economy until $\beta = 1$; and the conditions in Proposition 2 (illustrated in Figure 6) also hold so that that $\beta_a^* < 1$ and farming is then adopted.

This case is exemplified by what the archaeologist Curtis Marean terms the coastal adaptation based on dense, immobile and hence defendable resources (Marean 2014). Among sedentary hunter-gatherers occupying such sites a shift from group-based territoriality to family held rights of possession may have occurred. An example are fishing communities such as the maritime hunter-gatherers of Huaca Preita on the northern coast of Peru who exploited the rich local fisheries using nets, floats and other gear.[13] It seems likely that the fishing gear and stores were owned by individuals or families. Subsequently cultivated lima beans and avocado became part of their diet and still other cultigens (including arboreal fruit and cotton) were added. The people of Huaca Preita appear to have first developed a system of private property rights as part of their fishing economy, and then extended these rights to crops, trees, and improved farmland, or as one of the foremost archaeologists of the period puts it: "fishing configured early farming."[14]

Case III. Institutional transitions, no technical change, $\beta_B^*(\mu_f, v_f) < \beta < 1 < \beta_a^*$.

This is identical to case II, but $\beta_a^* > 1$ (i.e., Proposition 2 does not hold). In this case even a transition to universal adoption of private property does not induce a transition to farming. This appears to have occurred in a number of resource rich sites exemplified by some populations in North America who did not take up farming prior to European contact (Arnold 1993, Bettinger 2015, Hayden 1997.) Similarly in the Baltic area

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[13] This account is based on Dillehay et al. (2012), Moseley (2006), and personal communication from Dillehay. Raised farming platforms demarked by ridges dating to about five thousand years ago have also been found, along with evidence of irrigation, indicating investment intensive farming that would have been facilitated by private property rights.

[14] The Peruvian coast is not atypical. Evidence of public storage followed by private storage predated farming by at least 7 millennia at Dobranichkevka in Russia (Soffer 1985, Soffer 1989).

(another example of a coastal adaptation) the abundance of spatially concentrated maritime resources and the importance of fishing gear, favored the emergence of a farming-friendly property rights template, but may have also made farming a feasible but initially unattractive alternative to maritime hunting and gathering (Zvelebil and Rowley-Conwy 1986, Price 1985).

Case IV. Institutions and technology coevolve, $\beta^*_B(\mu_a, \nu_a) < \beta^*_a < \beta < \beta^*_B(\mu_f, \nu_f)$.

The fraction Bourgeois exceeds the minimum required for farming to be a best response but falls short of that required for the deterministic proliferation of the Bourgeois strategy in the absence of farming. However, when farming is taken up this results in a value of $\beta^*_B(\mu_a, \nu_a) < \beta^*_a$ so that the fraction Bourgeois goes to 1.

This co-evolutionary case may represent a good number of the independent episodes of the Neolithic agricultural revolution in which, starting from an initial limited adoption of private property, then proceeds with the *pari passu* development of the novel technology and institutions. Included may be Abu Hureyra in southwestern Asia (Moore et al. 2000) and the exceptionally long transition from first domestication to widespread adoption of farming in some sites in the Americas (Smith 1997.)

8. CONCLUSION

In conjunction with what is known empirically our model is consistent with the following explanation of the Neolithic agricultural revolution: a) predating the first farmers, independent transitions to farming-friendly institutions occurred due to the bunching of unlikely chance events (accounting for the persistence of forager technology and institutions and the rareness of the observed transitions); b) because even before farming, sedentism reduced the probability that possession would be contested, the probability of the Neolithic transition increased once Holocene climatic conditions reduced pressure for mobility (accounting for the timing of the few independent occurances of the advent of farming); and c) once a transition to widespread adherence to private property norms had occurred at some farming-suitable locations, erstwhile foragers could benefit materially by taking up farming even if it was not more productive, because cultivation and animal tending made possession less ambiguous and more enforceable.

Climate amelioration is no less central in our interpretation than it is in the work of Richerson et al. (2001), but its effect, we have suggested, operated first by reducing the resistance to a transition to a self-sustaining private property regime, that is from $\beta = 0$ to $\beta > \beta_a^*$ and only subsequently via its effect on the productivity of farming.

The summary of cases of transtion in the previous section suggests that the model replicates important features of the archaeological record. But there are discrepancies. By abstracting entirely from spatial-biological heterogeneity in the suitability of particular locations for farming each of the possible species that a group might have taken up, and by abstracting from the slow improvement in the productivity of cultivated species either deliberately or as a byproduct of their domestication, we make the transition to farming – when institutional and envireonmental conditions allowed this – an all or nothing mattter, occuring in a single period.

This may be considered a feature of the model in that it accurately reflects the contrast between the individual rationality that is often sufficient for the adopption of a new technology and the joint action that is required to adopt novel institutions when, as is often the case, adoption by one group member is a strategic complement to others' adoptions. It is also consistent with the apparently long persistence of forager institutions – probably extending over a hundred millennia or so – and much shorter transition times to the private owenership and farming regime occuring during the Holocene.

But the passage from initial domestication of one or two species that accounted for a modest portion of the diet to a primary commitment to food production was far from instantaneous and in some cases extended over many millennia (Smith 2001). Explicitly modeling the pace of adopting of farming by including the kinds of spatial-biological heterogeneity and the productivity improvements induced by food production would address this caveat; but we doubt that it would fundamentally alter the account we have offered.[15]

Caveats are also required about the "why" of the process. If groups were quite small, a decentralized stochastic process like the one that we model would have resulted in large realized excursions from the status quo forager convention. Thus a close to literal application of our stochastic model may have empirical relevance in Southern India where farming may have been introduced by very small groups of foragers (Fuller 2006b.) For analogous reasons it may provide a convincing explanation of the emergence of family possession based property (without farming) among California native Americans living in small groups prior to European contact (Bettinger 2015.)

But where the Holocene transition took place in sedentary groups of hundreds of individuals as in southwest Asia the time scales on which rare idiosyncratic play would generate a sufficiently large excursion from the status quo convention may be inconsistent with the observed institutional transitions taking place in the aftermath of the Holocene weather amelioration. In these cases collective action among community members possibly minimally differentiated by political roles may have coordinated the process of equilibrium selection.[16] Thus the evidence of a 'communal' political life at Abu Hureyra, Mureybet, Gobekli Tepe and other southwest Asian early Holocene pre agricultural villages may suggest another mechanism of transition, one that does not entail elite imposition, but rather deliberation among peers resulting in a selection among alternative (also peer-enforced) institutional conventions.

This is a reminder that idiosyncratic play in our model is a stand-in for variations in behavior not captured by the model, not a description of any literally random process by which people came to deviate from the status quo. Understanding this process of

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15 Agent based simulations of the dynamics of technology and institutions during the early Holocene in Bowles and Choi (2013) allow a more realistic temporal framework, and they replicate the long transitions found in the archaeological record.

16 At Abu Hureyra large scale hunting (with elaborate traps at which large numbers of gazelles were taken at a time) must have been based on a substantial level of coordination that could also have also been the basis of the emergence of entirely new instituitons (Moore et al. 2000.)

behavioral innovation would be an important contribution to explaining the Neolithic agricultural revolution.

Once independently established, the Neolithic package (sedentism plus farming plus private property) could have out-reproduced foraging populations due to the shorter birth spacing made possible by sedentism (Lambert 2009, Bocquet-Appel 2009.) Moreover the larger concentrations of population and the subsequent emergence of hierarchical political systems and eventually states eventually gave farmers a decisive military advantage over foragers, allowing the further spread of the Neolithic package. This diffusion process included both imposition by political elites as suggested by Scott (2009) and Acemoglu and Robinson (2012), and a process of cultural group selection implicit in the evolutionary thinking of Parsons (1964), Hayek (1988) and others. But our model addresses the independent emergence of farming not its spread, and hence does not include these processes.

APPENDIX

A. 1. Proof of Proposition 1

PROOF: Define the payoff advantage of being a Bourgeois as

$$\Delta^{B}(\beta,\delta,\mu) \equiv Er(B \mid \beta,\delta,\mu) - Er(C \mid \beta,\delta,\mu) .$$

Then we have

$$\Delta^{B}(\beta,\delta,\mu) = \frac{1}{2}\Big[(1+\mu)v - \delta\big((1-\mu)v + (1+\mu)(v+c)\big)\Big] + \beta\big[c(\delta + \delta\mu - \mu)\big]$$

(i) For Civic to be an evolutionarily stable strategy, it must be that Bourgeois have a payoff disadvantage when they are absent from the population, or

$$\Delta^{B}(\beta = 0, \delta, \mu) = \frac{1}{2}\big(v + \mu v - \delta(2v + c + \mu c)\big) < 0 .$$

Since $2v + c + \mu c$ is always positive, a necessary and sufficient condition for Civic to be evolutionarily stable is

$$\delta > \frac{v+\mu v}{2v+c+\mu c}.$$

(ii) For the Bourgeois strategy to be evolutionary stable, it must have a payoff advantage when Civics are absent, so we should have

$$\Delta^B(\beta=1,\delta,\mu)=\frac{1}{2}\Big((c-2v)\delta+v-\mu(2c-c\delta-v)\Big)>0,$$

Note that because $2c-c\delta-v$ and $(c-2v)\delta+v$ are always positive as $v<c$, a sufficient and necessary condition for Bourgeois to be evolutionarily stable is that

$$\mu<\frac{(c-2v)\delta+v}{(2-\delta)c-v}. \qquad \blacksquare$$

A. 2. Derivation of Equation (4) and Proof of Proposition 2.

Let $a=1$ if the individual adopts farming technology and $a=0$ if he chooses foraging. Consider the case of $\delta=1$ first. Then extending $r(\cdot)$ in Eq. (1a) to (1d) in the text to take account of technology choice gives the following expressions, in which to avoid irrelevant clutter, we suppress terms involving the payoff from the sub-game over the opponent's product because they do not affect the individual's technology choice.

$$r(C,C\,|\,\delta=1,\mu,a)=(1-a)\pi^f(D,D)+a\pi^a(D,D)+\cdots, \tag{A-1a}$$

$$r(C,B\,|\,\delta=1,\mu,a)=(1-a)[(1-\mu_f)\pi^f(H,D)+\mu_f\pi^f(H,H)]$$
$$+a[(1-\mu_a)\pi^a(H,D)+\mu_a\pi^a(H,H)]+\cdots \tag{A-1b}$$

$$r(B,C\,|\,\delta=1,\mu,a)=(1-a)\pi^f(H,H)+a\pi^a(H,H)+\cdots, \tag{A-1c}$$

$$r(B,B\,|\,\delta=1,\mu,a)=(1-a)[(1-\mu_f)\pi^f(H,D)+\mu_f\pi^f(H,H)]$$
$$+a[(1-\mu_a)\pi^a(H,D)+\mu_a\pi^a(H,H)]+\cdots \tag{A-1d}$$

A Civic adopts farming technology if

$$(1-\beta)r(C,C\,|\,\delta=1,\mu_a,a=1)+\beta r(C,B\,|\,\delta=1,\mu_a,a=1)$$
$$\geq(1-\beta)r(C,C\,|\,\delta=1,\mu_f,a=0)+\beta r(C,B\,|\,\delta=1,\mu_f,a=0), \tag{A-2a}$$

and for a Bourgeois the condition for adopting farming technology is

$$(1-\beta)r(B,C\,|\,\delta=1,\mu_a,a=1)+\beta r(B,B\,|\,\delta=1,\mu_a,a=1)$$

$$\geq(1-\beta)r(B,C\,|\,\delta=1,\mu_f,a=0)+\beta r(B,B\,|\,\delta=1,\mu_f,a=0)\,, \qquad \text{(A-2b)}$$

Eq. (A-2a) and (A-2b) are satisfied if and only if Eq. (4) in the text is satisfied. That is

$$\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)\equiv\frac{1}{2}\Big((v_a^g-z)-v_f\Big)-\frac{1}{2}z+\frac{1}{2}\beta\Big((v_a^g-v_f)+\mu_f(v_f+c)-\mu_a(v_a^g+c)\Big)\geq 0\,.$$

Therefore, letting $\beta=1$, we have

$$\Delta^a(\beta=1,\mu_a,\mu_f,v_a^g,v_f)>0 \text{ if and only if } \mu_a\leq\frac{2(v_a-v_f)+\mu_f(v_f+c)}{v_a+z+c}$$

in which case, there is some critical fraction of Bourgeois in the population less than unity

$$\beta_a^*=-\frac{\Big((v_a^g-z)-v_f\Big)-z}{(v_a^g-v_f)+\mu_f(v_f+c)-\mu_a(v_a^g+c)}=-\frac{v_a-v_f-z}{v_a-v_f+z+\mu_f(v_f+c)-\mu_a(v_a+z+c)}$$

in (0, 1) such that for $1\geq\beta>\beta_a^*$ the expected returns are greater in farming than in foraging.

Let's turn now to the case when $\delta<1$, (A-2a), the condition for a Civic to adopt farming, is satisfied if and only if

$$\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)=\frac{1}{2}(v_a^g-v_f)-z+\frac{1}{2}\beta\Big(\delta(v_a^g-v_f)+\mu_f(v_f+\delta c)-\mu_a(v_a^g+\delta c)\Big)\geq 0\,. \qquad \text{(A-3)}$$

As above, letting $\beta=1$ and given A1, we have $\Delta^a(\beta=1,\mu_a,\mu_f,v_a^g,v_f)>0$ if and only if,

$$\mu_a\leq\frac{(1+\delta)(v_a-v_f)-(1-\delta)z+\mu_f(v_f+\delta c)}{v_a+z+\delta c}\,. \qquad \text{(A-4)}$$

This is a necessary and sufficient condition for the existence of some β such that a Civic will adopt farming. By the same token, when $\delta<1$, (A-2b), the condition for a Bourgeois to adopt farming, is satisfied if and only if

$$\Delta^a(\beta,\mu_a,\mu_f,v_a^g,v_f)=\frac{1}{2}(2-\delta)(v_a^g-v_f)-z+\frac{1}{2}\beta\Big(\delta(v_a^g-v_f)+\mu_f(v_f+c)-\mu_a(v_a^g+c)\Big)\geq 0\,.$$

(A-5)

Letting $\beta = 1$, we have $\Delta^a(\beta = 1, \mu_a, \mu_f, v_a^g, v_f) > 0$ if and only if,

$$\mu_a \le \frac{2(v_a - v_f) + \mu_f(v_f + c)}{v_a + z + c}. \tag{A-6}$$

which is a necessary and sufficient condition the existence of some β in (0, 1) for a Bourgeois to adopt farming. We see (A-4) and (A-6) become identical when $\delta = 1$.

With both (A-4) and (A-6) satisfied, we have

$$\beta_a^* = -\frac{v_a - v_f - z}{\delta(v_a^g - v_f) + \mu_f(v_f + \delta c) - \mu_a(v_a^g + \delta c)} < 1 \quad \text{for Civics} \tag{A-7}$$

and

$$\beta_a^* = -\frac{(2-\delta)(v_a^g - v_f) - 2z}{\delta(v_a^g - v_f) + \mu_f(v_f + c) - \mu_a(v_a^g + c)} < 1 \quad \text{for Bourgeois.} \tag{A-8}$$ ■

A. 3. Proof of Proposition 3

PROOF: Suppose δ and μ are such that there exists β_B^* in (0, 1). A one-step escape from the basin of attraction of the Civic equilibrium requires at least n_B^* individuals to play the non-best response, B, where n_B^* is the smallest integer that exceeds $n\beta_B^*$. Therefore probability of a transition depends on both n_B^* and ψ.

What we need to show is (i) $\partial\Delta^B(\beta = 0, \delta, \mu)/\partial\mu < 0$ and (ii) $\partial\beta_B^*/\partial\mu > 0$. Letting $\beta = 0$ in Eq. (6) in the text, we have

$$\frac{\partial\Delta^B(\beta = 0, \delta, \mu)}{\partial\mu} = v - \delta c < 0 \quad \textit{iif } \delta > v/c$$

(ii) From Proposition 1, we know for $\delta > \frac{v + \mu v}{2v + c + \mu c}$ and $\mu < \frac{(c - 2v)\delta + v}{(2-\delta)c - v}$, there exists

$$\beta_B^* = \frac{\delta\big((1-\mu)v + (1+\mu)(v+c)\big) - (1+\mu)v}{2c(\delta + \delta\mu - \mu)},$$

in (0,1). Differentiating β_B^* with respect to μ, we have $\partial\beta_B^* / \partial\mu > 0$ if **A2** holds. Since n_B^*, the smallest integer that exceeds $n\beta_B^*$, n_B^* will be non-decreasing in μ if **A2** holds. From (i) and (ii), the transition probability is decreasing in μ. ■

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