Coevolution of farming and private property during the early Holocene

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The advent of farming around 12 millennia ago was a cultural as well as technological revolution, requiring a new system of property rights. Among mobile hunter–gatherers during the late Pleistocene, food was almost certainly widely shared as it was acquired. If a harvested crop or the meat of a domesticated animal were to have been distributed to other group members, a late Pleistocene would-be farmer would have had little incentive to engage in the required investments in clearing, cultivation, animal tending, and storage. However, the new property rights that farming required—secure individual claims to the products of one's labor—were infeasible because most of the mobile and dispersed resources of a forager economy could not cost-effectively be delimited and defended. The resulting chicken-and-egg puzzle might be resolved if farming had been much more productive than foraging, but initially it was not. Our model and simulations explain how, despite being an unlikely event, farming and a new system of farming-friendly property rights nonetheless jointly emerged when they did. This Holocene revolution was not sparked by a superior technology. It occurred because possession of the wealth of farmers—crops, dwellings, and animals—could be unambiguously demarcated and defended. This facilitated the spread of new property rights that were advantageous to the groups adopting them. Our results thus challenge unicausal models of historical dynamics driven by advances in technology, population pressure, or other exogenous changes. Our approach may be applied to other technological and institutional revolutions such as the 18th- and 19th-century industrial revolution and the information revolution today.

agent-based simulation | evolutionary game theory | technical change | institutional change | big history

Among the outstanding puzzles in human social dynamics is the simultaneous emergence and diffusion of novel economic institutions and new technologies. An important example is the appearance of private storage (1–4) and other indicators of individual property (5, 6) along with the advent of farming (7, 8), one of the greatest technological–institutional revolutions ever experienced by our species.

Economists, archaeologists, and historians often consider advances in technology to be an exogenous driver of innovations in property rights, wealth inheritance practices, or other institutions. Well-studied examples include the social and cultural impacts of the introduction of the horse on the US Great Plains in the 17th century or the sweet potato in the New Guinea Highlands a century later (9, 10). However, the technological and institutional innovations of the early Holocene are difficult to reconcile with this view because, as a number of archaeologists have pointed out (11–13), farming was probably not economically advantageous in many places where it was first introduced. Indeed, recent estimates suggest that the productivity of the first farmers (calories per hour of labor including processing and storage) was probably less than that of the foragers they eventually replaced, perhaps by a considerable amount (14) (*SI Appendix*). In many parts of the world, stature and health status appear to have declined with cultivation (15). Farming did raise the productivity of land and animals, and this, we will see, was critical to its success. However, why an erstwhile hunter–gatherer would adopt a new technology that increased the labor necessary to obtain a livelihood remains a puzzle.

The other often-proposed exogenous driver of the Holocene revolution—population pressure (16)—fares no better. What is thought to be the first independent emergence of farming—in the Levant—followed almost 8 centuries of population decline (17). The archaeological record is thus inconsistent with the idea that under the more favorable Holocene weather conditions, farming, once "invented," was simply a better way to make a living, and that the new property rights subsequently emerged in response to the needs of the new technology.

How, then, did this new technology and novel system of property rights emerge and proliferate? We propose that the new property rights and the new way of making a living coevolved, neither being viable alone but each providing the conditions permitting the advance of the other. This coevolution hypothesis is based on two empirically motivated premises: that farming required a novel system of property rights, and that (in the absence of exceptional circumstances) this system of farming-friendly property rights was not viable in an economy based on wild plant and animal species. This is why coevolution was possible and independent evolution unlikely.

Fig. 1 contrasts the causal structure of our coevolutionary model with the technology-driven approach. The vertical causal arrows (Fig. 1, *Right*) make it clear that farming was essential to the advent of novel institutions; however, in our interpretation, neither its advent nor its contribution to the spread of new property rights derived from any initial advantage in the productivity of labor.

In the next section, we explain the causal structure of our model, showing how farming and the extension of private property rights each provided conditions favorable for the proliferation of the other. We then represent this coevolutionary causal structure in a mathematical model. This allows an analysis of the configurations of technologies and institutions that could persist over long periods, as well as the process of transition from a configuration representing a hunter–gatherer economy to one representing farming with its associated property rights.

The test of the causal explanation expressed by the model is whether, when calibrated to represent late Pleistocene and early Holocene conditions, our simulations of the model reproduce the basic known facts about the timing, nature, and diversity of the transition process. These facts include not only the Holocene transition (where it occurred) but also the very long term persistence of foraging not only before the Holocene, but in many parts of the world extending right up to the middle of the last millennium. This is the test that we set for ourselves in the subsequent two sections, first using climate, archaeological, and other data to calibrate the model, and second to check whether the simulations do indeed replicate what is known about the emergence of farming and the novel institutions associated with it.

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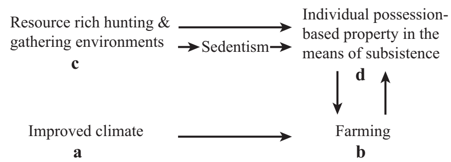

Fig. 1. Holocene coevolution of farming and private property. A conventional causal sequence is that **a** is a sufficient condition for **b**, which is then followed by **d**. Our model and simulations suggest a coevolutionary scenario: In the absence of farming, **c** is a necessary condition for **d**, which in conjunction with **a** provided the necessary but not sufficient conditions for **b**.

In addition to providing an alternative to the exogenous technology- or population-driven interpretation, our method is also unconventional in the study of prehistory. Evolutionary game theory combined with agent-based simulation allows us to track how, as a result of independent individual actions, a population may come to engage in new livelihoods and institutions. As a result, we can study a population when it is in motion, not only when it is stationary, allowing us to capture processes rather than focus on end points, or "before vs. after" scenarios. This contrasts with models in which entire groups are represented as though they were a single individual, so that group differences in livelihoods or institutions are an all-or-nothing matter. In our simulations, not everyone conforms to the same institutional norms and groups virtually always pursue mixed livelihoods, some mostly foraging, others with a majority of farming.

Mutual Dependence of Farming and Farming-Friendly Property Rights

Systems of property rights govern access to the things that people value, and they differ in who can legitimately exclude whom from what. These differences are often both subtle and complex, so we will represent the property rights of a group not categorically but as a continuum based on the diverse behaviors of the individuals making up the population. We simplify the multidimensional nature of property by letting each individual adopt either common property or private property based on individual possession. The latter (henceforth "private property") gives the holder (an individual or nuclear family, hence the term "private") the right to determine the use of the resource that is owned, including, of course, the right legitimately to exclude others from its use. Rights in this sense convey an expectation that their exercise will not generally be legitimately or successfully opposed by others.

Common property pertains to goods that are not covered by private property and instead cannot be legitimately monopolized by a single individual (or family). Common property does not entail equality in the use of resources, but it does prohibit monopolization of a resource by an individual or family. Under common property, the rights of use or exclusion are exercised by groups larger than a single family, as when the members of a foraging band exclude nonmembers from its territory or when a lineage claims territoriality over a fishing site.

If widely adopted in a group, a particular set of property rights may benefit its members when it accomplishes two things: providing incentives for the productive use of labor and other scarce inputs, and avoiding costly conflicts among group members. Which set of property rights best accomplishes these ends—private, common, or some admixture—depends on the nature of the goods and services making up the livelihood of a group. The property rights that worked well in a foraging economy were quite different from those adapted to farming.

Our first premise—farming required private property—is illustrated by the barriers to cultivation in the absence of appropriate property rights encountered by two would-be farmers, members of a group of foragers in Malaysia, the Batek: "The traditional Batek notions that all natural resources are unowned until collected and that any food obtained in excess of the needs of the procurer's family must be shared with other families seem well suited to a nomadic foraging life, but wholly unsuited to ... farming" (18). The two Batek men who had discovered cultivated rice tried planting some. However, their fellow group members simply harvested it (and, of course, felt obliged to share the harvest with the entire group). Similar cases of free riders' claims on would-be first farmers are found among the !Kung in southern Africa and the Hiwi in Venezuela (19). James Woodburn concluded that "the value systems of non-competitive, egalitarian hunter-gatherers limit the development of agriculture because rules of sharing restrict the investment and savings necessary for agriculture" (20).

The delayed returns from long-term investments in food production (both cultivation and animal tending) would not have been enjoyed by the first farmers in the absence of property rights ensuring that a family could effectively claim the food and other subsistence goods that they produced, excluding others. However, although foragers typically own some ornaments, tools, and other valued items, and entire groups of foragers sometimes delimit and defend hunting and gathering territories, the absence of effective storage combined with the need to smooth out the day-to-day vagaries of individual food procurement dictates that food be widely shared as it is acquired. (By "foragers," we mean mobile hunter–gatherers; we will see that sedentary hunter–gatherers are an exception that may account for one of the best-documented cases of the Holocene coevolution of farming and private property.)

Consumption smoothing through food sharing is practiced in all small-scale societies, and practices among forager groups differ (21). However, available data on recent and contemporary foragers and horticulturalists show that the fraction of the food one has acquired that is subsequently transferred to other households is substantial among foragers and is much greater than among hand-technology farmers (*SI Appendix*). An individual hunter may have the right to distribute his prey to others, but monopolizing it for his immediate family would typically be a serious transgression of social norms and would undermine the system of mutual insurance based on food sharing.

Widespread sharing of food among foragers would have been particularly pronounced during the extraordinarily volatile climatic conditions of the late Pleistocene. Thus, it seems likely that when climate variability ameliorated at the end of the Pleistocene, farming-friendly private property rights over the means of subsistence produced by one's labor were for the most part absent among foragers.

Our second premise—private property required farming—suggests a reason for this absence: Demarcating and enforcing individually held property rights were not cost-effective (or sometime even possible) in the diffuse and in many cases mobile wild species on which foragers subsisted. The exceptions—group rights in especially concentrated resource patches such as migratory routes of prey or the dwellings of sedentary foragers—are suggestive of how farming provided a more favorable environment for the property rights it required. What made the defense of concentrated resource patches feasible and cost-effective was that they were highly productive (in value per unit of space), so that a limited investment in demarcation and the exclusion of others would be justified by the substantial losses that these expenditures would prevent (22). Similarly, the concentrated and easily looted resources of a farming economy made possible by the associated increase in the productivity of land and animals—crops ready for harvest or in stores, as well as livestock—were worth defending. Thus, farming provided favorable conditions for the new property rights that it required.

Where the Holocene revolution occurred, acknowledgment of one's fellow first farmers' property rights in dwellings, crops, and animals became a convention, that is, a norm that persisted once it had become common because respecting the rights of others was in the interest of each as long as two conditions were met. The first was that most people accept the exclusion of others from one's possessions as legitimate. The second was that the things one valued could be made to be possessions, that is, they

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could be unambiguously demarcated and then defended so that contests over the facts of possession would be infrequent.

Whereas the facts of possession were unlikely to be contested when wealth took the form of domesticated animals and cereals stored within one's dwelling, in a foraging economy the second condition was unlikely to be met. As a result, individuals asserting private property rights in a foraging economy would not only be challenged by those upholding an alternative common property rule, they would even challenge one another over the facts of possession. The property rights that farming thus allowed did more than provide individual incentives for the investments that farming required. Where farming was introduced and where most people adhered to the norm of respecting others' possessions, private property attenuated costly within-group conflicts, allowing populations of the first farmers to prosper even if farming was not initially more productive than foraging.

Combining the two premises, it is easy to see that the farming–private property match, once established, could persist, just as the forager-common property match had persisted for tens of millennia. But how could the new institutions emerge in the first place? Unlike a new crop or method of cultivation, a system of new property rights could not be introduced piecemeal by a single individual. New institutions—novel property rights included—do not work well unless most members of a community adhere to them. Successful adoption of farming-friendly property rights thus required a critical mass. This critical mass problem could, in principle, be overcome by a governmental fiat introducing and enforcing a new system of property for an entire population. However, property rights appropriate for farming emerged and proliferated many millennia before there were governments that could enforce them, and any single individual initially asserting such rights would most likely have been unsuccessful, as the hapless Batek would-be rice farmers discovered.

In light of this critical mass problem and the likely absence of a productivity advantage for the first farmers, it is difficult to explain how either farming or the new property rights that farming required could have first emerged and then proliferated at the end of the Pleistocene, when both were rare. Emergence and subsequent proliferation are two distinct puzzles. The first requires an explanation of how a single group surviving entirely on wild resources could have taken up food production, and the second, an explanation of why, even in the absence of a labor productivity advantage, the farming practices of such a group would have spread throughout an ethnolinguistic unit, rather than being reversed.

It is not difficult to explain cases where, following its emergence and full development in one location, the farming-cum-private property package was introduced to a new area—as in the case of the importation of farming and herding to Cyprus around 10,500 B.P., or its expansion to many parts of Europe (23, 24). For this reason, we will focus on explaining the handful of well-studied cases of the independent emergence and local adoption of farming and its associated property rights.

Modeling the Coevolution of Technology and Institutions

No single account can capture the distinctive trajectories by which this occurred during the early Holocene (7, 8, 24–29). The conditions under which farming and farming-friendly property rights jointly emerged differed in many respects: the crops and animals that were cultivated and eventually domesticated, the environmental conditions under which this occurred, the degree of long-term investment required, and the nature of property rights best adapted for their use. We think, nonetheless, that there may be some common causal mechanisms underlying the Holocene revolution. An adequate model should provide the causal mechanisms accounting for what is known from archaeological, biological, and other evidence.

Enduring transitions occurred no more than 12,000 y ago and they were very rare; in most ethnolinguistic units, the farming-cum-private property package did not independently emerge. Transitions were slow and sometimes witnessed reversals. The passage from initial domestication of one or two species accounting for a modest portion of the diet to a primary commitment to food production in some cases extended over as many as six millennia. As a result, mixed societies with substantial portions of the diet coming from both farming and hunting–gathering persisted over long periods (30).

We provide a model of cultural evolution that captures the complexity and diversity of this process and allows us to identify the underlying causal mechanisms accounting for the joint emergence of the new technology and property rights. The model, described in *SI Appendix*, illuminates the population dynamics resulting from the causal mechanisms we have described. We modeled individuals' choices of both technology and behavior toward other group members. We then used the fluctuations in surface temperature over the past 40,000 y as an indicator of climatic volatility, along with estimates of migration, intergroup competition, and other aspects of the demography of late Pleistocene and early Holocene small-scale society to calibrate our model so as to capture the conditions under which the new individual strategies of ownership and procuring a livelihood might have proliferated.

Our model represents the social and technological dynamics of a population similar in size and composition to a late Pleistocene ethnolinguistic unit (600 individuals per generation), made up of many partially isolated subpopulations (called "groups," of 20 individuals per generation) about the size of forager bands or small villages. In this model, farming and private property spread as a result of adoption by most individuals in a group occurring either as the result of changes within the group or from emulation by a group of foragers and their subsequent adoption of the new institutions and technology.

There are three stages in the model: production, distribution, and cultural updating. In the production stage, individuals adopt one of two technologies: farming or hunting–gathering. These technologies differ in four ways: Foraging is more productive than farming; farming requires a prior investment that may be lost if the product is contested; the farming product is more readily demarcated and defended than the foraging product; and because of its sedentary nature, farming is more disadvantaged by volatile weather.

In the distribution stage that follows production, independent of the choice of technology, each individual interacts with a randomly paired other member of their group to divide their products according to a modified version of Maynard Smith's bourgeois–hawk–dove game (31). The strategies that an individual may adopt reflect patterns of sharing, aggrandizement, and collective discipline found in ethnographic studies of hunter–gatherers and horticulturalists (32–36). Similar to the dove in the hawk–dove game, the first behavioral type, the sharer, concedes half of the product to the other, or the whole product if the other claims it. Bourgeois individuals (the second behavioral type) claim the entire product if it is in their possession. A nonpossessing bourgeois may engage in contests with another bourgeois if possession of the product is contestable, which is less likely for farmed products. A key aspect of our model is that bourgeois behavior will differ markedly depending on the technology in use. Because farming wealth is readily demarcated and defended, bourgeois individuals respect the farmed possessions of others, whereas for foraged products they sometimes claim the possessions of others, resulting in conflicts.

The third behavioral type, the civics, act exactly like sharers when they meet a fellow civic or a sharer (they share), but when paired with an individual who refuses to share (e.g., a bourgeois in possession of the product), they join with any other civics in the group to contest the claims of the bourgeois, succeeding with a probability that is increasing with their numbers (*SI Appendix*, Fig. S2). If they succeed, they distribute the bourgeois' product among all the civics, whereas the losing bourgeois bears a cost. If, instead, the civics fail, they bear the losers' cost. [The civic strategy is based on ethnographic studies of the maintenance social order in stateless societies (36, 37) so as to allow a more realistic coordinated rather than individual punishment process (38).]

In addition to within-group individual interactions, groups of the same ethnolinguistic unit interact in what may be termed "emulation" contests. These could be outright violent conflicts or simply the encroachment by groups with higher payoffs on less successful groups. The key is that the group with the higher total payoff becomes a cultural model for the less successful group. Losing groups cede some resources to the winning group and are then culturally assimilated by the winners (explained below). In each generation, there is a probability that each individual will migrate randomly among groups.

In the cultural updating stage, individuals are paired with a cultural model (for example, an elder) who is more likely to be from the numerically predominant type in the group than would occur by chance (*SI Appendix*, Fig. S3), reflecting conformist cultural transmission (39). If the two are the same type, no updating occurs. However, if they differ, and if the model's payoff in the previous period was higher than the updating individual's, he or she switches to the type of the model. In groups that have not lost a contest with another group, the cultural model is selected from the group's own population, whereas in groups that have lost a contest in the previous period, updating individuals are paired with models drawn from the winning group, thereby tending to spread those technology–behavior types that are common in the winning group.

Persistence and Demise of Forager Technology and Institutions

In our model and simulations, a situation in which most individuals engage in hunting–gathering and are either sharers or civics represents the late Pleistocene forager technological and institutional order. We now use the model to ask how this forager distribution of types might endure over long periods, as it appears to have done for at least 100,000 y before the Holocene, and how it might be replaced by transitions to a farming–private property social order (in which most individuals are bourgeois farmers) under the influence of more farming-favorable Holocene weather conditions. To do this, we need to determine how the population share of each of the six technological–behavioral types will change from period to period. We can do this because, for any composition of a group (conditional on having lost or not lost an intergroup contest), the current fraction of each of the technology–behavior types uniquely determines the expected payoffs of each type and, hence, given the updating process just described, the expected change in population frequencies of the types in the next period. We are especially interested, of course, in those distributions of each of the types for which the model predicts no change and that could therefore represent a long period of institutional and technological stasis.

One of these so-called stationary states is a population composed entirely of civic hunter–gatherers. To see why this state is stationary, imagine that by migration or behavioral experimentation a few bourgeois types should appear in the group. Given the difficulty of demarcating and defending wild resources, bourgeois types in this setting simply act as aggrandizers, benefiting from others who share the goods in their possession while refusing to share, and occasionally engaging in contests with civics and other bourgeois types as a result. [This is consistent with the ethnographic literature and suggested by archaeological evidence (35, 40).] The all-civic state is stationary because the many civics rarely lose their contests with the few bourgeois types, instead inflicting costs on them. A hunter–gatherer society with a mixture of civics and sharers will also be stationary, as long as there are sufficiently many civics to win their contests with the occasional bourgeois "invaders."

If there are few civics, however, aggrandizing individuals will proliferate even in an economy based on wild resources, so that a mixed population with both sharers and bourgeois but no civics is also a stationary state. However, because individual possession is readily contestable given the hunter–gatherer reliance on wild species, hunter–gatherer groups with a significant number of bourgeois individuals are conflict-prone, and this reduces their average payoffs and weakens them in contests with groups composed mostly of civics and sharers. As a result, the foraging technology with its contestability of individual possession provided an unfavorable environment for the proliferation of the bourgeois strategy. This explains why before the improvement in property rights made possible by farming, sharer–civic populations would have prevailed over populations with a substantial bourgeois fraction. A consequence is that there would be few bourgeois individuals in the meta population, resulting in relatively low levels of within-group conflict among foragers. This prediction from our theory is confirmed in the simulated evolution of our populations, as we will see.

The introduction of farming alters the population dynamics by facilitating the delimitation and defense of rights of possession. The all-civic and mixed sharer and civic population distributions remain stationary states (as long as there are sufficiently many civics). However, as possession is less contestable for farmed goods, bourgeois individuals do not challenge each others' property. As a result, the all-bourgeois state is stationary: In an all-bourgeois population, one's payoffs are maximized by remaining a bourgeois. When universally adopted, private property in farmed goods thus represents an evolutionarily stable institution satisfying the two desiderata of property rights: providing incentives and avoiding conflicts.

As a result, farming-cum-private property groups could have had average payoffs at least as great as forager groups despite the inferior productivity of farming, because these groups endured fewer costly conflicts over possession. This would be more likely to occur, of course, during the Holocene, at times and places where for environmental reasons the productivity shortfall of farming relative to foraging was most attenuated.

This reasoning leads us to expect that, under Holocene climatic conditions, if a group somehow attained a substantial fraction of bourgeois farmers, the state would persist over long periods. This expectation, too, will be borne out in our simulations. However, the above reasoning does not explain how the critical mass required for the adoption of both farming and farming-friendly property rights could have occurred in the first place. Our next task then is to use our simulations to show how this may have occurred and to discover whether the causal model we have calibrated does indeed track what is known about the Holocene revolution.

Simulated Holocene Transitions

Our simulations reproduce the timing of the best-studied cases of the independent emergence of agriculture in the archaeological record (Fig. 2). Equally important, the chicken-and-egg problem of farming and private property in our model explains why the transition was a very unlikely event, occurring in only 31 of 1,000 metapopulations that we simulated. The results are robust to plausible variations in the parameters (*SI Appendix*).

Note in Fig. 2 that the brief climate ameliorations around 37,000–35,000 and 15,000–13,000 y ago are associated in the simulations with short-lived experiments with farming, the latter coinciding exactly with the well-documented Natufian proto-farming episode (41, 42). Fig. 3 shows that in the simulations, as in the archaeological record, mixed farming and hunting–gathering is the norm over very long periods, and that the process of transition when it occurred was prolonged, highly varied, and sometimes halting.

Process of Transition in the Archaeological Record

Exploring this process empirically is difficult because whereas farming leaves traces such as specialized tools and genetic and morphological markers of domestication in plants and animals, there are no comparable markers of property rights, for which evidence is as a result necessarily indirect. About storage, for example, Kuijt and Finlayson very plausibly write that a "transition

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from extramural to intramural storage system may reflect evolving systems of ownership and property . . . with later food storage systems becoming part of household or individual based systems" (2). However, one can hardly expect to find direct evidence for the coevolution of property along with technology during this period.

Southwestern Asia provides the best-documented cases providing evidence of the gradual adoption of food production along with evidence suggesting the emergence of private property in stores in the Levant between 14,500 and 8,700 B.P. (*SI Appendix*). At the beginning of this period, Natufians hunted and collected wild species and possibly practiced limited wild-species cultivation along with limited storage (41, 42). Somewhat before 11,000 B.P. there is direct evidence of storage of limited amounts of wild plants outside of dwellings, consistent with the hypothesis that access to stored goods was not limited to the members of a residential unit (2, 43). A millennium later, goats and sheep had been domesticated (constituting a substantial investment), and we find large-scale dedicated storage located inside dwellings, suggesting more restricted access (4, 44).

Over none of this period could one describe these communities as either simply foragers or farmers. Their livelihoods were mixed; in many cases, their residential patterns varied over time between sedentary and mobile, and it seems their property rights, too, varied among the types of objects concerned, with elements of both private and common property in evidence. Bogaard (4) and her coauthors found that at Catalhoyuk in central Anatolia (10,500–10,100 B.P.), "families stored their own produce of grain, fruit, nuts and condiments in special bins deep inside the house." This restricted-access storage coexisted with the prominent display of the horns and heads of hunted wild cattle. The authors concluded that "plant storage and animal sharing" was a common juxtaposition for "the negotiation of domestic [the authors elsewhere call it "private"] storage and interhouse sharing." The process of change was neither simple, nor monotonic, nor rapid. However, in both its institutions and its technology, Levantine people were living in a very different world in 8,700 B.P. from the world of the early Natufians almost six millennia earlier.

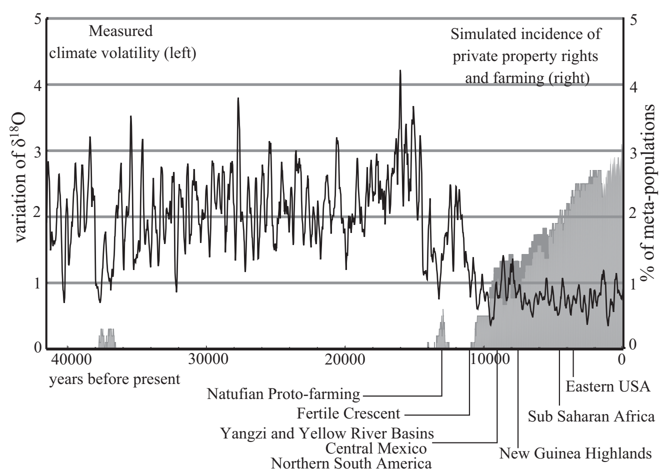

Fig. 2. Climate variability and the emergence of farming and private property. The gray bars (*Right*) indicate for the year given the number of simulated populations (of the 1,000 simulated) in which more than 50% of the entire population were bourgeois farmers. Estimated dates of some well-studied cases of the initial emergence of cultivation are on the horizontal axis (8, 54, 55). Climate variability (*Left*) is an indicator of the 100-y maximum difference in surface temperature measured by levels of $\delta^{18}O$ from Greenland ice cores (*SI Appendix*). A value of 4 on the vertical axis indicates a difference in average temperature over a 100-y period equal to about 5 °C.

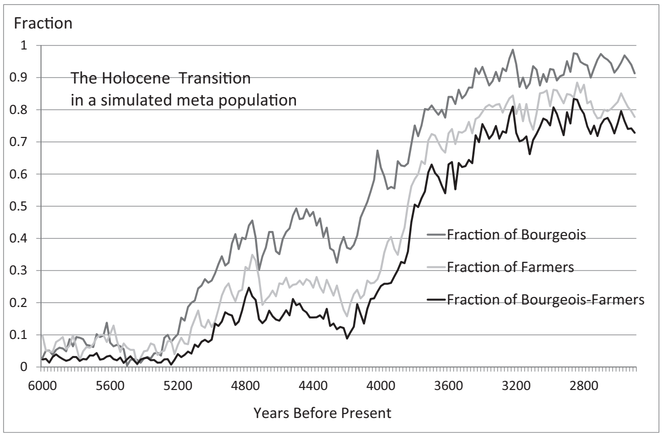

Fig. 3. Simulated process of transition. Shown are the dynamics occurring in a single implementation of the simulation (a single population representing an ethnolinguistic unit), indicating (vertical axis) the fraction of the population that are, respectively, farmers, adopters of the new property rights, and both (bourgeois farmers) for the given year.

Discussion

In many histories of technology, the key event is the invention; the subsequent spread occurs inexorably as the result of its superiority in lessening the toil required to sustain life. This model has been suggested for the Holocene revolution (45); but it does not work. No invention was necessary. Kent Flannery, who pioneered archaeological studies of the emergence of farming, observed that "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" (46). Moreover, foraging and farming populations interacted over long periods in the Levant, India, Scandinavia, and elsewhere. In these cases, those who remained foragers surely knew about the new technology, as did foragers long before the initial spread of farming. In our simulations, as in the archaeological record, groups with substantial fractions of farmers coexist over long periods with groups engaged almost exclusively in foraging.

Nonetheless, the independent adoption of farming was a rare event. Our coevolutionary model and simulations suggest that after the amelioration of climatic conditions at the end of the Pleistocene attenuated the productivity disadvantage of farming compared with foraging, in a few populations the new technology and behaviors proliferated synergistically. We thus provide another piece of evidence in support of the views of those archaeologists and anthropologists who have advanced the idea that cultural aspects of the Holocene revolution are essential to understanding the advance of farming as a new technology (13, 47, 48). The institutional changes required for the exploitation of cultivars, observed Andrew Sherratt, were "a privatization of resources [that] marked the end of the forager sharing ethic" (49). The key event here is thus not the "invention" of farming but the coincidence of sufficiently many individuals adopting both the novel property rights and the new technology so as to overcome the critical mass problem.

Once established, communities of farmers would eventually outreproduce foragers due to the lower costs of child rearing associated with sedentary living (17, 50) even if the productivity of farming fell short of foraging. The resulting demographic advantage may help to explain the second part of the puzzle—the spread of farming and private property once it was reasonably advanced within a group. However, this Neolithic demographic transition was protracted, especially in the Levant and other places where farming was independently introduced, extending over more than two millennia (51). As a result, the first groups where most individuals took up the farming–private property package would not have enjoyed significant demographic advantages for many generations (*SI Appendix*). Similar competitive advantages—institutional, demographic, and (following the further development of farming methods) economic—were enjoyed by entire ethnolinguistic units in which most groups had made the Holocene transition, as evidenced by the encroachment of Bantu farmers and herders on the territories of foragers in Africa, and similar expansions of populations of farmers of European descent virtually the world over.

Our model does not take account of this encroachment on foragers by farming ethnolinguistic populations with their formidable military capacities and political reach, in most cases occurring long after the advent of the Holocene. Had this not occurred, much of the world today might look much like the Australia, Western Cape of southern Africa, or California encountered by the first Europeans no more than half a millennium ago: populations of both sedentary and mobile hunter–gatherers practicing at most intensive foraging with limited rights of property based on individual possession.

Thus, it is possible that until improvements in the productivity of seeds and the food value of cultivars made farming significantly more productive, most of the independent Holocene transitions were not driven by the prior appearance of a superior technology but instead by a coevolutionary process. We therefore think that a conventional account of historical dynamics—that an advance in technology occurs and institutions follow—fails as a description of many of the archaeologically documented early transitions to farming and its associated property rights. The technology-driven account fails for two reasons: The new technology was not initially an advance, and it most likely did not precede the emergence of the institutions favoring farming as a livelihood.

Our model of the coevolution of institutions and technologies may find applications to other epochs that saw the joint emergence of apparently synergistic institutions and technologies (52). An example is the European industrial revolution of the 18th and early 19th century, which saw the introduction of steam power and mechanized production and the reorganization of production around a new economic institution: the factory and employment for wages rather than family-based production by independent producers (53). A further application may be to the challenges to intellectual property rights posed today by the new information-processing technologies.

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