The Neolithic Agricultural Revolution and the Origins of Private Property

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Familiar explanations of why hunter-gatherers first took up farming—superior labor productivity, population pressure, or adverse climate—receive little support from recent evidence. Farming would be an unlikely choice without possession-based private property, which appears to have existed among rare groups of sedentary hunter-gatherers who became the first farmers. Our model shows that among them, farming could have benefited first adopters because private possession was more readily established and defended for cultivated crops and domesticated animals than for the diffuse wild resources on which hunter-gatherers relied, thus explaining how farming could have been introduced even without a productivity advantage.

I. 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

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productivity of labor, encouraging adoption of the new technology (Childe 1942; Cohen 1977). In these accounts, under pressure of growing populations (and in some versions under increasingly adverse climatic conditions) 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 labour in hunting, a rise in the productivity of labour in agriculture, or [an] . . . expansion of the size of the labour-force" (North and Thomas 1977, 232). This, 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 (Smith 1975). The institutional innovations facilitating the agricultural revolution, namely, an expanded domain for possession-based private-property rights, reflected a similar technology-led view expressed by Harold Demsetz: "the emergence of new . . . property rights will be in response to changes in technology" (Demsetz 1967, 350).

How do these accounts stand up in light of what is now known about the advent of farming (Richerson, Boyd, and Bettinger 2001; Bellwood 2005; Barker 2006; Price and Bar-Yosef 2011a)? Empirical claims pertaining to populations living 10 or more millennia ago are necessarily subject to substantial uncertainty, but the available evidence now suggests the following brief overview. Beginning around 11,500 years ago, under more stable and warmer weather conditions favorable to plant growth and to a sedentary lifestyle, cultivation of domesticated species spread as hunter-gatherers converted to food production for their livelihood.

By comparison to these well-documented changes in climate, cultivation, and sedentism, evidence of novel private property and other aspects of economic institutions is intrinsically more difficult to come by before written records. Nonetheless, early farming is associated with archaeological traces of a novel set of property rights covering a greatly enhanced domain,

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including dwellings, private storage, and ownership of garden plots by families or lineages (Byrd and Monahan 1995; Earle 2000; Bogaard 2004; Kuijt 2008; Bogaard et al. 2009, 2013; Garfinkel, Ben-Shlomo, and Kuperman 2009; Kuijt and Finlayson 2009; Bogaard, Krause, and Strien 2011). This expanded role for private-property rights was not unique to farming populations. Some elements of private property were almost certainly common even among mobile hunter-gatherers. Among sedentary populations predating the advent of food production, these appear to have pertained to dwellings and storage (some evidence is reviewed in Sec. VIII).

In Section III, we review evidence that foragers took up farming under declining, not increasing, populations and that the Neolithic agricultural revolution occurred not under conditions of climatic adversity but instead under increasingly farming-friendly conditions, facilitating both plant growth and sedentism. While farming undoubtedly raised the productivity of land, some archaeologists have doubted that it raised labor productivity, at least not for many centuries after the advent of farming (Zvelebil and Rowley-Conwy 1986; Gregg 1988; Harlan 1992; Moore, Hillman, and Legge 2000; Bettinger, Barton, and Morgan 2010). Consistent with this view, we also provide new indirect evidence on calories of food per hour of labor that is inconsistent with the view that the first farmers were more productive than the foragers they replaced.

The putative labor productivity advantage of early farming is attractive because it provides a parsimonious explanation of an important and otherwise inexplicable fact: foragers took up farming. But lacking convincing evidence that farming was indeed more productive, it is worth asking, Could farming have been introduced even in the absence of a productivity advantage, and if so, how might this have taken place?

II. Could Foragers Have Taken Up Farming Even If It Were Not More Productive?

An important clue for the explanation of the Neolithic agricultural revolution is the rareness of the independent advent of farming (with perhaps a dozen cases at most), which cannot be explained (as might be the rareness of the development of writing) by the difficulty of "inventing" farming. Hunter-gatherers were of necessity experts in plant and animal biology.[1] Seeing that after the Last Glacial Maximum, virtually all human groups (excluding Arctic populations and a few others) were free to experiment with cultivation and animal tending and (as we see in Sec. VIII) that many did so without taking up farming over the long period, it is quite unlikely

[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, 68).

that foragers' ignorance of the possibilities of food production explains why the independent emergence of farming was so rare. We propose, instead, that an institutional bottleneck impeded the advent of farming.

Archaeologists, economists, and many others have long recognized the barriers to farming constituted by the collective decision-making and common property rights of foraging groups (Demsetz 1967; North and Thomas 1977; Woodburn 1982; Sherratt 1997; Bowles 2004; Smith 2012). These rights included open access to the resources of a group's conventional territory by any group member (and sometimes by outsiders as well, with permission) and sharing most food acquired in large amounts at a single time, for example, large prey or honey (Kaplan and Hill 1985; Boehm 2000; Wiessner 2005; Bowles and Gintis 2012). The long-term stability of this forager 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, Gintis, and Bowles 2010).

Applying these forager sharing norms in a farming setting—to an animal slaughtered or a crop harvested—would greatly reduce the individual incentive to undertake the investments that farming required. Free riders' claims on would-be first farmers' crops and animals are found among the twentieth-century !Kung in Botswana (Wiessner 1982), other groups in southern Africa (Hitchcock 1978), the Batek in Malaysia (Endicott 1988; discussed in Sec. VII), and the Hiwi in Venezuela. Even under environmentally favorable 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 recent small-scale economies along the foraging-farming continuum (Sec. III), suggests that the independent emergence of farming is better modeled as a process of selection among alternative equilibria than as in the standard economic account: that is, 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 population. We need answers to two questions. First, under what conditions could both a foraging and a farming equilibrium represent evolutionarily stable states for a population? And second, supposing that farming lacked a productivity advantage, 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 could have occurred

because of economies of scale in food production. But aside from large-scale irrigated farming (that came later), it is unlikely that food production was subject to significant economies of scale. An important source of positive feedbacks, we hypothesize, concerns the institutions supporting the introduction of farming, not the process of food production itself.

The impediments to the adoption of a new technology are fundamentally different from the barriers to institutional change. The expected payoff to the choice of a particular technology (planting and cultivating barley rather than harvesting wild barley, for example) does not depend much on the number of others adopting the same technology. By contrast, adopting the strategy of respecting the property rights of others and defending one's own possessions would be unlikely to yield positive payoffs if few of one's group mates adopted the same strategy. This complementarity among patterns of behavior that, if widely adopted, would represent a novel institution, motivates our representation of institutions as conventions (i.e., symmetric equilibria of noncooperative coordination games). Institutional change then takes a form of a transition to a new convention that is impeded by a "critical-mass" problem.

The second complementarity in our model 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 require significant long-term investment in field preparation, animal raising, dwelling construction, and storage. Moreover, these forms of wealth (animals and stored grains, for example) are vulnerable to appropriation by others. Second, these forms of the wealth of farmers 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 successfully contested and thus could form a basis of a new system of private property.

The livelihood of foragers, by contrast, depended on mobile, ephemeral, and dispersed resources, for which unambiguous individual possession was virtually impossible to establish. Much of the wealth of foragers, moreover, took the form of knowledge, skills, network connections, physical prowess, and other attributes that (in the absence of slavery) are intrinsically difficult for others to expropriate.

To sum up, without private-property rights, a would-be first farmer would not be motivated to undertake the long-term production process and fixed investments that farming required, but the novel rights required to motivate farming could not be adopted singly. And, by comparison to hunter-gatherers, the wealth of farmers was, for technical reasons, both more exposed to expropriation by others and more readily subjected to private property. These two complementarities—"the critical-mass institutional bottleneck" and "the farming-property synergy"—allow us to

model a technology (farming) and an institution (private property) as jointly constituting a convention.

Following Young (1998) and Binmore, Samuelson, and Young (2003), we use stochastic evolutionary game theory to study how this novel convention might emerge as the result of uncoordinated transition from a status quo convention in which food production and private property were largely absent. Evolutionary models of noncooperative games of this type are especially appropriate for the prehistoric societies we are studying because of the absence of states or other coercive bodies capable of simply imposing a transition to farming on a population (we review evidence for this in Sec. III).[2]

In Sections IV and V, we formalize these complementarities, using an extension of the biologist John Maynard Smith's Hawk-Dove-Bourgeois game (Maynard Smith 1982), modified to take account of both the possible contestation of possession (Bowles 2004) and ethnographic evidence on the role of peer punishment in sustaining social order in small-scale societies (Mahdi 1986; Boehm 2000; Wiessner 2005). In his model, where possession is unambiguous and hence is not contested, a convention of mutual respect for the private ownership of an individual's wealth (which Maynard Smith called the "Bourgeois" strategy) is evolutionarily stable; that is, a "Bourgeois population" is not invadable by Hawk or Dove mutant strategies. Private property widely adopted, then, could eliminate costly contestation among group members (Sugden 1986, 1989), raising the individual payoffs associated with farming, as a result of the fact that the possession and defense of farming wealth are more readily established than is the case for foraging wealth.

But if possession is sufficiently contestable, either mistakenly or intentionally, the Bourgeois strategy is not evolutionarily stable (Bowles 2004). 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, namely, the critical-mass problem and the synergy of farming and private property, are the basis of our answer to our first question, providing a reason why the two distinct equilibria could exist.[3]

[2] An often-noted empirical weakness of the stochastic evolutionary modeling approach is that unless groups are very small and non–best-response play frequent, the expected waiting time for a transition is extraordinarily long. But this characteristic of stochastic evolutionary game theory is a strength, not a shortcoming, in this case: the extremely unlikely nature of transitions entailed by the model is closely matched by the extraordinary rareness of the independent emergence of food production.

[3] We could model many more than two such technology-institutions equilibria, distinguished by the nature of the property rights (their domain of application and the ownership units [group territoriality vs. nuclear-family or even individual ownership], for example), the extent of rights of exclusion or alienation (inheritance, rent, lend, use), and the characteristics of the species from which food was produced (difficult-to-store tubers, cereals with a long shelf life, slow-maturing tree crops and large animals, for example). Ethnographies

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 in principle and very rare in fact. This, then, brings up the second question, namely, how a transition from the foraging equilibrium to the farming equilibrium might have occurred.

By introducing idiosyncratic (non–best-response) play in Section VI, we are able to explore the processes that could generate rare transitions from a state with weak or nonexistent private-property rights and the exploitation of wild species (the hunter-gatherer technology-institutional equilibrium) to a state with private property and farming. We then show (in Sec. VII) that this process could have taken place in the absence of a productivity advantage for farming. This provides the basis of our proposed contribution to the explanation of the Neolithic agricultural revolution.

To summarize briefly, the reduction of climatic volatility approximately 11,700 years ago moderated the pressure for mobility and allowed a more sedentary livelihood. This, in turn, provided conditions for more populations to adopt a private-property regime (defensible wealth such as territory, stores, and dwellings) before farming. This could have occurred among groups of sedentary hunter-gatherers occupying sites with highly productive, concentrated resources that could be delimited and defended.

If some of these sites were suitable for food production, the emergence of farming would then have been possible once climate change made this a feasible option. This could occur if the private-property-with-farming package reduced the likelihood of costly conflicts among members of a group. 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 which result in the eventual take-up of farming. In Section VII, we use archaeological data to illustrate each.

In the penultimate section, we ask whether our model gives a plausible account of the Neolithic agricultural revolution. We consider caveats and introduce alternative (possibly rival or complementary) accounts. 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 archaeological literature (especially recently) on cultural and institutional preconditions for farming (Bender 1978; Hodder 1990; Cauvin 2000; Bettinger, Richerson,

record a rich variety along these dimensions (e.g., Fürer-Haimendorf 1967; Goldstein and Udry 2008). But the Neolithic agricultural revolution was a shift in both technology and institutions sufficiently dramatic and rapid (on archeological timescales) to motivate our study of a single transition, rather than a series of stepping-stone movements.

and Boyd 2009; Kuijt and Finlayson 2009; Watkins 2010; Smith 2012; Willcox and Stordeur 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 preceded and facilitated the subsequent emergence of farming.

III. Empirical Doubts about Standard Explanations

Three pieces of evidence to be reviewed below are the basis of our conclusion that it is unlikely that farming emerged as a way to improve or sustain livelihoods under adverse climatic conditions or increasing population. We then introduce three additional empirical observations that have guided us in providing a more adequate model.

A. *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 coauthors have documented the Neolithic Demographic Transition from a roughly stationary population of foragers to a slowly growing population of farmers. They show that the first farming, in the Levant, followed almost 8 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 (Bocquet-Appel 2002; Bocquet-Appel and Naji 2006; Guerrero, Naji, and Bocquet-Appel 2008). 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; Cauvin 2000).

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. The Neolithic Demographic Transition appears to have been a consequence, not a cause, of the Neolithic agricultural revolution, made possible by the shorter birth spacing that sedentism allowed (Lambert 2009; Bocquet-Appel 2009).

B. *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 period of climatic adversity called the Younger Dryas

(12,900–11,700 years BP, meaning before 1950; Bar-Yosef and Meadow 1995), an interpretation favored by the view that farming had raised productivity.

But recent improved dating of both temperature and growing conditions, on the one hand, and, on the other, the first independent cultivation of domesticated species appears to be 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, as is evident in figure 1, it predated the advent of the cultivation of domesticated species even at the earliest sites. The top panel indicates an increase in temperature and reduction in its interannual volatility, which favored both sedentary living and farming. The remaining panels provide measures of conditions favorable for plant growth.[4]

The dates for the advent of farming refer to domestication, which can be dated more precisely than cultivation of wild crops, which may have predated domestication by a matter of centuries. Thus, the possibility that farming (meaning cultivation) began at the very end of the Younger Dryas in Southwest Asia cannot be entirely excluded. But this does not seem likely in light of the most recent evidence;[5] and as can be seen from the figure, farming emerged at the other sites long after the climate amelioration. It seems clear that the independent emergence of farming occurred virtually everywhere under climatic conditions increasingly favorable to both plant growth and sedentism, not during the adverse Younger Dryas.

C. *Recent Evidence Does Not Support the Hypothesis That Farming Was More Productive*

The fact that in many parts of the world stature and health status declined with the introduction of cultivation (Cohen and Crane-Kramer 2007) does not provide evidence on labor productivity per se, as this could reflect the health vulnerabilities experienced by people living in close proximity with large numbers of (human and nonhuman) animals.

However, physical measures of productivity—energetic output per hour of labor (including processing)—can be computed for a few ethnographic forager populations and for some cultivars farmed under conditions and

[4] The substantial reduction in interannual variation in temperature at the end of the Pleistocene shown in fig. 1 reduced the pressure for mobility that had constituted an obstacle to the investments in dwellings, stores, and land improvements associated with farming. Matranga (2019) 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.

[5] A critical date in this respect is the initiation of cultivation at Abu Hureyra, thought to be one of the first farming communities. A recent reassessment of the evidence (Colledge and Conolly 2010) has cast doubt on earlier conjectures that this had occurred at the end of the Younger Dryas (Moore et al. 2000).

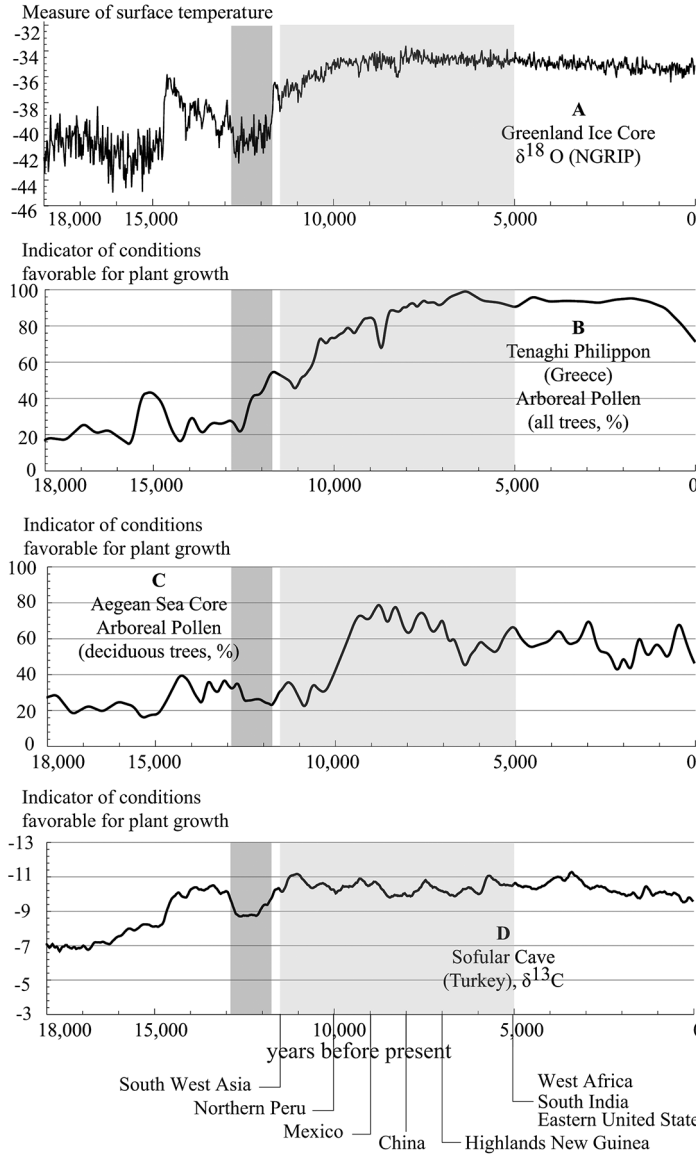

FIG. 1.—Holocene climate amelioration and the advent of farming. The dark shading refers to the Younger Dryas, the end of which marks the advent of the Holocene geological epoch; the light shading refers to the period of the independent emergence of farming, the dates of which are indicated below the time axis. These data are sourced and more fully explained and documented in Section A.1 of the appendix, available online. The farming dates are first domestications from Price and Bar-Yosef (2011b), except that for India (Karnataka), which is from Fuller (2006). NGRIP: North Greenland Ice Core Project.

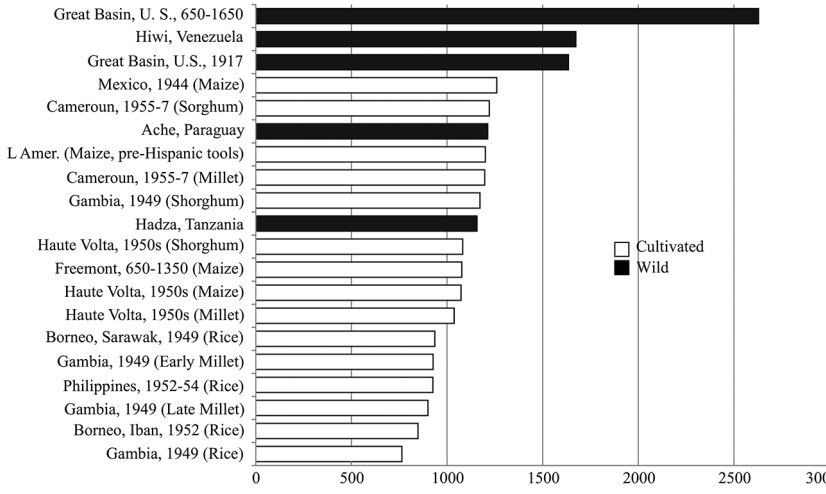

Fig. 2.—Net kilocalories per hour of direct and indirect labor: wild and cultivated species. Excluded are return rates for wild species in cases where atypically rich resource concentrations were encountered, where vehicles or firearms were used, or where data were available for one sex only or for a limited span of time. Cultivated data are for cereals only because of the lack of the comparable data on noncereal cultivars of the first farmers (such as avocado, bottle gourd, and squash). L. Amer.: Latin America. Source: Bowles (2011).

technologies that appear to have characterized the first farming (absence of animal traction being a critical distinction; Bogaard et al. 2018). Using data for 15 cultivars similar to the first cultivated crops and five hunting and gathering populations, Bowles (2011) found that the mean caloric return per hour of labor for the cultivars is 63 percent of the mean for wild species.[6] The data are shown in figure 2.

To what extent are these data indicative of conditions in the late Pleistocene and early Holocene? Given the paucity of relevant data, a definitive answer is beyond our reach.[7]

But we are reasonably confident that, while the evidence is indirect, the lack of a productivity advantage of farming apparent in figure 2 is not a

[6] 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 limited 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. The data in fig. 2 abstract from these risk and time delay considerations. All of the farmer-forager differences in means—the two just mentioned and that in the figure—are statistically significant at conventional levels.

[7] We explore the question in detail in Sec. A.4 of the appendix, available online.

statistical artifact. Our estimates of the productivity of farming do not come from marginalized groups or localities but instead are typical of their regions. By contrast, the hunter-gather productivity estimates come from populations that had been militarily and demographically encroached upon and displaced. As a result, in the historical period on which our ethnographic evidence is based, hunter-gatherers occupied what are, for the most part, unwanted environments. Some of these environments included remote but rich migratory routes of fish and ungulates, but none of our hunter-gatherer estimates in figure 2 come from these unusually rich places. Moreover, as figure 1 suggests, it is unlikely that temperature and conditions for plant growth were more favorable to farming in southwestern Asia at the time of the first farming there than in the past century, which is the source of our ethnographic estimates.

The closest to direct evidence is based on the following. To replicate early Holocene conditions, using a flint sickle Jack Harlan, a botanist, harvested wild einkorn, a species that was exploited opportunistically by foragers in Anatolia before it was cultivated and eventually domesticated (Harlan 1967). He later commented,

> The Biblical view of agriculture as a curse has support from these studies. . . . [I]f we are to understand the origins of agriculture, we must visualize situations in which man is willing to expend more energy to obtain food. . . . [F]arming is not so attractive that gatherers are likely to take it up on sight or first contact. Some rather compelling reasons would seem to be required. (Harlan 1992, 42)

Because it seems likely that it was for the most part sedentary hunter-gatherers who took up farming, the sites at which this took place—Abu Hureyra in southwestern Asia, for example—were likely to have been selected for their richness in wild resources, not their suitability for farming. This contributes to our thinking that the data in figure 2 (which are not from unusually rich hunter-gather sites) are difficult to reconcile with the view that farming was more productive where it was first introduced.

A key empirical motivation of our model is thus the lack of convincing evidence that farming was initially more productive. A second motivation is that there is little doubt that, from the outset, farming vastly increased the productivity of land and animals. Unlike wild resources, the domesticated resources fundamental to the livelihood of farmers were sufficiently valuable and limited spatially to make private ownership technically feasible.

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

The contrasting effects of the introduction of farming on labor productivity and land productivity pose a puzzle. Land was abundant relative to labor through the early Holocene[8] and, measured in "efficiency units," almost certainly was increasing in supply after the end of the Younger Dryas, because of the improvement in conditions for plant growth. At the same time, population appears to have been declining, or at least not increasing, in the places that adopted farming. These are conditions under which livelihoods were most likely to be limited primarily by labor inputs and in which, therefore, labor productivity is the appropriate measure of the benefits of adopting one technology over another.

Thus, it is difficult to explain why people would adopt a land-saving technology (namely, farming) that did not raise labor productivity, except if it had some other advantages. These, our model shows, could have arisen because once a private-property regime was established, as occurred among some sedentary hunter-gatherer communities, taking up farming facilitated the possession and defense of one's privately held wealth.

Three additional pieces of information suggest directions for a plausible alternative explanation.

D. Small-Scale Economies Are Bimodally Distributed between Foraging and Farming

The data on calories per hour of labor just cited refer, necessarily, to average, not marginal, labor productivity. But even taking at face value the higher average productivity of labor in foraging (shown in fig. 2), this does not imply that a modest amount of farming would not be advantageous. It is likely that in some locations, for example, the marginal productivity of a limited amount of time devoted to farming (on the best or nearest land, for example) would have been considerably higher than that of hunting or gathering the lowest-ranked wild species.[9]

[8] There were perhaps 5 million humans on the entire planet at the end of the Pleistocene (Klein Goldewijk et al. 2017) and an estimated 28,800 (95 percent confidence interval: 1,300–72,600) in Europe (Bocquet-Appel et al. 2005).

[9] For example, the lowest-ranked wild species taken in the Great Basin data in figure 2 yielded considerably fewer calories per hour of labor than the mean of the data on cultivated species in that figure (Simms 1987).

If this were the case, 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 broadly across most populations under the more farming-favorable climate of the Holocene or the 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 sustained evidence of farming earlier than 11,500 years before the present.

Another piece of evidence also tells against the standard account. Data on 870 small-scale societies collected by ethnographers, for the most part around the middle of the past century (fig. 3), display a strikingly bimodal distribution along the forager-to-farmer continuum, measured by percentage of food produced by cultivation and herding. As can be seen, almost half of the societies are at the extremes of the distribution, that is, either foragers with 15 percent or less of food derived from farming (23.1 percent of all populations) or 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.

E. Even under Farming-Friendly Early Holocene Climate Conditions, Foraging Persisted, Even in Many Locations Well Suited for Food Production

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 eighteenth 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, 85)

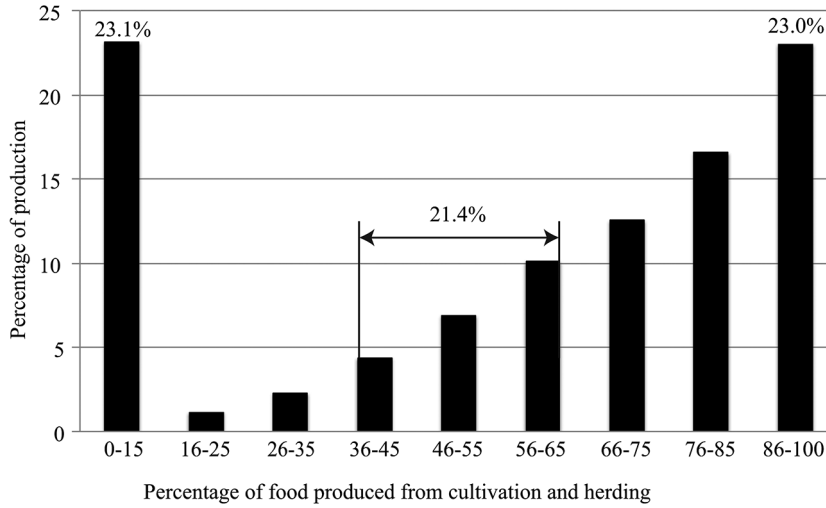

FIG. 3.—Distribution of 870 small-scale societies (309 New World and 561 Old World) by source of livelihood: food production or hunting and gathering. Source: Bellwood (2005).

Cook was right to be puzzled. Figure 4 shows that areas of Australia populated by hunter-gatherers at the time of his visit are well suited for the cultivation of four crops that elsewhere played a major role in the Neolithic agricultural revolution, including in nearby Papua-New Guinea as early as 7,000 years ago. 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. Long before European contact, Australians borrowed extensively (including technologies) from farmers in the region, and a good number of plants that were cultivated in Melanesia were exploited wild by Australians (Peterson 1976, 1993; Chase 1989; 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, namely, private property. As in Australia, in other areas of the world—parts of California and the Western Cape of South Africa, for example—that were suitable for farming, hunter-gatherers living on prime farmland persisted until European contact less than half a millennium ago (Kroeber [1925] 1953; Sadr 1998; Smith 2007; Bettinger 2015).

F. It Appears Unlikely That Farming Was Imposed by Centralized Elite Authority

An explanation of the advent of farming consistent with the data introduced up to this point is the proposal by Acemoglu and Robinson (2009,

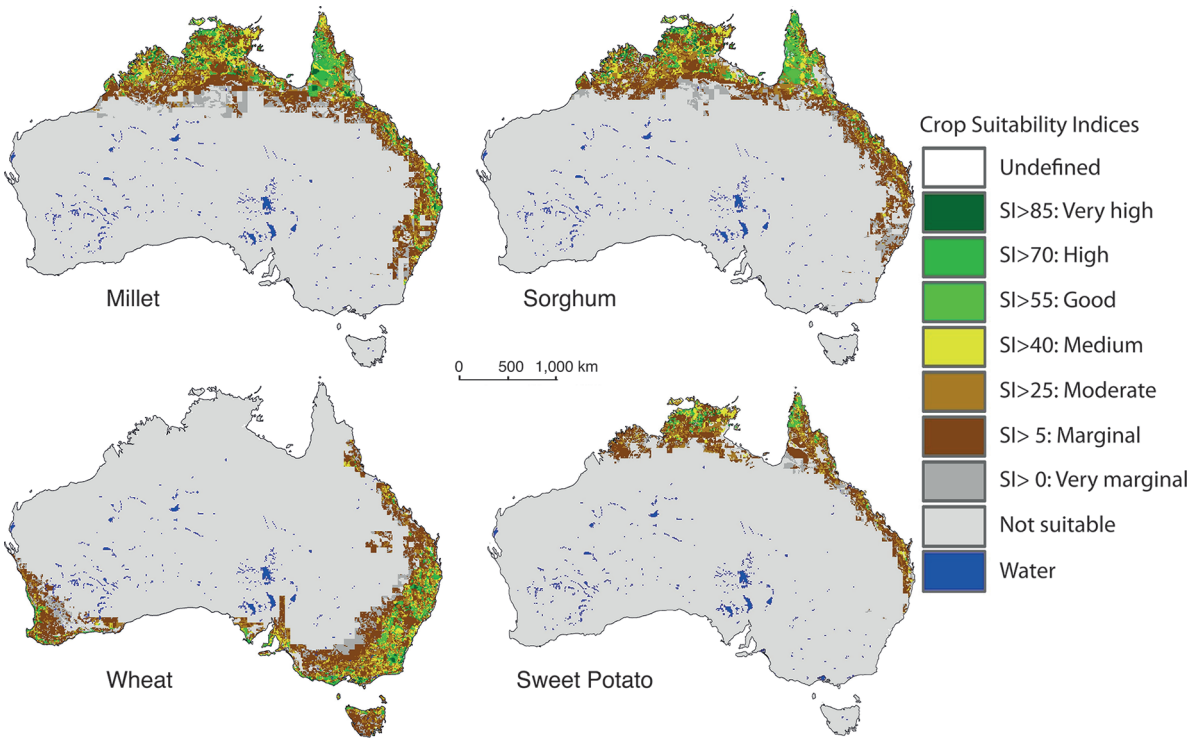

FIG. 4.—Areas suitable for rain-fed cultivation in Australia. What are thought to be the locations of the greatest concentration of hunter-gatherers before European contact include substantial areas of rich farmland, including what is now termed the wheat belt and the northern and eastern coastal regions suitable for yam and sweet potato (the latter of which came much later). The Food and Agriculture Organization's Global Agro-Ecological Zones (GAEZ) 2002 database is available from http://www.iiasa.ac.at/Research/LUC/SAEZ. SI: suitability index. Source: Fischer et al. (2002).

2012) 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. And, if true, it could resolve a puzzle posed by the leading archaeologists of one of the first farming sites, Abu Hureyra: "No hunter-gatherer occupying a productive locality with a range of wild foods able to provide for all seasons are likely to have started cultivating their caloric staples willingly. Energy investment per unit of energy return would have been too high" (Moore et al. 2000, 393).

There is ample evidence from more recent epochs that to facilitate tax collection, states have sought to enforce both sedentism and the production of easy-to-expropriate-and-store cereals on erstwhile mobile or root-crop-growing populations (Scott 2009). There is also evidence from ethnographic hunter-gatherers, as well as archaeological data, 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 Neolithic package of sedentism, farming, and private property.

But it seems quite unlikely, on the basis of current archaeological evidence, that any of the forms of political differentiation among group members that might have been extant at the time of the first farmers—"big-men" systems or chiefdoms, for example—could have included a centralized authority sufficiently powerful to enforce sedentism on a heavily armed, mobile population from whom surpluses would then be extracted.[10] Without exception, the independent adoptions of farming long predate the first states, as we show in table 1.

The monumental constructions at Göbekli Tepe in Anatolia have been taken as evidence of a political elite that might have imposed sedentism and farming (Acemoglu and Robinson 2009, relying on Bender 1978), but two facts based on recent work on the site speak against this interpretation. First, according to Ofer Bar-Yosef, one of the leading archaeologists of the area, farming predates the Göbekli Tepe constructions by at least half a millennium (Bar-Yosef 2014, 162). Second, even accepting the now widely disputed claim that the constructions were evidence of an extractive political elite, the kind of structures found at Göbekli Tepe are, according to Bar-Yosef, unique for the area and time. He interprets "Göbekli Tepe society as a trial with a novel social structure . . . within one specific farming community," concluding, "The disappearance of this group, possibly due

[10] We survey the evidence on political structures and economic inequality before the advent of farming in southwestern Asia in Bowles (2015a).

TABLE 1
REGIONS AND DATES OF EARLY DOMESTICATIONS AND EARLY STATES OR PROTOSTATES

Region (Contemporary Geographic Designations)	First Domestications, years BP (Crop)	First State, years BP (Earliest State or Protostate in Region)
Southwest Asia	11,500 (einkorn, emmer, barley)	5,500 (Late Uruk)
China	8,000 (millet, rice)	4,100 (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 (Australian) colonization
West Africa (Sahel)	5,000 (sorghum; animals at 9,000)	1,500 (Ghana, Dhar Tichitt)
South India (Karnataka)	5,000 (millet)	3,200 (elite burials)
Eastern United States	5,000 (pepo squash, sunflower)	European colonization

NOTE.—Years BP: years before the present (1950). Except as noted below, the approximate dates of the first named states are from Trigger (2003, 32), with the defining characteristic that "central governments possessed ultimate control over justice and the use of force" (47). The first domestications, except that for Karnataka, are from Price and Bar-Yosef (2011b; cultivation probably predated domestication by many centuries). Dates for Ghana are from Holl (1985) and Munson (1980). Evidence for India from Fuller (2006) is at best suggestive of the presence of a state. Evidence on Dhar Tichitt is also not entirely clear.

to intra-societal conflict, is an example of the failure of a new kind of social organization" (158). And "A similar investment in human energy in constructing public buildings did not occur again in this region for several millennia until the emergence of Mesopotamian civilization" (165).

The large and apparently nonresidential buildings at Mureybet (in modern-day Syria) and other early Neolithic sites are now believed by archaeologists to have been used for communal meetings and rituals (Bar-Yosef and Meadow 1995; Stordeur et al. 2000; Cauvin and Estévez 2008; Flannery and Marcus 2012). Flannery and Marcus refer to them as "men's houses" (138) or "ritual houses" (136), not dwellings of members of a political elite, analogizing them to the kivas of the Pueblo sites in the southwestern United States.

One of the best-studied cases of the Neolithic agricultural revolution is 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, 495, 505). These substantial sedentary communities "could be formed and maintained without social hierarchies of power" as the archeologist Trevor Watkins (2010, 632) put it, describing the Neolithic revolution throughout the Levant. "[A]scribed status, social hierarchies and inequalities of power" would later follow but did not precede the advent of farming and private property, according to Watkins (632). The modest levels of wealth inequality (measured by the distribution of grave goods, dwelling size, and storage) among early farmers in southwestern Asia and

Europe before the formation of states are consistent with this view (Kohler et al. 2017; Bogaard, Fochesato, and Bowles 2019; Fochesato, Bogaard, and Bowles 2019).

IV. The Evolutionary Dynamics of Possession-Based Property

Because our model is designed to explain a rare event, the independent emergence of farming, the propositions that we prove do not concern the parameter values under which a unique and globally stable farming equilibrium would emerge, so that a transition away from the forager equilibrium would occur with certainty. Rather, motivated by archaeological and ethnographic evidence, we study conditions under which equilibria with and without farming exist and then characterize the conditions affecting the probability of a decentralized transition from a "forager" to a "farmer" equilibrium.

We model a population in which each individual produces an output, using one of two technologies (farming or foraging), and interacts with another individual to determine the distribution of their products based on one of two rules (equal division or possession-based private property, the latter meaning that each individual retains the product they produced). In this section, we introduce the Civic-Bourgeois game to model the distribution of products and to study the conditions under which a property-respecting strategy can evolve. In Section V, we extend the model to incorporate individuals' technology choice and show how, in a status quo where sharing rather than possession is the norm, the synergy between farming and private property and the critical-mass bottleneck for institutional innovation can be impediments to a transition to a farming-with-private-property outcome. In Section VI, we model the transition process.

A. *The Civic-Bourgeois Game and the Evolution of Private Property Rights*

Consider a population where each individual is randomly paired with another group member. The individuals produce a good (in a manner to be considered in Sec. V) and then play two simultaneous games, each of which determines the distribution between the two players of the product that each has acquired.

1. Strategies

Individuals use one of two strategies (Civic and Bourgeois) that conditionally use actions Hawk (H) and Dove (D), where, as in the standard

Hawk-Dove game, Doves divide the good equally and Hawks take the good from Doves and engage in a costly fight over the good when paired with another Hawk. For each game, the action space ($A = A_1 \times A_2$) and the payoff function of actions for each player ($\pi : A \rightarrow R$) are defined as in the standard game: $\pi(\mathrm{H}, \mathrm{H}) = (v - c)/2$, $\pi(\mathrm{H}, \mathrm{D}) = v$, $\pi(\mathrm{D}, \mathrm{H}) = 0$, and $\pi(\mathrm{D}, \mathrm{D}) = v/2$, where v is the value of the product in question (when we introduce the choice of technology, we distinguish between agriculture [v_a] and foraging [v_f]); c is the cost to the individual if H loses a contest over the distribution of the good, occurring with probability 1/2 should a contest take place; and $v < c$.

The two strategies 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 bears a stigma if in the past he has refused to share with others. In this case Civics play H; they play D otherwise. Civics themselves are not stigmatized for playing H because it is public information that their playing H is a social sanction on someone who has refused to share.[11]

A Bourgeois conditions his action on possession of the good, that is, whether the good 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 of his possession and fights to defend it if challenged. If the good was acquired by the other, Bourgeois plays D unless possession is contested. 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 Hawk in Maynard Smith's standard game, and if $\mu = 0$, a Bourgeois will play H only if it was he who acquired the product to be distributed and will play D otherwise.

2. Payoffs

Let $r(X, Y|\mu)$ represent the expected payoffs for the individual who plays strategy X in an interaction with another playing Y (where $X, Y \in \{\mathrm{C}, \mathrm{B}\}$), conditional on the value of μ. (We use C and B, respectively, to indicate the Civic and Bourgeois strategies.) In equations (1), we write $r(X, Y|\mu)$ in two parts: the individual's payoff from the subgame over his own product in the first square bracket and the individual's payoff from the subgame over his opponent's product in the second square bracket. Then the payoffs from the Civic-Bourgeois game are

[11] 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 (Mahdi 1986; Boehm 2000; Wiessner 2005) and that we have modeled it elsewhere (Boyd et al. 2010), little would be gained by repeating the exercise here.

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

$$r(\mathrm{C}, \mathrm{B}|\mu) = [(1 - \mu)\pi(\mathrm{H}, \mathrm{D}) + \mu\pi(\mathrm{H}, \mathrm{H})] + [\pi(\mathrm{H}, \mathrm{H})], \tag{1b}$$

$$r(\mathrm{B}, \mathrm{C}|\mu) = [\pi(\mathrm{H}, \mathrm{H})] + [(1 - \mu)\pi(\mathrm{D}, \mathrm{H}) + \mu\pi(\mathrm{H}, \mathrm{H})], \tag{1c}$$

$$\begin{aligned} r(\mathrm{B}, \mathrm{B}|\mu) = {} & [(1 - \mu)\pi(\mathrm{H}, \mathrm{D}) + \mu\pi(\mathrm{H}, \mathrm{H})] \\ & + [(1 - \mu)\pi(\mathrm{D}, \mathrm{H}) + \mu\pi(\mathrm{H}, \mathrm{H})]. \end{aligned} \tag{1d}$$

B. *Updating Strategies and Dynamics*

Equations (1) allow us to characterize the deterministic dynamics (i.e., in the absence of idiosyncratic play) of the population share of the individuals with the Civic or the Bourgeois strategy. We consider a finite population (sufficiently large to ignore integer problems) in which each player periodically has an opportunity to update his or her strategy, best responding to the distribution of strategies in the previous period, resulting in a payoff monotonic dynamic.

Define the population fractions of Bourgeois and Civics in a group as β and $1 - \beta$, respectively. From equations (1), the expected payoffs to Civic and Bourgeois can be written as

$$E[r(\mathrm{C}|\beta, \mu)] = (1 - \beta)r(\mathrm{C}, \mathrm{C}|\mu) + \beta r(\mathrm{C}, \mathrm{B}|\mu), \tag{2a}$$

$$E[r(\mathrm{B}|\beta, \mu)] = (1 - \beta)r(\mathrm{B}, \mathrm{C}|\mu) + \beta r(\mathrm{B}, \mathrm{B}|\mu). \tag{2b}$$

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

$$\begin{aligned} \Delta^{\mathrm{B}}(\beta, \mu) &\equiv E[r(\mathrm{B}|\beta, \mu)] - E[r(\mathrm{C}|\beta, \mu)] \\ &= -\frac{1}{2}[v(1 - \mu) + c(1 + \mu)] + \beta c. \end{aligned} \tag{3}$$

According to the payoff-monotonic best-response learning process, β increases if $\Delta^{\mathrm{B}}(\beta, \mu) > 0$ in the previous period and decreases if the inequality is reversed. Equation (3) confirms that as long as $\mu < 1$, there exists $\beta_{\mathrm{B}}^{*} = [(v + c)(1 - \mu) + 2c\mu]/2c$ in (0, 1), such that under a deterministic payoff-monotonic updating process, β increases if $\beta > \beta_{\mathrm{B}}^{*}$ and decreases if $\beta < \beta_{\mathrm{B}}^{*}$, where $\beta = 0$ and $\beta = 1$ are evolutionarily stable states representing, respectively, a norm-based sharing economy and a possession-based private-property economy. Equation (3) demonstrates the "critical-mass" complementarity, namely, that the payoff to Bourgeois is increasing in the fraction Bourgeois (i.e., $\partial\Delta^{\mathrm{B}}(\beta, \mu)/\partial\beta = c > 0$).

V. Technology Choice between Foraging and Farming

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

Upon choosing a technology, an individual is either a forager or a farmer and, as a result, acquires v_f or v_a^g, respectively, irrespective of behavioral strategy. 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 $v_a \equiv v_a^g - z = (\rho - 1)z$, where $\rho - 1$ is the rate of return to the farmer's investment.

For concreteness, but without loss of generality, we suppose that the farmer uses a single product production process with inputs of labor and an amount z of the previous period's output (as seeds, for example). 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.[12]

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.

A. *Conditions for a Transition to Farming*

We now identify the empirically motivated condition 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 of the switch. The first, which, as we have shown above, appears unlikely, 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 that farming improves net output per unit of labor.

[12] 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.

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 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 $\beta > 0$, being a farmer also reduces the likelihood that one 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 it had a productivity disadvantage, we assume

$$v_a - v_f < 0, \qquad \text{(assumption 1)}$$

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:

$$\begin{aligned}\Delta^a(\beta, \mu_a, \mu_f, v_a^g, v_f) &= \frac{1}{2}[(v_a^g - z) - v_f] - \frac{1}{2}z \\ &\quad + \frac{1}{2}\beta[(v_a^g - v_f) + \mu_f(v_f + c) - \mu_a(v_a^g + c)].\end{aligned} \tag{4}$$

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. In this dynamic, a transition to and subsequent persistence of farming is possible if and only if there exists some $\beta_a^* < 1$.

Proposition 1 shows that whether this occurs 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 1 (Payoff advantage of farmers). Given assumption 1, there exists

$$\begin{aligned}\beta_a^* &= -\frac{[(v_a^g - z) - v_f] - z}{(v_a^g - v_f) + \mu_f(v_f + c) - \mu_a(v_a^g + c)} \\ &= -\frac{v_a - v_f - z}{v_a - v_f + z + \mu_f(v_f + c) - \mu_a(v_a + z + c)}\end{aligned}$$

in (0, 1), if and only if

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

Proof. See Section A.2 of the appendix.

Proposition 1 gives conditions under which an evolutionarily stable farming equilibrium will exist: the stake that farmers may lose in a contest (because of the investment cost z) must be more than offset by the lesser probability that farmed (rather than foraged) produce will be contested ($\mu_a < \mu_f$).

Figure 5 presents alternative versions of equation (4). The top line represents the standard view that farming was introduced and proliferated because of its productivity advantages even in the absence of private property. But as can be seen in the figure, this route to the Neolithic agricultural revolution would have required a farming productivity advantage over foraging exceeding the investment cost of farming (namely, $v_a - v_f > z$) in order to allow farming to be adopted de novo without private-property rights.

We have labeled this line "Later Holocene" because it may be an accurate representation of the situation well into the Neolithic agricultural revolution in those areas where the labor productivity of farming had substantially increased (because of the use of ox teams for plowing, for example, or the biological improvements in cultivated species). The empirically relevant case for the initial emergence of farming is the bottom line in the figure, where assumption 1 and proposition 1 hold.

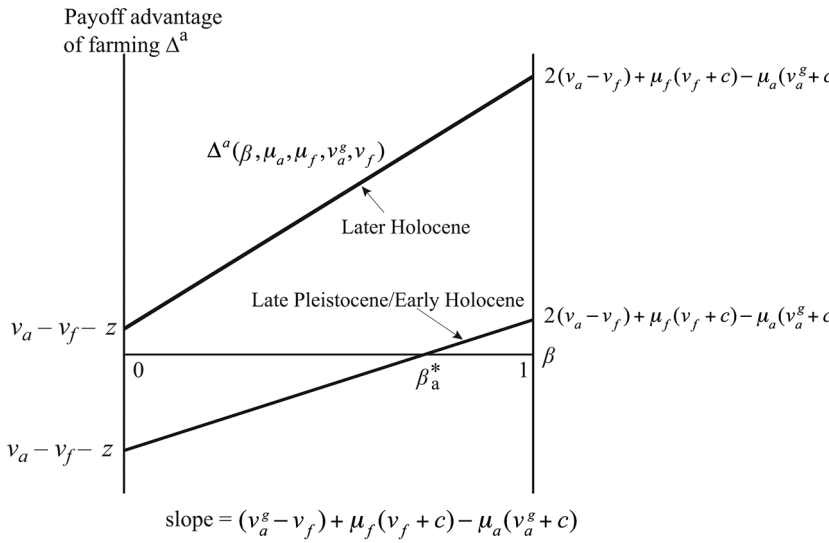

FIG. 5.—Why institutional innovation was a precondition for the Neolithic agricultural revolution.

To explore this critical trade-off 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 1 ensures the existence of some distribution of strategies in the population to which farming will be a (strict) best response. This requires that $\beta_a^* < 1$, so setting $\beta_a^* = 1$ and holding μ_f constant, we have the solid curve in figure 6, which separates the parameter space in which farming may evolve (below the line) from the space in which it may not (above the line) for a population in which all members of the population are Bourgeois and farming is as productive as foraging ($v_a = v_f$). The dashed line shows a similar locus but for farming less productive than foraging, that is, with $v_a < v_f$, as might have been the case under the highly volatile climatic conditions during the Pleistocene and even well into the Holocene.

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

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

which is satisfied if proposition 1 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 was 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 $\mu_a < 1$ (i.e., holding v_a

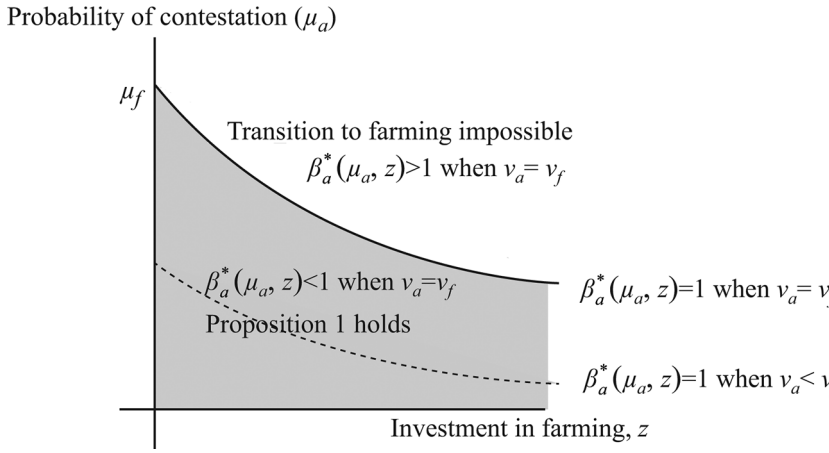

FIG. 6.—Contestability, farming investment, and the possibility of a transition to farming when farming and foraging are equally productive. (The dashed line indicates the effect of a lesser level of farming productivity, $v_a < v_f$).

TABLE 2
STRATEGIC COMPLEMENTARITIES IMPEDING THE NEOLITHIC AGRICULTURAL REVOLUTION

Complementarity	Economics	Result
Bourgeois strategies are strategic complements	Payoff advantage of Bourgeois increasing in β	From eq. (3): $\partial\Delta^{B}(\beta, \mu)/\partial\beta > 0$
Farming and Bourgeois are strategic complements, I	Payoff advantage of Farming increasing in β	If proposition 1 holds: $\partial\Delta^{a}(\beta, \mu_a, \mu_f, v_a^g, v_f)/\partial\beta > 0$
Farming and Bourgeois are strategic complements, II	Payoff advantage of Bourgeois decreasing in μ	From eq (3): $\partial\Delta^{B}(\beta, \mu)/\partial\mu < 0$

constant, $\partial(\partial\Delta^{a}/\partial\beta)/\partial z = 1 - \mu_a$). 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.

B. *Strategic Complementarity between Farming and the Bourgeois Strategy*

Proposition 1 addresses the complementarity between private property and farming that arises because a greater fraction of Bourgeois increases the payoff advantage to farming, ensuring that a transition to a durable farming state is technically feasible. The dual of this complementarity is that the payoff advantage of being a Bourgeois increases as farming is more prevalent (i.e., $\partial\Delta^{B}(\beta, \mu)/\partial\mu = v - c < 0$), which is true because of the lesser likelihood of possession ambiguity over the products of farming (i.e., $\mu_a < \mu_f$). Table 2 summarizes the relevant complementarities.

Proposition 1 thus explains why farming could be adopted despite its productivity disadvantage, as long as the effects of the offsetting reduction in conflict associated with adopting farming were sufficiently great. Because this offsetting conflict-reduction effect is present only in interactions of farmers and bourgeois members of the population, proposition 1 makes clear why the advent of farming (even were it to have lacked a productivity advantage) required the widespread adoption of a new set of property rights.

VI. The Emergence of Farming-Favorable Institutions

The final step of our explanation, then, is to characterize the conditions under which (before farming) the adoption of private-property rights could become sufficiently common not only to sustain farming as a payoff-advantageous technology (given by β_a^* in proposition 1) but also to sustain itself (given by β_B^* in eq. [3]).

To do this, we modify the updating stage of the game, so that rather than best-responding with certainty, individuals are now boundedly rational: they 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 before 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 and also decreasing in ϕ, the (finite) degree of rationality of the agent, which is common to all members of the population. Deviating from the best response in this case means playing Bourgeois instead of Civic, so the deviation cost is just $-\Delta^{\mathrm{B}}(\beta, \mu)$. Thus, we have the probability that the individual responds idiosyncratically:

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

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 $n\beta_{\mathrm{B}}^{*}$, that is, the lowest 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 $\beta = 0$ that fall short of $n\beta_{\mathrm{B}}^{*}$ are returned in the next period almost certainly to neighborhood of $\beta = 0$.

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 $n\beta_{\mathrm{B}}^{*}$. This is a process where "an equilibrium is upset by large 'jumps' (from the equilibrium to the basin of attraction of the other equilibrium)," as in Kandori, Mailath, and Rob (1993, 52) or where a "single burst of mutations" is considered, as in Binmore et al. (2003, 309).

Let $n_{\mathrm{B},t}$ 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 $S = \{0, 1, 2, \cdots, n\}$. Then, following Kandori et al. (1993, lemma 2), we have the probability that in any period in the all-Civics state, n_{B}^{*} or more individuals idiosyncratically adopt the Bourgeois strategy:

$$\Pr\left(n_{\mathrm{B},t+1} \geq n_{\mathrm{B}}^{*} \middle| n_{\mathrm{B},t} = 0, \mu, n\right) = \sum_{n_{\mathrm{B}}=n_{\mathrm{B}}^{*}}^{n} \binom{n}{n_{\mathrm{B}}} \psi(\Delta^{\mathrm{B}}(\beta = 0, \mu), \phi)^{n_{\mathrm{B}}} (1 - \psi(\Delta^{\mathrm{B}}(\beta = 0, \mu), \phi))^{n-n_{\mathrm{B}}}. \tag{6}$$

Recall that our proposed resolution of the puzzle of the independent emergence of farming is that the reduction in interannual climate volatility at the end of the Pleistocene reduced pressures for forager mobility and allowed some groups to settle more or less permanently, acquiring high-value durable 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 equation (6) to determine the effect that a reduction in contestability (μ) would have on the probability of a transition to a private-property regime. In equation (6), 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, ψ. 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 we know that $\partial\Delta^{\mathrm{B}}(\beta = 0, \mu)/\partial\mu < 0$, so a reduction in μ lowers the cost of deviating from the best response and instead idiosyncratically playing Bourgeois. To show the second, we differentiate β_{B}^{*} (obtained from eq. [3]) with respect to μ and find that $\partial\beta_{\mathrm{B}}^{*}/\partial\mu > 0$. Since n_{B}^{*} is the smallest integer that exceeds $n\beta_{\mathrm{B}}^{*}$, n_{B}^{*} will be nondecreasing in μ. These two results give us the following proposition:

Proposition 2 (The transition of a private-property regime). A fall in the contestability of possession, μ, induces a greater per-period probability of a transition from an all-Civic-forager to an all-Bourgeois-forager population.

Proof. See Section A.3 of the appendix.

VII. The Neolithic Agricultural Revolution

We have just seen that the minimum fraction of Bourgeois required for the deterministic dynamic to carry the population to universal adoption of private property is increasing in μ and hence is lower in a farming economy than in a foraging economy, which we express as $\beta_{\mathrm{B}}^{*}(\mu_{\mathrm{a}}, v_{\mathrm{a}}) < \beta_{\mathrm{B}}^{*}(\mu_{\mathrm{f}}, v_{\mathrm{f}})$. Also recall that β_{a}^{*} is the threshold of β, such that when $\beta > \beta_{\mathrm{a}}^{*}$, the expected farming payoff exceeds the expected forager payoff, and as a consequence, in the absence of idiosyncratic play, the farming transition will occur.

Combining these results, we see that even without an initial productivity advantage, a transition to farming is possible under two scenarios—cases II (institutions first) and IV (coevolution, initiated by institutions)—that are summarized in figure 7. We postpone to Section VIII consideration

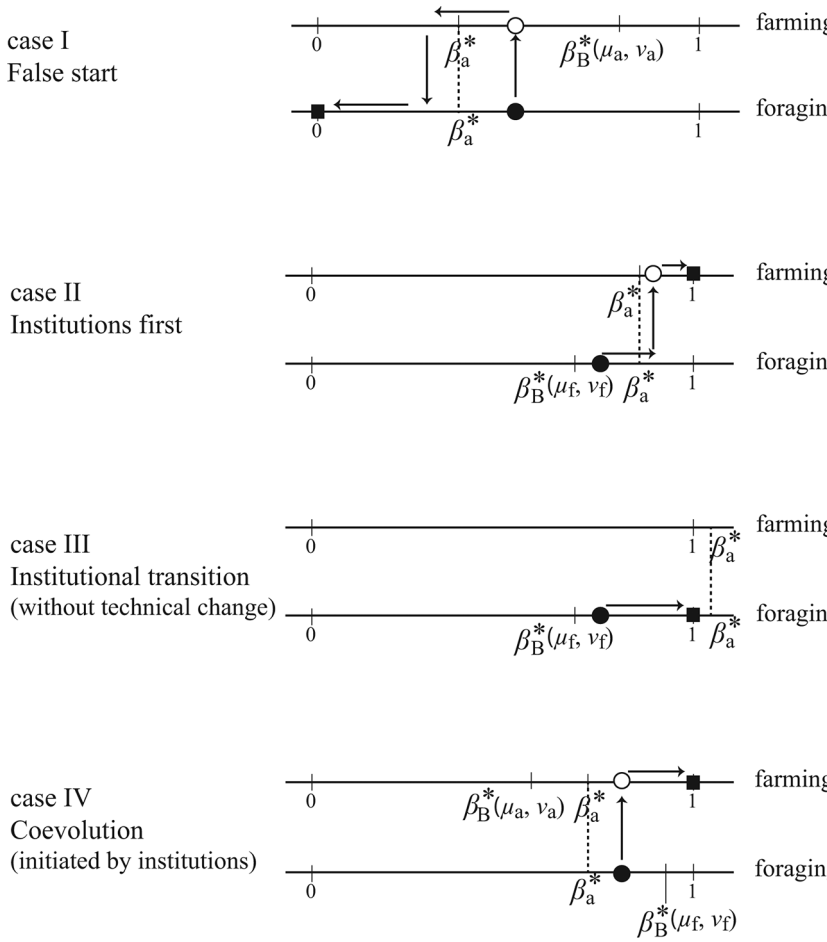

FIG. 7.—Technological and institutional transitions in the Neolithic revolution. β_a^* is the threshold value of Bourgeois required for adopting farming technology to be a best response; $\beta_B^*(\mu_f, v_f)$ and $\beta_B^*(\mu_a, v_a)$ are the threshold values of Bourgeois required for the transition to the private-property regime in a foraging economy and a farming economy, respectively. Filled circles indicate the realization of 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; squares indicate the end point of this transition process.

of the contrary possibility of a "technology-first" transition led by an initial productivity-enhancing technological change without a prior introduction of private property.

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

In this case, the level of idiosyncratic adoption of the Bourgeois strategy is sufficient to make farming initially a best response, that is, $\beta > \beta_a^*$; but

the reduction in μ resulting from the introduction of farming is insufficient to motivate adopting the Bourgeois strategy as a best response, that is, $\beta < \beta_{\mathrm{B}}^{*}(\mu_{\mathrm{a}}, v_{\mathrm{a}})$. As a result, the fraction Bourgeois declines deterministically, reaching a level below β_{a}^{*}, at which point those who recently took up farming in response to the chance occurrence of a sufficient number of Bourgeois in their population now best respond by a 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 protofarming briefly practiced by the Levantine Natufians during the brief warming around 15,000–13,000 years ago.[13] Another false start is the Ohalo II site, where 23,000 years ago, sedentary hunter-gatherers for a time cultivated wild cereal species, using stone harvesting and grinding tools. This group is unlikely to have been entirely unique (Whitlam et al. 2018), but they apparently abandoned their experiment with protofarming. The next 8 millennia of well-studied archaeological assemblages in the area contain nothing comparable.

The Batek people, foragers in Malaysia half a century ago, provide another illustration of case I (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 I illustrates a possible derailing of a transition according to the conventional account, in which farming is first introduced, providing the basis for the subsequent evolution of private property.

B. *Case II. Institutions First, Then Technology,* $\beta_{\mathrm{B}}^{*}(\mu_{\mathrm{f}}, v_{\mathrm{f}}) < \beta < \beta_{\mathrm{a}}^{*} < 1$

In case II, by contrast, the fraction Bourgeois exceeds β_{B}^{*}, so that private property proliferates in a hunting-gathering economy until $\beta = 1$; the conditions in proposition 1 (illustrated in fig. 6) also hold, ensuring that $\beta_{\mathrm{a}}^{*} < 1$, so farming is then adopted.

Illustrative of this case are the hunter-gatherers at Abu Hureyra (Moore et al. 2000), whom some have credited with being the first farmers. Sedentism made possible by proximity to a rich concentration of resources

[13] On Barbary sheep, see Barker (2006). Ofer Bar-Yosef refers to Natufians as "perhaps the earliest farmers" (Bar-Yosef 1998), while Unger-Hamilton (1989, 101) concludes that "the evidence appears to favour 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).

(including gazelle migrations) allowed the accumulation of valued objects (including dwellings), the possession of which would have been unambiguous, with access granted by permission and not by any collective right. These private-property rights may have provided a template that could be extended to crops and later to domesticated animals, facilitating a transition to food production.

This case is also 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. Examples include fishing communities such as the maritime hunter-gatherers of Huaca Prieta on the northern coast of Peru, who exploited the rich local fisheries using nets, floats, and other gear.[14] It seems likely that the fishing gear and stores were owned by individuals or families. Subsequently, intensely 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 Prieta 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 Thomas Dillehay, one of the foremost archaeologists of the period puts it, "fishing configured early farming" (personal communication).[15]

This, along with case IV, seems the most likely trajectory for the Neolithic agricultural revolution.

C. *Case III. Institutional Transitions, No Technical Change,* $\beta_{\mathrm{B}}^{*}(\mu_{\mathrm{f}}, v_{\mathrm{f}}) < \beta < 1 < \beta_{\mathrm{a}}^{*}$

This is identical to case II, but with $\beta_{\mathrm{a}}^{*} > 1$ (i.e., proposition 1 does not hold), so 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 before European contact. Property rights in stores, ocean-going boats, fishing gear, bead currency, and other essential economic goods were well established in precontact California, where farming was not introduced (Arnold 1993; Hayden 1997; Bettinger 2002, 2015). In the Baltic area, similarly to the Peruvian coast,

[14] This account is based on Dillehay et al. (2012), Moseley (2006), and a personal communication from Dillehay. Raised farming platforms demarked by ridges dating to about 5,000 years ago have also been found, along with evidence of irrigation, indicating investment-intensive farming that would have been facilitated by private-property rights.

[15] 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, 1989).

the abundance of spatially concentrated maritime resources and the importance of investment-intensive fishing gear in the exploitation of these resources would have favored the emergence of a farming-friendly property-rights template and may have made farming a feasible but initially unattractive alternative to maritime hunting and gathering. Archaeologists Marek Zvelebil and Peter Rowley-Conwy suggest that in these cases sedentism may have "preadapted the coastal communities to farming" but that "local foraging adaptations were relatively productive and reliable and therefore remained a viable alternative to farming" (Zvelebil and Rowley-Conwy 1986, 67, 88; see also Price 1985).

D. *Case IV. Institutions First, Then Institutions and Technology Coevolve,* $\beta_B^*(\mu_a, v_a) < \beta_a^* < \beta < \beta_B^*(\mu_f, v_f)$

The fraction Bourgeois initially exceeds the minimum required for farming to be a best response ($\beta_a^* < \beta$) but falls short of that required for the deterministic proliferation of the Bourgeois strategy in the absence of farming ($\beta < \beta_B^*(\mu_f, v_f)$). However, when farming is taken up, this results in a value of $\beta_B^*(\mu_a, v_a) < \beta_a^* < \beta$, so that the fractions Bourgeois and farming both go to 1.

This coevolutionary case may represent some of the independent episodes of the Neolithic agricultural revolution, which, starting from an initial limited adoption of private property, then proceeds with the pari passu development of the novel technology and institutions. These economies would most likely have been supported by social norms, with private property in some domains and common property in others. This is suggested by the division of household space in Çatalhöyük (Anatolia) 9,000 years ago: difficult-to-access, apparently private storage of farmed goods coexisted with the display (and presumably sharing) of hunting successes in public spaces (Bogaard et al. 2009).

VIII. Caveats and Alternative Accounts

In conjunction with what is known or can reasonably be inferred empirically, our model is consistent with the following explanation of how the Neolithic agricultural revolution could have occurred in the absence of a productivity advantage for farming: (1) predating the first farmers, family-based private-property institutions occurred at a few sites of rich resource concentrations; (2) because, even before farming, sedentism reduced the probability that possession would be contested, these sites became more common once Holocene climatic conditions mitigated pressure for mobility; and (3) once a transition to widespread adherence to private-property norms had occurred at a farming-suitable location, erstwhile foragers could benefit materially by taking up farming even if it was not more productive,

because cultivation and animal tending made possession less likely to be contested. Jointly, these three observations provide a plausible explanation of both why the independent emergence and persistence of farming was a rare event and why it took place during the early Holocene.

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, away from $\beta = 0$ to $\beta > \beta_B^*$—and only subsequently via its effect on the feasibility of farming.

Two leading archaeologists in the field recently wrote that "we do not yet have a good answer to 'why did hunters become farmers?'" (Price and Bar-Yosef 2011b, S171). While the summary of cases of transition in the previous section suggests that the model replicates important features of the archaeological record, we cannot claim to have provided "the answer."

A. *Caveats*

First, while we have drawn on evidence from all of the sites of early farming, southwestern Asia has been far more exhaustively studied, and unavoidably the preponderance of our evidence comes from that region. As a result, we are considerably more confident that our interpretation is a valuable contribution to understanding the Neolithic revolution there than in the rest of the world.

Second, societies combining farming and hunting-gathering have persisted over periods of time that are long in a historical sense (many centuries) but remarkably short in biological or archaeological time. Foraging under collective property appears to have persisted for a hundred millennia, for example, and then in some cases disappeared in a millennium or two. Our model abstracts entirely both 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 from the slow improvement in the productivity of cultivated species either deliberately or as a by-product of their domestication. As a result, other than identifying the four possible cases just discussed, our model is ill equipped to study the often quite protracted process of transition itself.

Third, during a prolonged transition there may have been a hybrid system of division rules, with some rules applying to hunted and gathered foods and others applying to farmed foods, evidence for which at Çatalhöyük we mentioned in case IV above. Something similar has been observed in transitional ethnographic populations: hunted and gathered goods, especially those acquired in large packages, are shared widely, while purchased or produced goods are less likely to be shared outside the immediate family (Kaplan and Hill 1985). Our model abstracts from the possibility that strategies could be based on division rules that are

conditional on the produced versus hunted-gathered nature of the good in question. Doing this would add to the possible ambiguity of possession a further ambiguity arising from the fact that whether a good is produced or hunted-gathered is itself open to contest, given that foragers commonly engage in the more or less intensive management of wild plants and even wild animals. If this second dimension of ambiguity were sufficiently minor, then a mixed hunting and farming economy could have persisted indefinitely. We have not explored this possibility.

Fourth, is the timescale on which the process we have described able to capture the observed Neolithic transitions? If groups were small—composed of a dozen or even fewer independent decision-making units—then a decentralized, stochastic process like the one that we model would have resulted in realized excursions from the status quo forager convention sufficiently large to induce the few rare independent transitions to farming. 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 2006). 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, family-based groups before European contact (as suggested by Bettinger 2015).

But for sedentary groups of perhaps even a hundred families, as in southwest Asia, the timescales on which rare idiosyncratic play would generate a sufficiently large excursion from the status quo convention could make it unlikely that any institutional transitions at all would have taken place in the aftermath of the Holocene weather amelioration. In these cases, joint action among community members, possibly minimally differentiated by political roles, may have coordinated the process of equilibrium selection. Thus, the evidence mentioned above of a "communal" political life at Abu Hureyra, Mureybet, and other southwest Asian preagricultural villages may suggest another mechanism of transition, one that does not entail elite imposition but instead deliberation among peers, resulting in a selection among alternative (also peer-enforced) institutional conventions.[16]

This is a reminder that idiosyncratic play in our model is a stand-in for non–best-response 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 behavioral innovation would be an important contribution to explaining the Neolithic agricultural revolution.

[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 might also have also been the basis of the emergence of entirely new institutions (Moore et al. 2000).

A final caveat concerns the interpretation of the climate-adversity hypothesis provided by Dow, Reed, and Olewiler (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 because of learning by doing. The timing of the climate adversity and the first farming (see fig. 1) appears to cast some doubt on this sequence, but their key mechanism—concentration of population at good sites—does not depend on climate adversity, as this could have come about for other reasons, as in our account from naturally occurring rich resource concentrations.

B. Alternative Accounts

We turn finally to two hypotheses that are more than caveats and that could be considered alternatives, whether complementary or rival, to our explanation of the introduction of farming and the expansion of the domain of private property during the early Holocene.

The first is that while farming could have been taken up even without a productivity advantage, this is not what in fact happened. Instead, according to this conventional account, farming was adopted as the result of superior labor productivity. Recall that our model shows that because of the investment sunk cost of farming, farmers had more to lose from a challenge to their possessions. So, in the absence of property rights, farming required a productivity advantage to be favored by erstwhile hunter-gathers.

Because of the lack of relevant data from the period, this possibility cannot be ruled out—even though there is no evidence, either direct (about the nature of the crops grown and methods of cultivation) or indirect (e.g., climatological influences on growing conditions), consistent with this view. But there are two additional reasons to doubt that this occurred.

Most important, had there been some extraordinary productivity advantage to farming, unless this was highly localized (for reasons we have been hard pressed to imagine), we would expect that once climate became more favorable, farming would have been adopted independently by a large number of populations. But this is not what occurred. The fact that the emergence of farming was a rare event even in localities ideally suited for cultivation suggests that there was some "critical-mass" kind of problem of the type that we model as an institutional innovation bottleneck.

Moreover, if farming had indeed been much more productive than hunting and gathering when it was first introduced, the growth in the food value of many crops, the significant drop in required seeding ratios, and other biological improvements in farmed species, make it difficult

to imagine what subsequent developments would explain the "reversal of fortune," such that by the twentieth-century, Neolithic-type low-tech farming appears to have become, if anything, less productive than hunting-gathering, as our figure 2 suggests.

A second alternative interpretation is that an expanded domain of private property and the advent of farming were facilitated at the end of the Pleistocene by cultural and cognitive changes substantially independent of the economic developments that we have stressed. This alternative view does not reverse our "institutional-bottleneck" hypothesis, but it delinks the institutional changes from the economic conditions on which our account turns, that is, sites of concentrated rich resources and the increased land and animal productivity associated with farming. Prior cultural changes could have been at work, making the implementation of private property less difficult. Rephrased in terms of our model, cultural changes independent of sedentism and rich resource concentrations could have contributed to a reduction in our μ (probability of a contest over possessions).

"Why did incipient food production not come earlier?" the archaeologists Robert Braidwood and Gordon Willey asked half a century ago. "Our only answer at the moment is that culture was not ready" (Braidwood and Willey 1962, 343). Responding explicitly to the question, the archaeologist Jacques Cauvin documented a late Pleistocene "transformation of the mind" associated with religion, that is, a "symbolic transformation preceding the agricultural economy" (Cauvin 2000, 66–72). Archaeologist Ian Hodder describes a "socio-symbolic process" involved in the creation of a specifically "domestic sphere" (Hodder 1990, 18), although this process appears not to have preceded farming but to have developed along with it. Though neither Hodder nor Cauvin suggest this, it is not difficult to imagine ways that these and related cultural changes could have facilitated the extension of possession-based private property to ever wider realms of social life, possibly in ways complementary to the material changes that we have stressed, namely, sedentism and farming.

IX. Conclusion

Once independently established, the Neolithic economic model (farming plus private property plus sedentism) out-reproduced foraging populations. Moreover, the larger concentrations of population and the subsequent emergence of hierarchical political systems and eventually states were to give farmers a decisive military advantage over foragers, allowing the further spread of the Neolithic model (Diamond 1997). This diffusion of farming and its associated property rights took place through a process of cultural group selection implicit in the evolutionary thinking of Parsons (1964), Hayek (1988), Tilly (1990), and others.

But we have addressed the independent emergence of farming and a new system of property rights, not its spread.

Our interpretation of the Neolithic agricultural revolution is a contribution to the literature questioning the common view that changes in economic institutions are accommodations to prior technical innovation. A prominent example of this "technology-first" line of reasoning 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 (350), "stem from the development of new technology and the opening of new markets, changes to which old property rights are poorly attuned."[17] This perspective, dating back to the writings of Marx ([1859] 1904), has provided a fruitful framework of the study of institutional evolution (Cohen 1978).

By contrast, our interpretation of the Neolithic agricultural revolution is consistent with the idea that institutional change may predate and provide conditions for subsequent technical change. Examples of this "institutions-first" perspective include the role of credit contract enforcement in promoting the farming of cotton, rather than vegetables, among former slaves in the antebellum US South (Ransom and Sutch 1977); the emergence of factory employment of wage workers replacing the putting-out system in Great Britain, in some cases before any significant technical innovations (Marglin 1974); the effect of political power on the strength of one's property rights and hence on land use in West African agriculture (Goldstein and Udry 2008); the contribution of institutions that sustained high wages in eighteenth-century England to induced labor-saving technical change and the industrial revolution (Allen 2009, 2011); and the fact that premodern agrarian autocracies often required farmers to cultivate easy-to-expropriate-and-store cereals rather than root crops (Scott 2009).

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[17] We initially shared this view (Bowles and Choi 2002), which we later modified, using agent-based simulations to illustrate the possibility that farming and private property coevolved (Bowles and Choi 2013). But the evolutionary model presented here, along with archaeological evidence, suggests that a leading or perhaps even coevolutionary role of technology in the independent emergence of farming is unlikely.

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