THE ANT AND THE GRASSHOPPER: SEASONALITY AND THE INVENTION OF AGRICULTURE *

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The Neolithic revolution saw the independent development of agriculture among at least seven unconnected hunter-gatherer populations. I propose that the rapid spread of agricultural techniques resulted from increased climatic seasonality causing hunter-gatherers to adopt a sedentary lifestyle and store food for the season of scarcity. Their newfound sedentary lifestyle and storage habits facilitated the invention of agriculture. I present a model and support it with global climate data and Neolithic adoption dates, showing that greater seasonality increased the likelihood of agriculture's invention and its speed of adoption by neighbors. This study suggests that seasonality patterns played a dominant role in determining our species' transition to farming. *JEL codes:* O33, O44, N50.

I. Introduction

After 200,000 years in which humans survived as hunter-gatherers, colonizing all major landmasses, agriculture was invented by at least seven hunter-gatherer populations roughly 12,000 to 5,000 years ago, with independent inventions

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documented in the Fertile Crescent, sub-Saharan Africa, north and south China, the Andes, Mexico, and North America. The long-term benefits of agriculture are obvious: more food, more people, and more specialized labor, among others. However, archaeological evidence shows that the first farmers were shorter and had more joint diseases than hunter-gatherers did, suggesting that they consumed less food and worked harder (Cohen and Armelagos 1984; Mummert et al. 2011). While our understanding of this period has increased tremendously in the past century, we still lack a unified theory of why agriculture appeared in those particular times and places and why our ancestors accepted what seemed to be a lower standard of living.

To explain the Neolithic revolution, I propose a new theory and test it against a panel data set of climate and adoption dates. I document how the start of the Neolithic coincided with a spike in climatic seasonality, caused by well-understood oscillations in the shape of Earth's orbit (Milanković 1930) I argue that this led to increased seasonality in the food supply of hunter-gatherers, and some of the most affected populations responded by intensively storing the nonperishable wild foods they gathered, which in turn required them to become sedentary in the vicinity of their granary. This combination of sedentarism and storage greatly simplified the development of cultivation technology and made it all but inevitable that eventually some groups would transition to agriculture. Crucially, eliminating the regular famines caused by dry or cold periods would have made settled life desirable even if farmers ate less on average (Testart 1982).

To develop this intuition and inform the empirical analysis, I create a model analyzing the mobility strategies of hunter-gatherers exposed to food availability that varies predictably across space and time. The model shows that higher seasonality and lower geographic heterogeneity could push a band to become sedentary even before they knew how to farm. It also makes it likelier that bands that do not themselves invent farming will adopt it quickly once exposed to it from neighbors. I test these predictions against a global historical climate data set and find that greater climate seasonality is indeed associated with a higher probability of invention and faster adoption of agriculture. Overall, a one standard deviation increase in temperature seasonality (an extra 8°C difference between winter and summer temperatures) is associated with a given location adopting agriculture 1,000 years earlier. I replicate the analysis in a higher-resolution

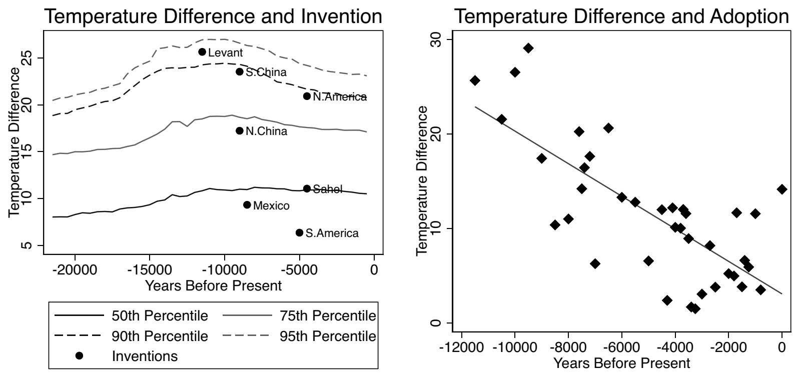

FIGURE I

Seasonality, Invention, and Adoption

Left: the evolution of percentiles in difference between winter and summer temperature averages, with the locations that invented agriculture and their temperature difference. The locations with low temperature seasonality are in the monsoon zone and experienced high precipitation seasonality. Right: binned scatterplot of temperature seasonality by date of adoption; early adopters tend to have a larger difference between summer and winter temperatures.

regional data set covering Western Eurasia and find very similar results. Figure I demonstrates the basic stylized facts of this relationship.

A detailed analysis of the archaeological record provides further support for the theory that seasonality led to storage and sedentarism and that these preceded the invention and spread of agriculture. There is abundant archaeological evidence for an intermediate phase in which ancestral populations—for example, the Natufians in the Middle East and Native Americans in the Pacific Northwest—were sedentary and storing but not yet farming. This intermediate phase facilitated the development of agriculture and related technological and social innovations, such as stratified societies and the accumulation of physical capital.

This article contributes to the literature on the economic effects of climate and environment and explains how similar agricultural technologies could emerge in different places. I develop a model to rationalize the independent development of the technological advances of the Neolithic revolution by groups with no known contact and generate clear empirical predictions that I test against paleoclimatic records, topographic data, and evidence from the skeletal remains of the first farmers. The reduction in consumption per capita with the adoption of farming has been attributed to various factors, but my unified theory can explain both the pattern of adoption and the decrease in consumption.

II. Literature Review

Climate change has been widely proposed as a trigger for the Neolithic revolution. Agriculture's emergence shortly after the last ice age suggests that global climate was a key factor in its simultaneous development across continents (Richerson, Boyd, and Bettinger 2001). This period saw warmer climates that potentially facilitated farming (Diamond 1997), perhaps in conjunction with institutional innovations such as property rights (Bowles and Choi 2013), or made hunting and gathering less viable because of drier conditions (Braidwood 1960). Dow, Reed, and Olewiler (2009) posit that a major climatic shift led to increased population densities in warmer climates, followed by a reversion to near-glacial conditions, driving hunter-gatherers to more hospitable areas. However, these theories face the challenge of explaining why agriculture did not emerge earlier in areas closer to the Equator, which were inhabited and enjoyed similar climatic conditions for tens of thousands of years with no agricultural development.

Ashraf and Michalopoulos (2015) suggest that moderate climate volatility across decades and centuries facilitated the accumulation of agricultural knowledge. Their study, using modern climate data, indicates that high and low temperature variability delayed the adoption of agriculture. My approach aligns with theirs in that I use climate data to understand agricultural adoption, but my focus differs: while they concentrate on the effect of unpredictable yearly climate changes on technological growth, I emphasize the role of seasonality within a year pushing nomads to become sedentary to store food. Other research has explored the role of demographic factors in agricultural adoption: for example, arguing that population growth drove reductions in nomadic territory and increased sedentarism (Locay 1989) or environmental overexploitation that reduced the viability of hunting and gathering (Smith 1975; Olsson and Paik 2020). This article argues instead that the reduced attractiveness of nomadism stemmed from high climate seasonality rather than a reduction in average resources per capita.

The long-term effects of agriculture's invention have also been extensively studied. Cohen and Armelagos (1984) find significant health declines after each population switches to farming. Diamond (1997) argue that early agriculture adopters gained technological advantages, influencing colonialism. Agriculture also influenced human genetics, selecting for specific psychological and physiological traits (Galor and Moav 2007; Galor and Michalopoulos 2012), and affected gender norms through its physical exigencies, such as plowing (Alesina, Giuliano, and Nunn 2013). Moreover, cultivation of identical crops yielded social institutions that varied with geography (Mayshar, Moav, and Pascali 2022). Olsson and Paik (2020) observe that sustained farming increased land productivity but often led to more autocratic societies.

In the Malthusian framework, populations typically cannot sustain consumption above subsistence levels. Galor and Weil (2000) suggest that continued population growth spurred technological advancement and human capital investment, leading to economic growth and the evolution of beneficial genetic traits (Galor and Moav 2002). Voigtländer and Voth (2013) propose that significant population reductions could force a shift to higher-mortality, lower-fertility systems. Dutta et al. (2018) argue that if people value nonfood items such as entertainment, incomes can exceed subsistence levels. This article adds to this line of inquiry by showing that seasonal food availability can also lead to an equilibrium with high consumption per capita by making more food necessary in aggregate to sustain a population during the lean season.

Other studies have explored ways that geography affects economic outcomes. Nunn and Puga (2012) finds that Africa's rugged areas resisted the slave trade, while Michalopoulos (2012) and Fenske (2014) highlight how topographical variety influenced ethnolinguistic groups and trade incentives. Latitude's correlation with development has been attributed to factors ranging from outright racism (Montesquieu 1748) to thin soils, harmful parasites, ferocious diseases, unstable rainfall, and scarce coal deposits (Bloom and Sachs 1998). Acemoglu, Johnson, and Robinson (2001) emphasize the role of institutional outcomes arising from geographic differences, a view supported by Easterly and Levine's (2003) linking of GDP, institutions, settler mortality, and resource measures. I suggest the development delay in the tropics might be partly due to delayed agriculture adoption, given the close link between latitude and seasonality.

A final literature stream examines how risk preferences shape development. McCloskey (1991) illustrates that medieval English farmers preferred to diversify labor across fields, sacrificing productivity for reduced risk. Acemoglu and Zilibotti (1997) find that large, risky projects could hinder technological progress. Tanaka, Camerer, and Nguyen (2010) observes increased risk aversion in poorer Vietnamese villages. My analysis posits that our ancestors traded a risky but abundant lifestyle for a more stable but less prosperous one, driven by risk aversion, particularly among populations near subsistence levels.

III. Model

In this section, I model the incentives faced by a single band of hunter-gatherers as they adapt their life strategy to a changing environment. First, I present a simple static model in which population size is constant. I assume a pure endowment economy in which the underlying resource base varies across space and time. I find that low seasonality makes the band choose nomadism, precluding the development of agriculture. However, a sufficiently large increase in seasonality causes the band to prefer settlement, catalyzing the development of farming. When the band becomes sedentary, it loses access to some resources that could be accessed only nomadically, but the novel ability to smooth consumption through storage more than makes up for the loss in consumption per capita.

I extend this basic intuition to a dynamic setting (sketched in the main text and fleshed out in Online Appendix C.1), in which population evolves endogenously. I start from a basic Malthusian setup and modify it so that fertility is still increasing in consumption per capita but now also decreasing in consumption seasonality. Nomads are unable to perfectly smooth their consumption, resulting in lower net fertility and higher consumption per capita in equilibrium. Settlers, by contrast, can perfectly smooth their consumption through storage. Their stable diet ensures the maximum possible fertility, so they have the lowest consumption per capita possible in a population equilibrium.

In the model, I assume that average productivity is fixed. I justify this assumption by the fact that population levels adjust to the average level of resources available, and therefore, two nomadic populations living in environments with different average resources will in expectation have different population levels but the same consumption per capita.[1] In the static version of the model (Section III.B), this equilibrium is assumed to already have been reached. Furthermore, it is easy to show in the dynamic version that multiplying all resource levels by a fixed constant (i.e., increasing the average resource availability) affects only the equilibrium population levels, not the equilibrium utility levels or optimal switching points.

The model is also silent on the effect of seasonal variability from one year to the next or one decade to the next. Variation at these scales can certainly affect the viability of incipient agricultural communities (as documented in Ashraf and Michalopoulos 2015), but this effect is almost entirely separable from what I examine here. Seasonality is by definition extremely predictable and takes place within a single year. These two characteristics allow a population with a suitable storage technology to smooth its consumption essentially perfectly—as long as its members accept becoming sedentary. In contrast, seasonal variability across years is essentially unpredictable, creating uncertainty over how much storage would be necessary. In addition, because of the longer time frames involved, spoilage would necessarily take a much greater toll on accumulated stores.

III.A. Setup

The unit agent of the model is a band with exclusive control over a specific territory. There are two locations in the band's territory, the hill (H) and the valley (V), and two months in the year, December and July. The hill provides an endowment of $1 + \sigma$ in July and $1 - \sigma$ in December, while the valley provides no food

1. In fact, the direct effect of the natural food productivity of a territory on the likelihood of agriculture being adopted is ambiguous in principle. Logically, a more fertile area will have higher agricultural productivity but also higher productivity for hunter-gatherers, raising the opportunity cost of farming. In practice, we can expect the basic fertility of an area to be positively correlated with agriculture for two reasons. (i) Below a certain level of average productivity, it becomes impossible for a population to become sedentary at all because the land simply will not produce enough food within a reasonable radius of daily travel for even the smallest viable group size. (ii) Higher population densities favor the exchange of ideas and the first domesticated crops, so denser populations are more likely to acquire the initial set of starting techniques and seeds necessary to make agricultural progress self-sustaining.

TABLE I
ENDOWMENTS OF EACH LOCATION IN EACH SEASON

	July	December
Hill	$1 + \sigma$	$1 - \sigma$
Plain	0	$1 - \sigma + \gamma$

in July and $1 - \sigma + \gamma$ units of food in December. The parameter σ indicates the amount of climate seasonality in the region, and γ represents how much extra food is available in the valley in December. Table I summarizes the endowments.

For example, we could imagine that the general area has a warm but dry July and is cold and rainy in December. The hill is usually colder than the nearby valley but receives more rainfall. Therefore, we would expect that in July, the hill will be hot and wet, plants will grow with ease, and food availability will be very high. In December, however, the hill is too cold and provides much less food. In the valley, the lack of rainfall makes food extremely hard to find in July, but in December, the valley is warm and wet enough to provide more food than the hill. This general pattern can be adapted to model a variety of seasonal resource availability regimes.

Generally speaking, the amount of food available through hunting and gathering will depend on the amounts extracted in the past. The values given in the model should therefore be interpreted as the maximum sustainable amounts that could be harvested indefinitely.

The band has a log utility function defined over consumption per capita in each period:

$$U = \log(c_J) + \log(c_D). \quad (1)$$

III.B. Static Model

I compare the outcomes from the two strategies of interest—nomadism versus sedentarism and storage—in a static model in which I assume that population size is fixed. If the band is nomadic, it will spend each month in whichever ecosystem has more resources in each period. It will therefore choose to spend July on the hill but will descend into the valley in December. Its mobility will allow it to smooth its consumption geographically but will prevent it from storing food. If the band instead decides to become sedentary, it will settle on the hill (which has the higher aggregate endowment) and will be able to perfectly smooth its consumption through storage. However, it will no longer be able to access the resources of the valley, so aggregate consumption will necessarily be lower.

Specifically, the nomadic band will consume C_N, and the settled band will consume C_S, where

$$C_N = \{1+\sigma, 1-\sigma+\gamma\} \tag{2}$$

$$C_S = \{1, 1\}. \tag{3}$$

Each consumption profile shows first consumption in July and then consumption in December. The utilities from the two strategies are simply:

$$U(N) = \ln(1+\sigma) + \ln(1-\sigma+\gamma) \tag{4}$$

$$U(S) = 0. \tag{5}$$

The utility of the settlers is therefore always zero, but that of the nomads depends on the environmental parameters. A higher σ lowers nomadic utility, while a higher γ increases it. These relationships are represented in Figure II.

For the band to be indifferent between the two strategies, it must be true that:

$$\sigma = \frac{\gamma + \sqrt{4\gamma + \gamma^2}}{2}. \tag{6}$$

The higher the level of γ, the higher seasonality must be before the band is willing to switch to sedentarism. From these results, we can reach the following conclusions.

PROPOSITION 1. In the static model, we find that:

i. If the climate is not very seasonal (low σ) and the band has access to uncorrelated ecosystems (high γ), nomadism is optimal.

ii. An increase in seasonality can cause settlement to become optimal.

iii. The higher γ is, the more seasonal the climate must be before settlement becomes optimal.

iv. Consumption per capita is lower after the transition.

III.C. Dynamic Model

In the dynamic version of the model, I modify a standard Malthusian framework by specifying that population is an

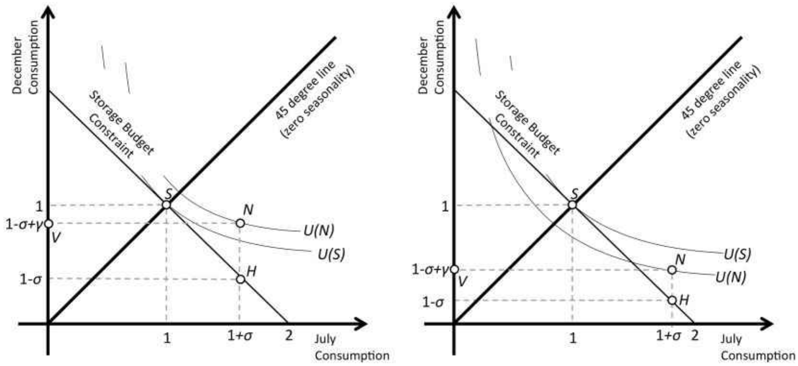

FIGURE II

Diagram of the Main Model Results

Circles H and V represent the endowments of the hill and the valley, respectively. The nomads can always reside in the best territory during each month and therefore enjoy a consumption profile of N. The settlers can only harvest the resources of H but can smooth consumption costlessly. This therefore equalizes consumption across periods and achieve a consumption profile of S. In the left panel, seasonality σ is low, and the usefulness of mobility γ is high. The band has higher utility if it remains nomadic. In the right panel σ is higher, and γ is lower. A nomadic band would now be exposed to high consumption seasonality, so that utility is now higher if it switches to settlement. This is true despite settlement resulting in lower consumption per capita.

increasing function of average consumption and a decreasing function of consumption seasonality while all endowments and choices over the settlement pattern remain as before. As detailed in Online Appendix C.1, this model generates essentially the same predictions as the static one for both the short and long run.

III.D. Predictions

The model results generate a number of empirical predictions that I can evaluate using the archaeological and paleoclimatic record on the invention and spread of agriculture.

i. If a nomadic band becomes settled, average consumption per capita immediately decreases because of the loss of access to the December refuge endowment, but consumption seasonality disappears.

ii. In the long run, average consumption per capita of the settlers remains lower than during nomadism (since consumption seasonality no longer depresses fertility).

iii. For any level of γ, a sufficiently large increase in seasonality can make settlement optimal in both the short and the long run.

iv. The higher γ is, the higher σ has to be for settlement to become optimal.

Thus, we would expect settlement to be adopted en masse where food availability is highly variable in a predictable way, and correlated across locations. These are precisely the conditions that became common shortly before agriculture appeared, as climate seasonality increased.

IV. Qualitative Evidence for the Role of Seasonality

IV.A. The Neolithic as a Global Phenomenon

This article posits that extreme climatic seasonality triggered the Neolithic revolution. This seasonality arose from changes in three key parameters describing Earth's orbit: the axial tilt, which determines the extent of seasonal variation in each hemisphere; the orbital eccentricity, which describes how elliptical Earth's orbit is; and the precession of the equinoxes, which alternates which hemisphere is pointed toward the Sun when Earth is closest to it.

At the peak of the last ice age, 22,000 year ago, the smaller tilt in Earth's axis led to milder seasonal variations. In addition, when the Northern Hemisphere was tilted toward the sun, Earth was at its aphelion, further reducing seasonality. But after that peak, changes in these orbital parameters increased global climate seasonality, so that by 12,000 BP the Northern Hemisphere experienced seasonal sunlight variation which was unprecedented in the past 50,000 years.

In the Northern Hemisphere's temperate zone, hunter-gatherers faced abundant resources in summer but harsh winters. Tropical regions experienced constant warmth but intense rainfall seasonality. Remarkably, all independent farming inventions occurred within these climatic zones: in the temperate zones of the Middle East, eastern North America, north China, and south China, and in monsoonal zones on either side of the Equator, namely, the Sahel, Mexico, and the Andes.

The change in seasonality was also responsible for the end of the last ice age (Milanković 1930), with warm summers melting ice and cold winters reducing snowfall because of lower ocean

	Seasonality Before Agriculture	Sedentarism Before Agriculture	Sedentarism Before or During Storage	Storage Before Agriculture	Averages
Middle East	1	1	1	1	1
Sahel	1	1	1	1	1
North China	1	1	1	1	1
South China	1	1	1	0	0.75
South America	1	1	0	1	0.75
Eastern North America	1	0	0	1	0.5
Mesoamerica	1	0	1	0	0.5
Averages	1	0.71	0.71	0.71	0.79

FIGURE III

The Four Main Predictions of the Model and the Results for the Seven Independent Transitions

evaporation. This led to the retreat of glaciers in the northern hemisphere and a global temperature rise of 7°C to 8°C. Thus, while the literature has mostly argued that the Neolithic was caused by the end of the Ice Age, I argue that both the Neolithic and the end of the Ice Age were caused by a decrease in seasonality.

IV.B. The Neolithic Invention Sequences in Detail

My analysis centers on four key predictions regarding the evidence from each of the archaeological sequences of the seven independently developed agricultural systems: (i) that agriculture's introduction was preceded by increased seasonal variability in temperature or rainfall, (ii) that there was a transitional sedentary or semisedentary phase among hunter-gatherers before agriculture emerged, (iii) that intensive storage became prominent only after populations settled, and (iv) that storage was practiced prior to the advent of agriculture. The findings are summarized in Figure III. Detailed analyses of each sequence appear in Online Appendix B.

Paleoecological records such as local oxygen isotope, pollen, and lake sediment data[2] from all seven original Neolithic sequences reveal a significant increase in seasonality before the advent of agriculture (Prediction (i)). The archaeological evidence on the other three predictions is mixed but generally supportive. For three sequences (those in the Middle East, north China, and the Sahel), we see affirmative evidence for all four predictions, indicating that sedentarism and storage preceded agriculture. For

2. These data align with the global data from He (2011) used in the general analysis.

two sequences (South America and south China), there is positive evidence for three predictions, with South America showing early storage before full sedentarism and south China no evidence of intensive storage prior to agriculture. For the remaining two sequences (eastern North America and Mesoamerica), the answers to only half of the predictions are affirmative. In eastern North America, limited food storage began while the population remained nomadic and was followed by cultivation and then sedentarism. In Mesoamerica, some forms of agriculture were adopted first, and then came sedentarism and storage.

My method tests 28 location–prediction pairs (the seven locations times the four predictions), confirming 22 of them. The failure to confirm some of the predictions might reflect gaps or ambiguities in the archaeological record rather than inaccuracies in the model, however. Discrepancies may arise, for example, from the brief duration of periods of hunter-gatherer sedentarism with storage, which could make it easy to overlook in archaeological records, especially in areas with limited excavation or poor preservation conditions. Moreover, the theory focuses on storage which is vital for a population to survive year-round, not just improve its security or benefit from economies of scale, and the categories of evidence used in my model do not always align with archaeological data with respect to residence patterns, agriculture extent, and storage usage.[3]

V. Overview of Empirics

The model predictions discussed in Section III.D now need to be taken to the data. The goal of this section is to show that climatic seasonality was the main driver of the multiple invention of agriculture. First, I check whether agriculture was in fact adopted earlier in more seasonal locations (regardless of whether it was independently invented there or imported from abroad) and find that a one standard deviation increase in temperature seasonality is associated with adoption of agriculture 1,500 years earlier.

3. Distinguishing occasional cultivation from subsistence farming in archaeological records can be complex. For instance, a farming population that was fully sedentary in any given year but moved every few years (as is common even today in areas that practice slash-and-burn agriculture) would leave material remains remarkably similar to those of a farming population that moved camp every few months.

Second, I check whether the areas in the world where agriculture was invented independently were unusually seasonal, and I find that more seasonal locations did indeed invent agriculture earlier. Third, to check whether climate seasonality made agriculture spread faster, I measure the spread of agriculture from the Middle East into Europe. I find that populations inhabiting seasonal climates adopted faster after being exposed to farming. This allows me to compare my results to those of Ashraf and Michalopoulos (2015), who use interannual volatility instead of seasonality.

Further verification of the model's predictions comes from the Neolithic paleopathological record: analysis of skeletal remains has shown that consumption per capita did indeed decrease after the invention of farming, but the absence of growth arrest lines, a marker of highly discontinuous nutrition during childhood, confirms that consumption seasonality decreased as well.

VI. Data

The ideal data source to evaluate my model predictions would be a panel data set covering the full population for every time period since the emergence of the first *Homo sapiens* 150,000 to 200,000 years ago, detailing the precise moment they adopted agriculture, whether it was an independent invention or the product of cultural transfer from neighbors, the precise climatic conditions prevailing at each moment in time, and full nutritional diaries for each individual throughout this period. Obviously such a data set does not exist, but I take advantage of a variety of different data sets to investigate the most salient elements of my model predictions.

VI.A. Invention and Spread of Agriculture

I use information on the invention of agriculture from two main sources: direct archaeological evidence of plant domestication, typically dated by ^{14}C, and DNA sequencing of large populations of modern crops, which are then compared with the DNA sequences of modern wild plants to determine the locations with the closest match and the time elapsed since the last common ancestor (and hence the approximate time and place of domestication). Purugganan and Fuller (2009) synthesize evidence from these two distinct lines of research and distinguish 7 generally accepted primary (i.e., independent) domestication centers and another 17 potentially important secondary domestication centers. However, these data provide dates only for these domestication centers, which correspond to a very small share of all land areas.

To overcome this limitation, I complement the Purugganan and Fuller (2009) data set on invention locations with data from Putterman and Trainor (2006), which provides the time of agricultural transition for 160 countries, where transition is defined as the year by which the first local population in each country was obtaining at least half of its calories from domesticated plants and animals. Given the two different definitions of agricultural adoption in these sources (domestication of plants versus half of calories from agriculture), it is not surprising that the respective transition dates do not align exactly. To harmonize the data sets, I assign to individual cells whichever adoption date is earliest: the date assigned to the country that the cell belongs to (from Putterman and Trainor 2006) or the date of any domestication area that the cell may be part of (from Purugganan and Fuller 2009). This means that in large countries that independently domesticated crops within their borders, the specific regions where domestication occurred could have transition dates earlier than those for the rest of the country. For example, the areas of the northeastern United States that domesticated crops independently are coded as adopting agriculture 4,500 years ago (following Purugganan and Fuller 2009), while the rest of the country is coded as having transitioned 3,500 years ago (following Putterman and Trainor 2006).

While the Putterman data set enables me to track the adoption of agriculture on a global scale, the use of countries as the unit of analysis limits my ability to examine regional diffusion. To do so, I employ the finer-grained data set used by Ashraf and Michalopoulos (2015), which is based on earlier work by Pinhasi, Fort, and Ammerman (2005), which give the dates for the first evidence of agriculture in 750 different archaeological sites in western Eurasia. These sites chronicle the spread of the set of crops (mainly barley and various types of wheat) domesticated in the so-called Fertile Crescent, which diffused into Europe at an average speed of approximately one kilometer a year.

VI.B. Climate Data

My main source for climate data is the TraCE Dataset (He 2011), which uses the CCSM3 model to simulate global climatic conditions for the entire planet for the past 22,000 years. The model uses the orbital parameters of Earth, extent of glaciation in each hemisphere, concentrations of various greenhouse gases, and changes in sea level. The model outputs average temperature and precipitation totals for each trimester for 3.75×3.75-degree cells at yearly frequency. I aggregate the time dimension of the data set to 44 periods of 500 years each. These data allow me to analyze the invention and spread of agriculture using climate conditions contemporaneous to the Neolithic rather than proxying them using modern data sets.

The TraCE data have the advantage of providing insight into past climates, but for the regional analysis, their spatial resolution is marginal. Therefore, in the regressions using the higher-resolution Ashraf and Michalopoulos (2015) data set on European adoption dates, I instead use present climate data from the WorldClim 2.0 project (Hijmans et al. 2005), which is representative of average conditions between 1950 and 2000 and is available at 10 km resolution. From this data set, I use mean temperature, mean precipitation, average temperature of coldest quarter, average temperature of hottest quarter, average precipitation of driest quarter, and average precipitation of wettest quarter.[4]

VI.C. Other Data Sources

The altitude data used in the elevation range analysis are obtained from the Shuttle Radar Topography Mission, as described in Farr et al. (2007). For part of the analysis, I limit the data set to the subset of archaeological sites that had access to barley, emmer wheat, or einkorn wheat. I derive these by digitizing the maps from Harlan (1998, 94 onward).

VI.D. Variable Construction

The model predicts that agriculture was adopted when nomadic hunter-gatherers had to suffer through periods of seasonal

4. The use of present data to proxy past weather conditions could be problematic, especially when we compare outcomes very distant in space or time (e.g., New Zealand has a similar climate to western England today, but that does not mean this was true in the distant past, especially before deglaciation). Here, however, the analysis is limited geographically to western Eurasia and chronologically to the period after the end of the Ice Age. Together, these constraints allow us to tentatively assume that ordinal relationships are largely preserved (i.e., if Denmark is colder than Lebanon in the present, it is very likely that it was also colder in 8,000 BCE).

scarcity. This would have tended to happen when a given region experienced high seasonality in temperatures, precipitation, or both. Under these conditions, plant growth would be vigorous during part of the year but virtually absent in another.

The response of plants to temperature is not linear. In particular, no photosynthesis can occur once groundwater freezes, meaning that below 0°C, further decreases in temperature have little effect. At first sight, a location where winter is 40°C colder than summer might appear to be highly seasonal. However, if this oscillation is between −10°C and −50°C, in practice, there is never any food, and resource seasonality is effectively zero.

To avoid counting such a location as seasonal, I concentrate on the temperature range above 0°C:

$$TempSeas = \max(Temp.Warmest, 0) - \max(Temp.Coldest, 0).$$

That is, I first censor the average temperatures of each quarter at 0°C and then take the difference between the two. The logic behind this measure aligns with that of several commonly used agricultural suitability measures that also censor temperature variation below a specified limit. For example, growth degree days are calculated by first taking the maximum between the temperature of each day and a baseline value and then summing all the results. The baseline varies depending on the species analyzed, but is always above 0°C. The measure I use is therefore approximately proportional to the difference in growing degree days experienced in different seasons.

For precipitation, I use the amount of precipitation during the wettest month, minus the level during the driest, divided by mean precipitation, that is, the percent relative range:

$$PrecipSeas = \frac{Precip.Wettest - Precip.Driest}{MeanPrecip.}.$$

This measure is preferable to the simple range in precipitation across seasons because it does not place unwarranted emphasis on areas that are very rainy to begin with. An area with 1,000 mm of rain in the “dry” season, for example, and 3,000 mm during the wet season is unlikely to experience lack of food due to drought, while a region with precipitation of 200 mm in one season and 600 mm in another almost certainly will. This measure is also preferable to the simple ratio of wettest-to-driest precipitation level because it does not go to infinity as dry season precipitation goes to zero, which otherwise would overpower all other variation in precipitation seasonality or require me to introduce arbitrary cutoffs. The two seasonality variables share a correlation coefficient of 0.24.[5]

I proxy the average food supply with climatic averages. Mean temperature is the average temperature in degrees Celsius across the four seasons. Similarly, mean precipitation is the the average amount of rainfall in the four seasons, measured in millimeters per day.

VII. Results

VII.A. Global-Scale Analysis

The climatic data from He (2011) consist of 48 × 96 × 22,000 observations (latitude × longitude × years). My first step is to contract the data set along the time dimension by averaging the climatic variables by 500-year periods. The resulting data set has 48 × 96 × 44 observations, each representing the conditions present in a specific latitude and longitude during a specific period. I drop all observations for areas covered by water, Antarctica, and Greenland, leaving 1,024 cells in each period.

To this data set, I merge my data on agricultural invention by generating a dummy that takes the value of one if agriculture was invented in a particular place and time and zero otherwise. This variable is coded from the map in Purugganan and Fuller (2009). I generate another dummy—based on the Putterman and Trainor (2006) data on agricultural adoption—taking value one if agriculture had already been adopted in a particular time and place (regardless of whether it was invented locally or adopted from neighbors).

I further restrict the sample to those locations where we would expect significant human habitation, and agriculture to be feasible, by removing any location that receives less than 0.5 mm of rainfall on average, or has an average temperature colder than 0°C.

I begin by presenting some summary statistics on the Neolithic revolution (Table II). I collapse the data to a cross section of 1,024 cells by averaging all values of each variable for

5. Although it would be desirable if the two seasonality measures were symmetric, it does not make sense to normalize the temperature seasonality measure by the average temperature since it would risk dividing by zero and the zero point of the Celsius scale is arbitrary, making temperature an interval scale rather than a ratio scale.

TABLE II
SUMMARY STATISTICS FOR CROSS-SECTIONAL AGRICULTURAL ADOPTION DATA SET

	Mean	Std. dev.	Min	Max
Agri. adoption, years BP	−4,703.7	2,708.0	−11,500	0
Temperature seas.	11.87	8.06	0.50	33.14
Precipitation seas.	1.54	0.73	0.070	3.39
Mean temperature (°C)	16.42	7.54	0.32	28.23
Mean precipitation (mm/day)	2.51	1.89	0.10	10.51
Observations	587			

a given location through time. Of these, 587 are both warmer and wetter than the thresholds specified above. *YearAdop* is the date of the earliest evidence for agriculture in a given country, expressed in years before present. The very first farmers appeared 11,500 years ago, while some locations (e.g., Greenland) are still populated by hunter-gatherers today. The average location on Earth that passes the rainfall and temperature thresholds started farming 4,700 years ago, has an average temperature of 2.5°C, received 2.5 mm/day (approximately 650 mm/year) of rainfall, and had a temperature seasonality of 8°C and a precipitation seasonality of 1.5.

As Figure IV shows, six out of the seven independent inventions occurred precisely in—or very near—areas where seasonality increased. The outlier is Mexico, where dry lands with highly seasonal rainfall coexist in close proximity with tropical rain forests on the other side of mountains. The spatial resolution of the climate data set is marginal for these conditions as it necessarily averages rainfall figures that vary tremendously on the ground. Today, Oaxaca state (where Central American agriculture originated) has an extremely seasonal precipitation pattern, with virtually all rainfall occurring during half the year.

In any case, as summarized in Section IV.A and detailed in Online Appendix B, the specific archaeological sequences of all seven independent inventions show very high levels of seasonality, with spikes in close chronological proximity to the actual invention events.

1. *Impact of Seasonality on Date of Agriculture Adoption.* A first obvious question to ask regarding these data is whether agriculture appeared earlier in locations with greater seasonal-

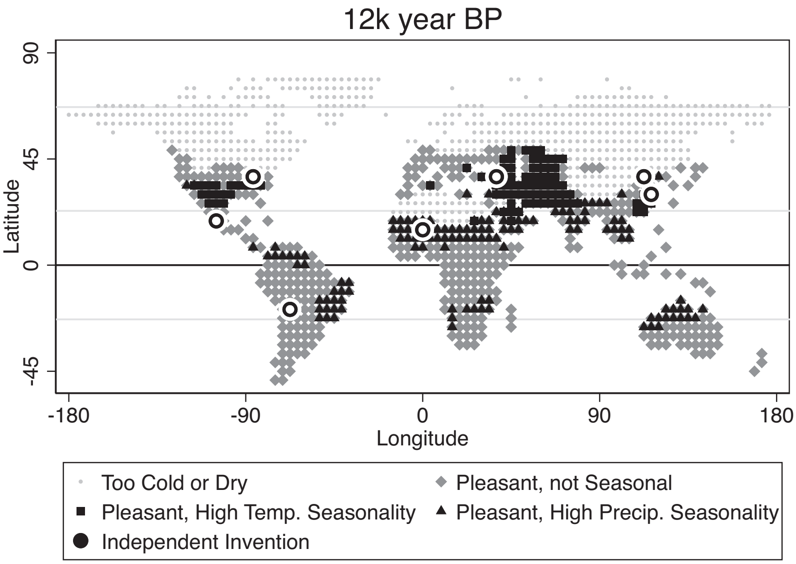

FIGURE IV

Global Distribution of Seasonal Locations

The map shows the global distribution of seasonal locations at the start of the Neolithic period. Seasonal temperatures were clustered around the mid-latitudes of the Northern Hemisphere. Seasonal precipitations were clustered in the monsoonal areas on each side of the Equator.

ity. For this part of the analysis, I collapse the data into a cross section where the dependent variable is the date of adoption and each explanatory variable takes the value it had when agriculture was adopted in the respective location. Locations with average temperature below 0°C rainfall below 0.5 mm/day have been dropped. Each observation is one 3.75×3.75-degree cell. The statistical specification is as follows:

$$Y_i = \alpha + \beta_1 T_i + \beta_2 P_i + \boldsymbol{\gamma C_i} + \varepsilon_i, \quad (7)$$

where Y_i is the date when cell i adopted agriculture, in years BP (i.e., 10,000 years ago is represented as $-10{,}000$), T_i is temperature seasonality, P_i is precipitation seasonality, and $\boldsymbol{C_i}$ is a vector of controls.

Table III shows the results. A negative coefficient implies that the given explanatory variable leads to earlier adoption of agriculture. Temperature seasonality is statistically significant across all specifications, and precipitation seasonality is

TABLE III
EFFECT OF SEASONALITY ON ADOPTION

	Temp. seas. (1)	Precip. seas. (2)	Basic (3)	Controls (4)	Controls + dist. (5)	Neighbor FE (6)	Neigh. + dist. (7)
Temperature seas.	−129.9***		−129.7***	−183.0***	−130.5***	−48.1	−39.8
	(32.7)		(32.8)	(49.0)	(45.2)	(30.3)	(30.8)
Precipitation seas.		105.1	73.2	−254.8	−156.6	−492.7**	−481.0*
		(318.8)	(289.2)	(318.6)	(272.4)	(243.0)	(244.0)
Mean temperature				367.4***	142.4	8.6	−2.4
				(111.2)	(86.5)	(63.5)	(67.2)
Mean precipitation				126.6	111.9	67.3	110.4
				(366.8)	(338.3)	(194.3)	(188.2)
Absolute latitude				118.7***	30.1	46.7	39.0
				(39.2)	(33.3)	(31.1)	(33.4)
Distance					−36.8		6.3
					(450.7)		(353.1)
Distance^2					116.7*		35.3
					(63.8)		(48.3)
Extra controls	No	No	No	Yes	Yes	Yes	Yes
Geographic FE	No	No	No	No	No	Yes	Yes
R^2	0.15	0.00	0.15	0.30	0.50	0.88	0.88
N	587	587	587	587	587	587	587

Notes. Linear regression of the date of adoption on time-averaged climatic variables for each cell. All columns: clustered errors for 104 geographic neighborhoods of 4 × 4 cells. Extra controls are the squares of mean temperature, mean precipitation, and absolute latitude and a dummy for the Americas. Standard errors are in parentheses. *$p < .1$, **$p < .05$, ***$p < .01$.

significant with the inclusion of the baseline controls. All columns report standard errors clustered at the level of square neighborhoods of 4×4 cells, of which there are 104.

Columns (1), (2), and (3) report the direct effect of temperature seasonality, precipitation seasonality, and both together, without any controls. In column (4), I add controls for mean temperature and precipitation and their squares, absolute latitude, and a dummy for the Americas. The results actually get slightly larger. In column (5) I add controls for the distance to the closest location that invented agriculture and its square. In column (6) I add 104 fixed effects for the 4×4 cell geographic neighborhoods. This moderates the effect size (likely at least partly because of attenuation bias), but the estimates in both columns are of the right sign and the coefficient on precipitation remains significant. Column (7) adds the distance controls to column (6). In the specifications with neighborhood fixed effects the effect switches from temperature to precipitation seasonality.

If we take column (4) as the preferred specification (i.e., with all controls), the results imply that an increase in temperature seasonality of one standard deviation (approximately 8°C) led to agriculture being invented some 1,500 years earlier, while the locations with the most seasonal temperatures (approximately 28°C) would be expected to adopt agriculture some 4,000 years earlier than locations with absolutely no temperature seasonality. Similarly, an increase in precipitation seasonality of one standard deviation (approximately 0.7 index points) would cause agriculture to appear some 500 years earlier, whereas the areas with the greatest precipitation seasonality in the sample (with an index of 3.5) would be expected to start farming approximately 2,500 years ahead of a hypothetically identical location with perfectly uniform rainfall.

The results from a spatial lag model with Conley geographically adjusted standard errors are similarly strong. These robustness check results are presented in Online Appendix A.3.

2. *Independent Invention.* Having established that climate seasonality predicts the date of agriculture adoption in the global sample, I now attempt to quantify the impact of seasonality on the invention of agriculture alone by using the data on independent domestications from Purugganan and Fuller (2009) and the panel of climate data from He (2011). As in the cross-sectional exercise, each observation is one 3.75×3.75-degree cell, but now

during a specific 500-year period. Again, locations with average temperatures below 0°C, or rainfall below 0.5 mm/day have been dropped. The basic specification is as follows:

$$\log\left(\frac{Pr(I_{it}=1)}{1-Pr(I_{it}=1)}\right)=\alpha+\beta_1\mathrm{T}_{it}+\beta_2\mathrm{P}_{it}+\boldsymbol{\gamma C_{it}}+\varepsilon_{it}, \tag{8}$$

where I_{it} is an indicator for onset of agriculture in cell i at time t, α is a constant, T_{it} is temperature seasonality, P_{it} is precipitation seasonality, and $\boldsymbol{C_{it}}$ is a vector of controls. The adoption dummy I_{it} is zero for all locations and periods representing times and places where agriculture was not invented, and has only seven ones, which represent the times and places where agriculture was invented. As soon as each location in the data set either invents agriculture or adopts it from neighbors, I drop it from the panel since it is no longer possible for agriculture to be independently invented there.

I use logistic regression to estimate the model and present the results in Table IV. All columns report exponentiated coefficients and standard errors clustered at the level of 104 square geographic neighborhoods of 4 × 4 cells. In columns (1), (2), and (3), I present my results with the baseline controls—first temperature and precipitation seasonality individually and then both together. Both coefficients show the expected sign, but only that on temperature seasonality is significant. The same pattern holds in column (4), where I add 500-year fixed effects, and in column (5), where I include a New World dummy, quadratic terms for absolute latitude, and quadratic terms for the climatic means. In column (6) I add 500-year fixed effects, and in column (7), I add controls for temperature and precipitation seasonality today, which confirms that the effect comes from climate conditions at the time of invention rather than modern conditions, ruling out the possibility that the effect runs through any correlation between present-day climate and current population density, income per capita, or funds for archaeological exploration.

The magnitudes implied by the coefficients are extremely significant. With all other variables fixed at their sample means, a location with zero temperature seasonality would be predicted to invent agriculture in any given 500-year period with odds of 1:20,000. At the sample mean temperature seasonality of 12°C, this probability would be 1:2,600, and at one standard deviation higher (8°C), the odds would be 1:700. Finally, the most seasonal locations, with a temperature seasonality of 33°C, would see

TABLE IV
LOGISTIC REGRESSION TO ESTIMATE THE EFFECT OF CLIMATE ON A DUMMY FOR THE INVENTION OF AGRICULTURE

	Temp. + basic (1)	Precip. + basic (2)	Both + basic (3)	Basic + 500 year FE (4)	Extra controls (5)	Extra controls + 500 year FE (6)	Modern weather (7)
Temperature seas.	1.192***		1.189**	1.220**	1.188**	1.180*	1.283*
	(0.077)		(0.083)	(0.095)	(0.089)	(0.102)	(0.193)
Precipitation seas.		2.165	1.854	2.121	1.760	1.426	0.758
		(1.543)	(1.116)	(1.490)	(1.027)	(1.066)	(1.323)
Mean temperature	0.983	0.926	0.992	0.882	0.883	0.738	0.966
	(0.070)	(0.057)	(0.065)	(0.074)	(0.213)	(0.223)	(0.088)
Mean precipitation	1.603*	1.370	1.851**	1.749*	2.813*	2.143	1.807*
	(0.458)	(0.326)	(0.530)	(0.584)	(1.734)	(1.502)	(0.592)
Absolute latitude	0.996	1.034	1.025	0.951	1.140	1.186	1.017
	(0.035)	(0.030)	(0.035)	(0.038)	(0.100)	(0.173)	(0.039)
Temp. seas. today							0.910
							(0.199)
Precip. seas. today							3.121
							(5.375)
Extra controls	No	No	No	No	Yes	Yes	Yes
500 year FE	No	No	No	Yes	No	Yes	No
Pseudo-R^2	0.07	0.03	0.08	0.13	0.09	0.15	0.09
N	16,989	16,989	16,989	2,212	16,989	2,212	16,989

Notes. Each observation is a particular place during a particular 500-year period, and each location is dropped from the sample after it adopts agriculture. All columns report standard errors (in parentheses) clustered at the level of 104 squares of 4 × 4 cells each. Exponentiated coefficients. $^{*}p < .1$, $^{**}p < .05$, $^{***}p < .01$.

agriculture invented with a probability of 1:77, over 30 times the likelihood of a location with average seasonality, and 260 times that of an otherwise perfectly average place with perfectly stable temperatures throughout the year.

Since the coefficients on precipitation seasonality are not significant, I will not go into as much detail, but the estimates still imply that going from perfectly even yearly rainfall to the greatest seasonality seen in the sample would increase the probability of agricultural invention from about 1:6,300 to 1:850, or about a sevenfold increase across the observed range.

These results are robust across a number of alternative specifications, as I show in the Online Appendix. Specifically, the results are not significantly affected when I include dummies for periods of 500, 1,000, 2,000, and 5,000 years (Online Appendix Table A4). They are also robust to my clustering based on geographic squares of 7, 15, and 30 degrees of latitude and longitude (Online Appendix Table A5) and to my using rare events logit and Firth logit, two alternative estimation techniques specifically designed to produce better estimates of standard errors in data sets with only a few positive observations (Online Appendix Table A6).

In principle, it would be desirable to include location fixed effects to ensure that the effect of seasonality is identified from the time variation alone. Unfortunately, doing so would reduce the data set to only the seven locations that invented agriculture independently, placing an excessive burden on the accuracy of the archaeological record and the precise timing of climate changes in each area. Nonetheless, as I show in Online Appendix Table A2, while culling all locations that never adopted agriculture removes the significance of seasonality when I use the dummy variable for the invention of agriculture, the results hold when I use the date of transition to a sedentary lifestyle for the places for which it is available in the sources consulted to compile Section IV.B.

In short, the data set has clear limitations given the few locations that independently invented agriculture and the high level of noise with which both the outcome and independent variables are measured. Nonetheless, even in this challenging econometric setting, seasonality performs remarkably well as a single explanatory factor common to the seven independent Neolithic transitions but not common during the preceding ice age, and the results of the statistical analysis confirm that this pattern is unlikely to be a simple coincidence.

VII.B. Spread of Agriculture in Western Eurasia

Despite their usefulness for the global-scale analysis, the data from He (2011) have only limited resolution, making them marginal for regional analysis. The methodology to construct the climate data set does not take into account small- to medium-scale topography, which has a large effect on the realized climate outcomes. In addition, the dependent variable (agricultural adoption) is coded with a single value for each state, which creates issues when we are dealing with large countries. In any case, different regions around the world have been excavated to different degrees, leaving open the possibility that agriculture was adopted in, say, the Amazon or sub-Saharan Africa at a much earlier date than is currently known.

To verify the findings of the global analysis in a setting not subject to these particular shortcomings, I look at the spread of agriculture from the Middle East into Europe. These regions have been at the center of concentrated study for well over a century and represent undoubtedly the most researched case of agricultural invention and expansion.

Specifically, I use data on 750 archaeological sites analyzed in Ashraf and Michalopoulos (2015) and originally published in Pinhasi, Fort, and Ammerman (2005). This data set includes the dating of the earliest definite evidence of agriculture, as established through ^{14}C dating. The resolution of the TraCE climate data set is far too low to be useful on this scale, so I substitute the WorldClim data from Hijmans et al. (2005), which are representative of average climatic conditions from 1950 to 2000 but have the advantage of being available at 10 km resolution.

As Figure V shows, the earliest agriculture in this sample emerged in a wide arc joining the eastern Mediterranean to the Persian Gulf. In fact, this area is currently believed to have featured the earliest case of plant domestication anywhere in the world. From the flanks of the Zagros and Taurus mountains, farmers and their crops spread out onto the plains of Mesopotamia and westward across the Bosporus, into the Balkans, and in two parallel thrusts into the northern European plains and the central and western Mediterranean.

Since agriculture was invented only once within this region, systematic statistical techniques clearly cannot be used to investigate invention. However, we can note that the Fertile Crescent is fertile only relative to the surrounding desert and semidesert

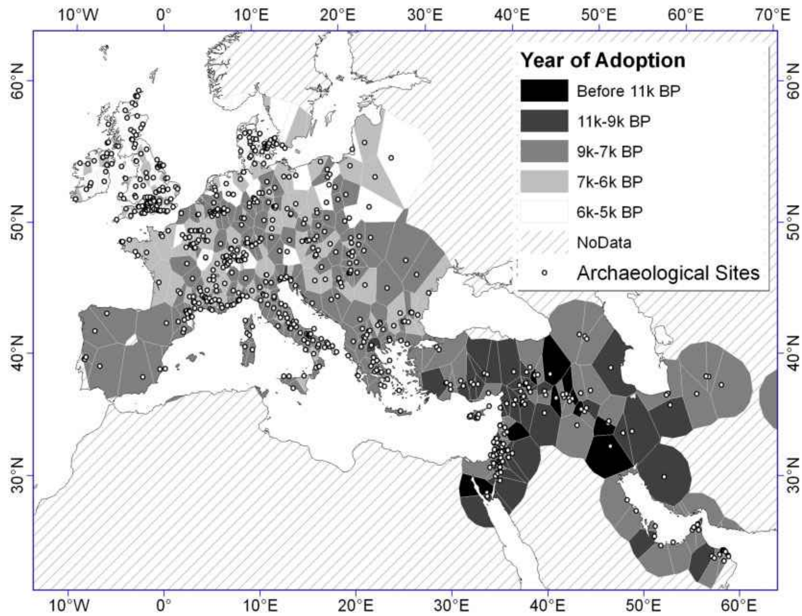

FIGURE V

Height and the Neolithic Transition

The Ashraf and Michalopoulos (2015) data set provides ^{14}C dates for the onset of agriculture in 750 locations, chronicling the spread of agriculture from the Middle East into Europe.

areas. Many locations on the northern shore of the Mediterranean enjoy similar conditions of high average temperatures and adequate rainfall. What seems to set the area apart is the fact that it is simultaneously a pleasant environment and an extremely seasonal one. Thus, the western Eurasian story of invention conforms to the general pattern observed globally in which the most seasonal locations adopted agriculture sooner.

Another advantage of this data set is that it allows me to directly test the validity of my theory alongside that of Ashraf and Michalopoulos (2015), who instead argue that agriculture was favored by intermediate levels of year-on-year climate variation. The two stories are in principle distinct and compatible with each other since both factors could have independently favored the invention of farming. However, the two explanations could potentially produce similar data patterns, making them hard to distinguish empirically. This is because the mid-latitudes have very high seasonality and intermediate variability from year to year (since in general year-on-year variation is correlated with seasonality). In fact the correlation coefficient between my temperature seasonality measure and their interannual variation in temperature measure is 0.6 in the western Eurasian sample. Nonetheless, including both sets of explanatory variables shows that seasonality is a good predictor of the adoption date of agriculture.

The basic specification is the same as that of the basic linear model in Section VII.A:

$$Y_i = \alpha + \beta_1 T_i + \beta_2 P_i + \boldsymbol{\gamma C_i} + \epsilon_i, \tag{9}$$

where Y_i is the year in which archaeological site i adopted agriculture, T_i is temperature seasonality, P_i is precipitation seasonality, and C_i is a vector of controls, including the interannual volatility measures used in Ashraf and Michalopoulos (2015). The result is presented in Table V, column (1) which once again shows that high seasonality is a strong predictor of early adoption, even when I include controls for distance to the locations where agriculture originated, altitude, and distance to the coast and the usual controls from the previous regressions.

In column (2), I replace the seasonality variables with the interannual average measures, and I find the same pattern described by Ashraf and Michalopoulos (2015), with moderate levels of volatility promoting early adoption and volatility at either extreme delays it.

Adding the seasonality and interannual volatility measures to the same regression (column (2)), I find that the temperature and precipitation seasonality measures retain their explanatory power; this is also true when I use interannual variation for only spring, summer, or fall temperatures. The only partial failure occurs when I use the interannual variation in winter temperatures, in which case the coefficient on precipitation seasonality remains significant but that on temperature seasonality is no longer statistically significant (though its sign is preserved and the estimate remains at similar magnitudes). Note that in this specification, the interannual variability measures are themselves insignificant. Further, across all specifications, the estimated effect of the seasonality when the volatility measures are included is consistent with what I obtain without those variables.

While the data set on hand is not ideal for differentiating between for the two theories, on the whole, we can rule out that the

TABLE V

COMPARISON OF EFFECTS OF SEASONALITY VARIABLES WITH THOSE OF INTERANNUAL VARIATION AS CALCULATED BY ASHRAF AND MICHALOPOULOS (2015)

	Seasonality (1)	IA average (2)	Both (3)	IA spring (4)	IA summer (5)	IA autumn (6)	IA winter (7)
Temp. seas.	−60.79**		−53.00*	−50.51*	−61.32**	−63.11***	−40.33
	(23.96)		(26.43)	(28.54)	(24.47)	(23.28)	(33.61)
Precip. seas.	−500.2***		−524.5***	−537.4***	−516.4***	−398.5***	−549.0***
	(126.3)		(118.3)	(124.4)	(125.6)	(113.2)	(118.7)
IA std. dev. avg.		−5,088.9*	−5,162.9**				
		(2,608.2)	(2,388.7)				
IA std. dev. avg. sq.		2,287.6**	2,390.8**				
		(1,070.0)	(962.0)				
IA std. dev. spring				−5,935.1***			
				(2,114.4)			
IA std. dev. spring sq.				3,037.6***			
				(965.2)			

TABLE V
CONTINUED

	Seasonality (1)	IA average (2)	Both (3)	IA spring (4)	IA summer (5)	IA autumn (6)	IA winter (7)
IA std. dev. summer					−1,087.0		
					(3,518.5)		
IA std. dev. summer sq.					508.4		
					(2,040.6)		
IA std. dev. autumn						−6,930.3***	
						(2,130.6)	
IA std. dev. autumn sq.						3,882.8***	
						(1,158.6)	
IA std. dev. winter							−1,793.0
							(1,571.1)
IA std. dev. winter sq.							514.1
							(412.6)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	750	750	750	750	750	750	750
R^2	0.705	0.694	0.711	0.713	0.706	0.713	0.709

Notes. All columns control for climate means and their squares, latitude, distance to origins of agriculture, and altitude, with residuals clustered at country level. Column (1): results for temperature and precipitation seasonality. Column (2): results for the standard deviation of interannual (IA) temperature averages and their squares. Column (3): results for both sets of explanatory variables at the same time. Columns (4)–(7): results for the seasonality measures and the standard deviations of average temperatures for spring, summer, autumn, and winter and their respective squares. All columns report standard errors (in parentheses) clustered at the country level. $^{*}p < .1$, $^{**}p < .05$, $^{***}p < .01$.

results are entirely or mostly driven by the presence of intermediate levels of interannual volatility (at least as measured by the data available). The data instead suggest that both sets of factors contributed to the timing of the Neolithic. One plausible scenario is that the increase in seasonality created the preconditions for the development of agriculture, while the interannual volatility determined the speed of agriculture's progress once it had been initiated.

VII.C. Impact of Large Seeded Grasses

The analysis conducted so far has established that seasonality is strongly associated with the adoption of agriculture. These findings align with the results from the model previously developed and suggest that farming was invented in locations where the incentive to store food was high.

However, there is another possible explanation for the observed pattern in the data: perhaps seasonal climates lead to the proliferation of plants that are somehow easier to domesticate. For example, Blumler (1992) shows that the Middle East has the largest concentration of large seeded grasses, which he argues were excellent targets for domestication. This theory has been popularized and expanded by Diamond (1997). Therefore, it is possible that the observed association between seasonality and agriculture adoption is due not to the decision to become sedentary to store but rather to the abundance of easily domesticable plants found in such climates.

To test this hypothesis, I add the domesticable plants measure from Hibbs and Olsson (2004) to the basic regression from Table III. These results are shown in Online Appendix Table A1. I find that while this variable has independent explanatory power, it does not significantly impact the coefficients for climate seasonality, or their significance. Therefore, the presence of domesticable plant species cannot be the only reason for the observed effect of seasonality.

VIII. Consumption Seasonality and Human Health

The model suggests that the transition from nomadic hunting and gathering to settled agriculture results in lower average food consumption but greater stability in food supply (Prediction iv). This section examines the different impacts of chronic malnour-

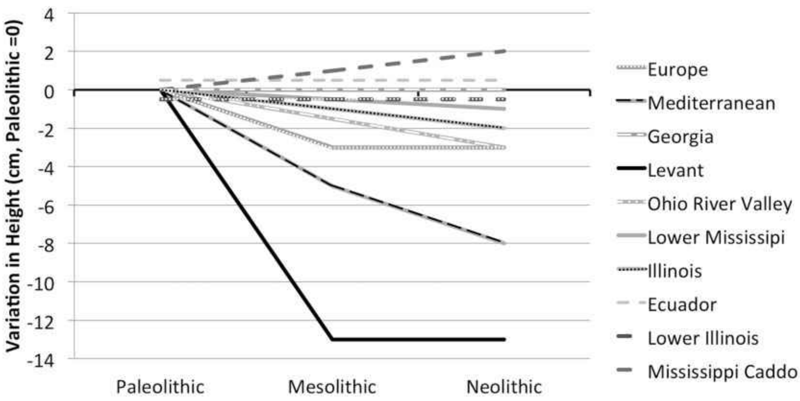

FIGURE VI

Height and the Neolithic Transition (Males)

Achieved adult height across the Neolithic sequences reported in Cohen and Armelagos (1984). Each line represents the progression in observed heights in one location, expressed as a difference from the value during the Paleolithic (nomadic hunting and gathering). The sedentary (Neolithic) farmers were clearly shorter than their nomadic ancestors. In the cases for which independent data were independently recorded for the Mesolithic (settled hunter-gatherer) phase, the decrease in standard of living can be seen to have predated the Neolithic.

ishment and acute starvation on the human body. It also compares these impacts with the health outcomes observed during the Neolithic revolution.

While healthy adults have fat reserves to buffer against short-term malnutrition, prolonged starvation can be fatal if energy demands exceed the available resources. Data show a decrease in per capita consumption when agriculture replaced hunting and gathering. Notably, as first documented in Cohen and Armelagos (1984) and later confirmed in Mummert et al. (2011), adult height, a proxy for health, significantly declined with the rise of agriculture. Other indicators of health deterioration include reduced skeletal robustness, increased tooth wear, and evidence of joint diseases and infections. These findings prompted Diamond (1987) to describe the agricultural transition as “the worst mistake in the history of the human race”.

Figure VI illustrates trends in average male height across regions in the Mesolithic and Neolithic relative to the Paleolithic. The decline in height during the Neolithic was not solely due to the dietary shift from meat to cereals. Late Paleolithic communities often relied on plants that were later domesticated, and early farmers continued to hunt (Humphrey et al. 2014). For example, the Natufian people's height decreased when they became sedentary and started food storage, even before cereals were a dietary mainstay.

This aligns with the model's prediction that average consumption would drop with a sedentary lifestyle and storage, remaining constant after farming adoption. However, measuring consumption seasonality is challenging. Height primarily indicates average nutrition in childhood, while food intake volatility is less detectable. Although acute starvation can temporarily halt skeletal growth in children, catch-up growth often leads them back to their original growth trajectory, masking starvation episodes (Williams 1981).

Nevertheless, catch-up growth leaves traces in the bones. Long bones grow outward from their ends, and rapid post-starvation growth leads to a layer of spongy bone inside the normally hollow bone. These layers, known as Harris lines, record growth disruptions until adolescence ends (Harris 1933). Harris lines can be observed through bone sectioning or X-rays.

In most locations where Harris lines have been counted for human remains from periods before and after the transition, they have been found to be numerous in skeletons from the nomadic hunting-gathering stage while comparatively rare in remains from the farming Neolithic. Cohen and Armelagos (1984) report Harris line counts for seven pairs of pre- and post-transition groups and find marked decreases in five pairs, no significant movement in one case, and a slight increase in the last pair. For example, nomadic hunter-gatherers in the Central Ohio Valley were 165 cm tall on average and had an average of 11 Harris lines each. When they started to farm, they became about three centimeters shorter but had only four lines on average. This evidence from Harris lines, together with that from height, suggests that hunter-gatherers ate well on average but starved for part of the year.

IX. Conclusion

What caused the Neolithic revolution? To answer this question, I examine the invention and early spread of agriculture. I propose that the most likely trigger was increased climatic seasonality, which forced nomads to become sedentary to store food, thereby preadapting them to the development of farming.

Using archaeological and paleoclimatic data, I find that agriculture appeared earlier in areas characterized by high seasonality. This explanation can further account for the fact that early farmers were shorter than their hunter-gatherer ancestors, without requiring any sort of irrevocable mistake on the part of each farming population. This interpretation of agricultural development is also supported by the comparative absence of growth arrest lines in the bones of early farmers.

This article helps explain why the Northern Hemisphere enjoyed a distinct technological lead for most of human history. Today, countries such as New Zealand, Australia, South Africa, and Argentina have climates very similar to those where agriculture originated. Why did these southern temperate areas not invent agriculture during the Neolithic? The shock to seasonality that triggered the transition happened only in the Northern Hemisphere (Berger 1992). As a result, these areas never experienced the extreme seasonality affecting the populations that actually invented agriculture. This likely delayed the invention of agriculture at latitudes south of 30°S, even where conditions were otherwise favorable.

The theory of the origins of agriculture developed in this study has a further desirable characteristic: it provides a compact explanation for the main stylized facts of the Neolithic revolution as a global phenomenon while remaining sufficiently general to coexist with almost any explanation for why agriculture was adopted in a specific region, at a specific time, and in a specific way. This is because the theory predicts that the Neolithic transitions should have been more likely in a few key areas that experienced large seasonality increases during the early Holocene: these included the temperate latitudes of the Northern Hemisphere, away from the western coasts of continents,[6] where brutal winters made finding food difficult, and the monsoonal regions on either side of the Equator, where the same was true of the parched dry season. However, within these general areas of increased likelihood, a vast array of factors could have determined why a specific population domesticated a specific plant at a specific time.

6. Because of the prevailing winds blowing west to east, areas such as Northern Europe and the US Pacific Northwest tend to enjoy a less seasonal, maritime climate than areas that are either landlocked or on the eastern coast of land masses, such as New England or China.

The demographic intuition underlying the dynamic model is potentially relevant to a wide range of different historical settings. Many human societies were and remain subject to seasonal resource availability. If such conditions could not be smoothed through storage or trade, the affected populations would have experienced the same fertility-reducing fasting suffered by hunter-gatherers. The model predicts that such societies should have lower population density but higher consumption per capita.

This article shows that when presented with similar incentives, humans from an expansive variety of genetic and cultural backgrounds developed a fundamentally similar set of solutions and adaptations. Furthermore, they did so within broadly comparable time spans. This remarkable convergence is evidence of the enormous potential for innovation and adaptation we share as a species.

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Supplementary Material

An Online Appendix for this article can be found at *The Quarterly Journal of Economics* online.

Data Availability

The data underlying this article are available in Matranga (2024) in the Harvard Dataverse, https://doi.org/10.7910/DVN/WWYKMN.

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