The Ant and the Grasshopper: Seasonality and the Invention of Agriculture

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Abstract

During the Neolithic Revolution, at least seven different human populations independently invented agriculture, without any contact with one another. How is it possible that these rapid advancements in agricultural techniques all occurred in the same, relatively short period of time? In this paper, I argue that rapid agricultural innovation was a response to a large increase in climatic seasonality. In the regions most affected by this process, hunter-gatherers abandoned their traditional nomadism in order to store food and smooth their consumption. As a result of their newfound sedentary lifestyle, it was much easier for hunter-gatherers to invent and adopt agriculture. I present a model that captures the key incentives for the Neolithic Revolution, and I test the resulting predictions against a global panel dataset of climate conditions and Neolithic adoption dates. I find that invention and adoption were both systematically more likely in places with higher seasonality. The findings of this paper imply that seasonality patterns 10,000 years ago, were one of the major determinants of the order in which different regions adopted agriculture. JEL Codes: O33, O44, N50.

1 Introduction

How and why was agriculture invented? The long run advantages of abandoning hunter-gathering techniques and adopting agriculture are clear: farming brought about food

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surpluses that allowed population densities to rise, labor to become increasingly specialized, and cities to be constructed. Despite these seemingly intuitive advantages, we still don't know what motivated the transition from hunter-gathering to farming in the short run (Gremillion et al., 2014; Smith, 2014). After 200,000 years of hunting and gathering, agriculture was invented independently at least seven times, on different continents, within a 7,000 year period. Archaeologists agree that at a very minimum, independent inventions of agriculture occurred in the Fertile Crescent, sub-Saharan Africa, North and South China, the Andes, Mexico, and North America. Interestingly, the first farmers were shorter and had more joint diseases, suggesting that they ate less than hunter gatherers and worked more (Cohen and Armelagos, 1984). The question thus arises: why would seven different human populations decide to adopt remarkably similar technologies, around the same time, if it meant they would work more for less food?

I propose a new theory for the Neolithic Revolution, construct a model capturing its intuition, and test the resulting implications against a panel dataset of climate and adoption. I argue that the invention of agriculture was triggered by a large increase in climatic seasonality, which peaked approximately 12,000 years ago, shortly before the invention of agriculture. This increase in seasonality was caused by oscillations in the tilt of Earth's rotational axis, and other orbital parameters that have been well documented by astronomers and geophysicists (Berger, 1992). The harsher winters and drier summers, made it hard for hunter-gatherers to survive during part of the year, and some of the most affected populations responded to these changes by storing wild foods. This in turn forced them to abandon their nomadic lifestyles, since that would have forced them to spend most of the year next to their granaries, either stocking, or drawing from them. While these newly formed sedentary communities still hunted and gathered wild foods rather than grow crops, sedentarism and storage made it easier for them to eventually adopt farming.

To guide the empirical analysis, I develop a simple model that analyzes the incentives faced by hunter-gatherers relying on a resource base that varies across both space and time. I modify the standard Malthusian population dynamic by assuming that, keeping average food intake constant, seasonality in food consumption reduces fertility. I find that a large increase in the seasonality of the environment can cause agents to abandon nomadism and adopt settlement, even if they still don't know how to farm. Despite eating less on average, the ability to smooth consumption through storage more than made up for the decrease in average food intake . This meant that the settled farmers were better off both in the short and long run.

The theory suggests that more seasonal locations would adopt agriculture sooner. To test this prediction, I employ a panel dataset of reconstructed climates, covering the entire world for the past 22,000 years. Each cell represents an area of 3.75 degrees of latitude and longitude. My results are summarized in Figure 1. I find that both temperature and precipitation seasonality are strong predictors of the date of adoption of agriculture? [1] In the global sample, increasing the within-year temperature range by 10 °C causes the local population to start farming approximately 1,000 years earlier. This result comes through two channels. First, higher seasonality made the invention of agriculture easier: all seven locations in which agriculture was invented had recently become exceptionally seasonal, either in temperature or rainfall. Second, the more seasonal a given location was, the faster its inhabitants adopted agriculture after being exposed to it. I repeat the analysis in a higher resolution regional dataset, chronicling the invention and spread of cereal agriculture in Western Eurasia, and I obtain qualitatively similar results.

While the statistical relationship between climate seasonality and the adoption of agriculture is significant and robust, it could still be unrelated to the incentive to store

[1] The precise measures used are described in Section 6.4.

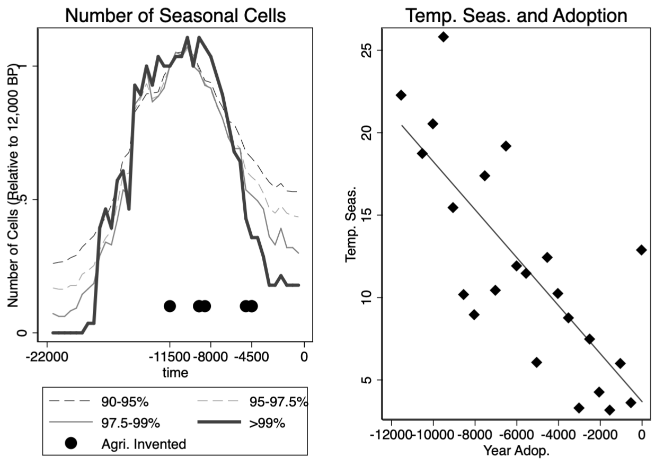

Figure 1: The left panel shows the number of cells that at a particular time fall within a specified interval of percentiles of seasonality, normalized by their prevalence 11,5000 years ago, at the very onset of the Neolithic period. The percentiles refer to the full distribution of the seasonality measure throughout all time periods. Thus, for example, until 18,000 years ago, no place in the world experienced conditions within the 1% of the full historical distribution of seasonality. The graph shows that the most seasonal conditions are the ones that experienced the greatest proportional increase. Right panel: binned scatterplot of temperature seasonality and adoption; early adopters tend to be highly seasonal, and vice versa.

food. For example, a short growth season might have favored the evolution of plants that were easier to cultivate (Diamond, 1997). To help separate these two channels, I look at a subsample of sites that had similar climates and availability of domesticable species, yet differed in the opportunities they offered to a nomadic band: some sites were close to large changes in elevation, meaning that nomads could migrate seasonally to areas with uncorrelated resource shocks; other sites were surrounded by areas of similar altitude to their own, rendering such migrations pointless. Consistent with my theory, I find that adding a 1000m mountain within 50km of a given site (i.e. out of reach of a settled band, but easily accessible to nomads) delays adoption by 500 years.

My theory is supported by a wealth of archaeological evidence. In the Middle East, the Natufians, ancestors of the first farmers, lived for thousands of years as settled hunter-gatherers, intensively storing seasonally abundant wild foods (Kuijt, 2011). Even in historical times, hunter-gatherers exposed to seasonal conditions have responded by becoming sedentary and storing food for the scarce season. For example, Native Americans in the Pacific Northwest relied on highly abundant, but highly seasonal salmon runs, which they would trap en masse and smoke for the winter (Testart, 1982). While the complex life cycle of salmon made them impossible to domesticate, they nonetheless enabled the emergence of societies that had almost all of the characteristics of farming villages, with the exception of farming itself. These included permanent houses in which inhabitants could live in year long, elaborate material cultures, and social stratification.

Taking storage into account can help us understand why agriculture was adopted in spite of the reduction in consumption per capita: the first settlers accepted a poorer average diet in exchange for the ability to smooth their consumption. Evidence from growth-arrest lines in their bones confirms that while farmers ate less than hunter-gatherers on average, they suffered fewer episodes of acute starvation (Cohen and Armelagos, 1984).

The technological advances of the Neolithic Revolution are unique insofar as very similar technologies were developed, in different places, by groups with no known contact with one another. Unlike the Industrial Revolution, for instance, in which steam technology spilled out of Britain before it could be duplicated elsewhere, it is therefore possible to draw parallels between different adoptions and identify their common elements.

Many contributions have focused on changes in average climate. Agriculture began and proliferated shortly after the end of the Late Pleistocene glaciation, which took place from 110,000 to 12,000 BP. This has led some researchers to hypothesize that warmer weather made hunter-gatherers evolve property rights, which in turn made the development of farming easier (Bowles and Choi, 2013), or indeed possible at all (Bowles and Choi, 2019). In contrast, others hypothesized that the accompanying drier conditions rendered hunting and gathering more difficult (Childe, 1935). Ashraf and Michalopoulos (2015) propose a variation on the climatic theme, arguing that intermediate levels of inter-annual climate volatility led to the gradual accumulation of latent agricultural knowledge. One drawback of these approaches is that they generally take for granted that the ultimate goal of the first farmers was greater *average* food consumption [2]. The fact that the first farmers ended up eating less than their foraging ancestors suggests that greater food consumption was an unlikely motive for abandoning hunting and gathering.

Other contributions have sought to explain the puzzling reduction in consumption per capita precipitated by the adoption of farming. This loss has been attributed, amongst other things, to unforeseen population growth (Diamond, 1987), the need for defense (Rowthorn and Seabright, 2010), or expropriation by elites (Acemoglu and Robinson, 2012). While these may well have been contributing factors, they do not explain why agriculture was invented in particular places at particular times. The key contribution of this paper thus lies in proposing a unified theory of the origin of agriculture which can explain both of these puzzles: the pattern of adoption of agriculture, *and* the decrease in consumption per capita that resulted. The model that I propose generates clear empirical predictions, which I test against the paleoclimatic record, the local topography of early adoption sites, and evidence from the skeletons of the first farmers.

This paper also contributes to the vast and growing literature on the economic effects of climate and the environment, for which Dell et al. (2014) provide an extensive review. I argue that increased climatic seasonality presented a challenge to humans' established modes of life. They responded by adopting a novel life strategy — sedentary storage — to mitigate the negative consequences of this change in climate. In itself, this new lifestyle was a big change, but it would be soon overshadowed by the even more momentous technological and social innovations that it facilitated: agriculture, increasingly stratified societies, and the accumulation of capital. As in Acemoglu et al. (2012), these finding remind us that when environmental factors force societies to invest in radically different technologies, the effect on the incentives to innovate are often more important than the immediate changes in lifestyle.

2 Literature review

A large multidisciplinary literature has sought to explain why humans abandoned hunting and gathering and started to farm. Early contributions (Darwin, 1868) took for granted the abundance of food that agriculture made possible, but the decrease in standard of

[2] Note that Bowles and Choi (2013) do not use utility maximizing agents, but instead describe the evolutionary dynamics of agents that have preordained behavioral strategies, which they then change over time based on their payoffs. Nonetheless their payoffs are specified over the *average* amount of food rather than incorporating any kind of seasonality or convex, so that in practice we would still expect food consumption to increase after the transition to agriculture.

living (which had not yet been discovered in Darwin's time) suggests that this was not the primary reason. Climate change is arguably the only factor capable of explaining the fact that agriculture was invented on different continents more or less simultaneously Richerson et al. (2001). Moreover, this explanation also agrees with the fact that agriculture was invented after the end of the last Ice Age. This suggested that warmer climates may have made farming easier (Diamond, 1997; Bowles and Choi, 2013), or that drier conditions made hunting and gathering worse (Braidwood, 1960). For Dow et al. (2009), the Neolithic revolution was the result of a large climatic reversal: first, warmer climates allowed population densities to rise, but a later return to near-glacial conditions forced hunter-gatherers to concentrate in the most amenable environments. A running issue with these climatic theories is that while they fit the archaeological sequences for the locations they describe, they have not been able to explain why agriculture did not emerge earlier in other locations were subject to similar conditions. The last Ice Age lacked neither warm conditions, nor dry ones, nor climatic improvements followed by rapid reversals, and yet agriculture was not invented. Humans had inhabited areas with similar conditions for tens of thousands of years without any sign of progress towards agriculture.

Ashraf and Michalopoulos (2015) propose that intermediate levels of inter-annual volatility favored the accumulation of latent agricultural knowledge. They use modern cross-sectional climate data to show that both very high and very low levels of year-on-year variation in temperatures appears to have delayed adoption. Their paper is in some ways similar to my own — both isolate a type of climate as crucial for agriculture and test their hypothesis using a variety of climate and adoption data. However, our contributions are both theoretically distinct, and empirically distinct. In this paper it is seasonality that plays a central role in the decision to store food, while they focus on unpredictable volatility from year to year, and its resultant impact on technological growth.

Other contributions have focused on the role of demographic increase. One possibility is that environmental overexploitation decreased the productivity of hunting and gathering (Olsson and Paik, 2020; Smith, 1975). Locay (1989) proposed another channel: rising populations reduced the size of each band's territory and thus reduced the need for nomadism. Populations responded by settling in a single place, which made farming much easier. As in the present paper, settlement is thus seen as an essential stepping stone towards the Neolithic. However, I argue that the loss of usefulness of nomadism came from a highly seasonal climate, which made all locations within migratory range similarly unproductive at the same time of the year.

An extensive multidisciplinary research effort has investigated the long run impact of the invention of agriculture. Cohen and Armelagos (1984) documented a large and persistent decrease in a number of health measures. Diamond (1997) argued that populations that transitioned early gained an early technological lead, that largely predetermined which continents would eventually inflict colonial conquest, and which would be subject to it. The switch to farming influenced our genes, by selecting for certain psychological and physiological traits which we still carry (Galor and Michalopoulos, 2012), (Galor and Moav, 2007). Crops that required plowing placed a premium on upper body strength, resulting in persistent differences in gender norms (Alesina et al., 2013). Indeed, cultivation of the same crops could result in very different social institutions, depending on the surrounding geography (Mayshar et al., 2022).Olsson and Paik (2013) suggest that continued farming gradually increased land productivity, but eventually led to more autocratic societies.

My analysis suggests that our ancestors rejected an abundant albeit risky lifestyle in exchange for one that had lower, but more stable returns. Risk aversion has been proven to be a powerful motive for lifestyle decisions, especially in populations close to the subsistence limit. McCloskey (1991) showed how English medieval farmers preferred to diversify their labor investment across scattered fields, even though this reduced their productivity. Acemoglu and Zilibotti (1997) argued that the presence of large risky projects slowed down technological progress. Tanaka (2010) examined farmer's utility functions in a series of field experiments in Vietnam and found that the inhabitants of poorer villages were more risk averse. In most of these articles, risk-aversion is seen as an economically costly trait. I show that a desire for stability can also promote economic growth, if the adopted risk mitigating strategies happen to make important innovations less costly.

In the basic Malthusian framework, populations should never be able to maintain consumption per capita significantly above subsistence. To explain how some societies have recently been able to enjoy high incomes for extended periods, Galor and Weil (2000) proposed that continued population growth increased the rate of technological progress, motivating parents to have fewer children, each with more human capital. This shift could have led to the proliferation of genetic traits that were complementary to economic growth (Galor and Moav, 2002). Alternatively, the death of a significant part of the population could force a shift to a production system that caused higher mortality (Voigtländer and Voth, 2013b), and lower fertility (Voigtländer and Voth, 2013a). Dutta et al. (2018) show that incomes can remain above subsistence if agents derive utility also from non-food items, such as entertainment. I contribute to this literature by showing that a population equilibrium with high consumption per capita can also be caused by seasonality in food consumption.

A number of recent contributions have explored the effect of topographic relief on economic outcomes. Nunn and Puga (2012) showed that rugged areas in Africa were partially protected from the incursions of the slave trade. Michalopoulos (2012) documented the role of ruggedness in forming ethnolinguistic groups, while Fenske (2014) noted that regions with more varied ecosystems experienced greater incentives to trade, and showed that the more successful African governments benefited from these conditions. My research contributes to this literature by showing that variations in altitude can have opposing effects depending on the scale at which they occur. In particular, they can create a variety of different microclimates within a compact region, affecting the usefulness of mobility.

Latitude correlates heavily with most measures of development. Explanations for this phenomenon have included unabashed racism (Montesquieu, 1748), thinner soils, more harmful parasites, ferocious diseases, unstable rainfall, and lack of coal deposits (Bloom et al., 1998). Acemoglu et al. (2002) maintain that the direct effect of these geographic differences is overshadowed by the institutional outcomes which they support. Easterly and Levine (2003) find support for this in a dataset linking GDP, institutions, the mortality of the first settlers, and several measures of natural resources. The results of this paper suggest that since latitude and seasonality are highly correlated, it is possible that part of the development lag of the tropics is due to their inhabitants having delayed the adoption of agriculture due to the lack of climatic seasonal conditions.

3 Historical background

3.1 The Neolithic as a Global Phenomenon

Agriculture was invented independently in at least seven different locations. Figure 2 shows the independent farming inventions and their dates (Purugganan and Fuller, 2009). It was a gradual process, set in motion by relatively minor actions – such as pulling up weeds, and culminating in highly complex endeavors – such as the construction of massive irrigation channels. Eventually these processes culminated in the domestication of the cultivated species, which made them more productive and easier to harvest (Harlan, 1992).

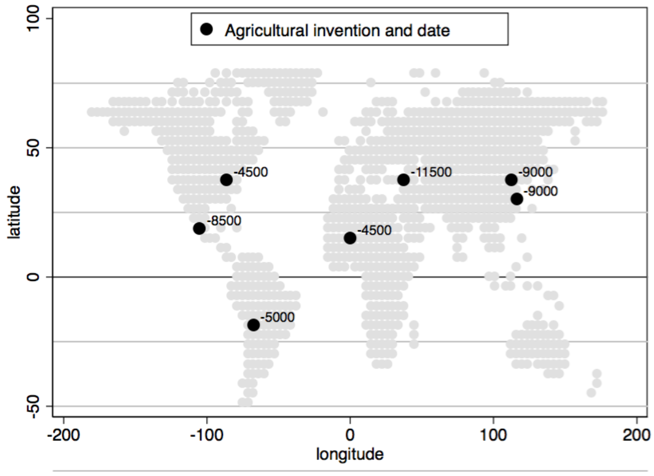

Figure 2: The locations where agriculture was invented and their respective dates in years before present.

Thanks to farming, the same amount of land could feed more people. The increased population density led to the rise of the first cities, with specialized labor and centralized leadership. Agriculture spread rapidly to neighboring communities, through various combinations of inter-marriage, conquest, and imitation. Eventually, hunter-gatherers were relegated to a few isolated or inhospitable locations. This process of diffusion is largely responsible for the current distribution of ethnic groups, languages, and food staples (Ammerman and Cavalli-Sforza, 1984). Furthermore, farmers were sedentary, and thus free to accumulate more personal possessions than nomads. Pottery, metalworking, and architecture were just some of the technologies that emerged or improved rapidly as a result.

The lack of progress towards agriculture after achieving behavioral modernity was at least partly due to the nomadic lifestyle typical of hunter-gatherers. Since successful farming required constant interaction with the plants under cultivation, it would have been very difficult for a nomadic population to develop agricultural techniques. First of all, nomads would typically never witness the same individual plant growing throughout the year. They were thus less likely to understand how their actions affected plant growth. Second, even if they did find out how to cultivate certain plants, they would have found it hard to schedule their movements so as to be present when farm work needed to be done.

In this paper, I argue that the Neolithic was ultimately caused by extreme climatic seasonality. But what caused these conditions?

Changes in global patterns of climatic seasonality depend chiefly on the shape of Earth's orbit, as described by three parameters. The first is the tilt of Earth's rotational axis, which determines how far each hemisphere will be tilted towards the Sun during its own summer, or away during winter. This is the primary determinant of the alternating seasons in each hemisphere. The other two parameters have smaller effects, but are still important. They are the eccentricity of the orbit, which determines how elliptical Earth' orbit is; and precession, which indicates whether the closest approach of Earth to the Sun occurs during the summer of the Northern or Southern hemisphere.

During the Ice Age, the Earth's rotational axis was less tilted, and its orbit was less elliptic. Moreover, when the northern hemisphere (which has most of Earth's landmass) was tilted towards the Sun, the planet was at its aphelion — the furthest point from the Sun along its orbit. As a result, the two effects partially canceled out, and climate in the Northern Hemisphere was not very seasonal. Between 22,000 and 12,000 BP, changes in these parameters made global climate patterns become steadily more seasonal (see Figure 3). By 12,000 BP, sunlight seasonality in the northern hemisphere was higher than it had been at any time since our species had acquired behavioral modernity, some 50,000 years prior.

In the northern temperate zone (between 30°N and 40°N), hunter-gatherers could gorge themselves during the hot rainy summers, but they risked starving in the harsh winters. Conversely, tropical areas enjoyed warm weather year round, but often suffered from intensely seasonal rainfall. Between 15° and 20° on either side of the equator, vast areas would come to life during the wet season, only to become barren during the dry one. In fact, all confirmed independent inventions of farming occurred within these areas: the Middle East, Eastern North America, North China and South China all lay within the temperate zone of the Northern hemisphere, while Sub-Saharan Africa, Mexico, and the Andes are all within the tropical area of rainfall seasonality.

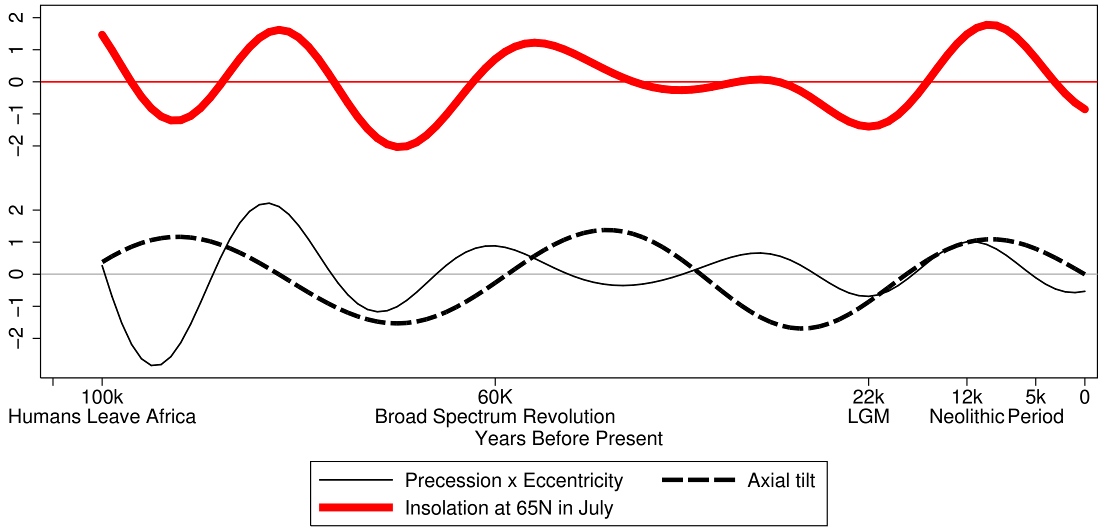

Figure 3: Three parameters combine to determine insolation seasonality in the northern hemisphere. During the Early Neolithic, these three cycles peaked simultaneously for the first time in over 100,000 years (black, I show the effects of axial tilt, and the combined effect of precession and eccentricity). As a result, the northern hemisphere was more seasonal then it had been at any point since humans left Africa. Data from Berger (1992). Seasonality conditions at 65° N (red) are indicative of those in the rest of northern hemisphere.

The change in seasonality was also responsible for the end of the last Ice Age. The warm summers caused ice to melt, while the cold winters actually inhibited snowfall (due to lower evaporation from the oceans). As a result, the glaciers which covered wide areas of the northern hemisphere retreated, raising global temperatures by 7 to 8° C. The spread of hunter-gatherers occurred against the backdrop of the Late Pleistocene glaciation (120,000 to 13,000 BP), during which average temperatures were up to 8 °C lower than today. Since agriculture was invented shortly after the start of the current warm period (the Holocene) it is tempting to assume that the emergence of agriculture was a response to higher average temperatures. Childe (1935) proposed that as the glaciation came to a close, drier conditions in the Fertile Crescent forced humans to concentrate in a limited number of oasis with a reliable supply of freshwater. These narrow confines would have provided the requisite incentives for developing agriculture.

Wright (1970) took the opposite tack, arguing that more *favorable* conditions at the end of the last Ice Age had allowed easily domesticable species such as wheat, barley and oats to colonize the Taurus-Zagros mountain arc, where agriculture would eventually emerge. While this explanation fits the evidence from the Middle East, it is unlikely that the global invention of agriculture was caused by changes in average climate. If the theory were true, we would expect farming to be developed in very warm locations. Instead, agriculture was invented in climates as different as those of Sub-Saharan Africa (hot and dry), Southern China (hot and wet), the Andes (cold and dry) and Eastern North America (cold and wet). While most of these locations did become warmer in the early Holocene, humans living closer to the Equator had experienced similarly pleasant conditions for tens of thousands of years.

3.2 The Neolithic Sequences in Detail

In this section, I summarize the archaeological sequences for the seven inventions of agriculture generally accepted as independent. I emphasize the evidence relevant to my hypothesis: storage, sedentarism, agriculture, and their relative chronology. I will draw broad conclusions on the the degree of agreement between my theory and the data, and propose explanations for the limited discrepancies I find. The more detailed discussion of each individual sequence is presented in Appendix B.

To summarize the multidimensional evidence, I have focused on four distinct questions. First, is the introduction of agriculture preceded by a sizeable increase in seasonality of either temperature or rainfall? Second, do we observe an intermediate stage of sedentary or semi-sedentary hunter-gatherers, before the appearance of agriculture? Third, do we find that intensive storage only appears after the population in question becomes sedentary? Fourth, do we observe the presence of storage before the introduction of agriculture? Figure 4 summarizes the findings:

	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 4: The four main predictions of the model, and the results for the seven independent transitions.

The clearest fit is with the climatic evidence: in all seven known original Neolithic sequences, the paleoecological record reveals a marked increase in seasonality before agriculture is introduced. This is local evidence from oxygen isotopes, pollen records or lake sediments, and is independent of the global scale reconstructed data from He (2011) used in the main empirical analysis. For the three remaining predictions, the record is more mixed, but nonetheless favorable. Three of the sequences (Middle East, North China, and Sahel) satisfy all four of the predictions. In each of these, the archaeological record shows that sedentarism and storage were already in place before agriculture appeared. Two further sequences satisfy three out of four predictions, each failing a different test: in South America there is evidence that at least some storage was undertaken before the populations became fully sedentary; while in South China there is no concrete evidence of intensive storage before the introduction of agriculture. Finally, two sequences satisfy only half of the predictions in the theory. In Eastern North America the evidence suggests that the local populations first began to store food even as they remained nomadic, then adopted significant cultivation, and finally became sedentary; while in the Mesoamerican sequence, agriculture appears first, followed by sedentarism and storage later.

Overall, the method I use to test the sequence of events, generates 28 possible location/prediction pairs (seven locations times four predictions), of which 22 are verified, and six are not. Various factors could explain the discrepancies: first and foremost, the amount of time spent in the intermediate stage of sedentary hunter-gatherers with storage is necessarily brief in comparison to the preceding period of nomadic hunting and gathering, and subsequent settled agriculture. It would therefore be easy for archaeologists to miss this stage altogether, particularly in those areas where only a small number of archaeological excavations have been performed, or where conditions are not ideal for preservation of soft remains.

Secondly, the categories that are of interest to the model do not map precisely to the types of evidence which archaeologists must rely on to determine residence patterns, the amount of agriculture performed, and the degree to which storage was employed. In the case of residency pattern, the model is interested in year-round occupation of the same site during normal years. This would allow enough time for to the population to gather food for the scarce season and live off of their stores, as well as eventually leading to the adoption of agriculture further down the line. Whether these settlements were occupied for decades or centuries, or for just one or two years (as is common even today in fully agricultural populations which perform slash-and-burn), is entirely immaterial to my theory. However, in practice it is difficult to distinguish a settlement which is used for three months, from one that is occupied for one or two years, unless the archaeologists are lucky enough to e.g. find different food remains that are each diagnostic of occupation in a different season. An archaeologist who was mainly interested in differentiating fully permanent settlements with complex architecture from everything else could well call both semi-sedentary and move on to describing other aspects.

Similarly for storage, my theory is interested in the accumulation of storable foods that are sufficient to sustain the entire population from one harvest season to the next, *and which are essential to the survival of the group even in normal years.* A given nomadic population might accumulate caches of food to improve their security after unpredictable climatic events, or because of economies of scale in collecting food sources which are in fact available throughout the year. As such caches were not crucial to the survival of the band in normal times, they could not be expected to represent a reliable tether confining the population to the same location year-round. By themselves, such cases of nomadic storage cannot reasonably be expected to result in the adoption of agriculture.

Finally, it is very possible for nomadic populations that remain in a single location for a few months at a time to engage in many forms of agriculture, even on a moderate scale. The question is again how central such activities are to the survival of the population. Even in modern developed contexts, a variety of people from all walks of life will tend a garden, growing some tomatoes or lettuce. In doing so, they use most of the same tools, and perform most of the same activities as a subsistence farmer that relies on the same crops for sustenance, but in practice they lack the efficiency, organizational know-how, and contingency plans to rely on their output for survival. And yet, if an archaeologist in the distant future were to find the remains of their gardening sheds, it would be very difficult without ample context for them to decide whether this clear example of cultivation was an occasional hobby, or a major part of their subsistence strategies.

It is therefore plausible that at least some of the apparent misses could reflect gaps and/or ambiguities in archaeological record, rather than failings of the predictions themselves.

4 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 will 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 will cause the band to prefer settlement, catalyzing the development of farming. When the band becomes sedentary, it loses access to some resources that could only be accessed nomadically, but the ability to smooth consumption through storage more than makes up for the loss in consumption per capita.

I then extend this basic intuition into a dynamic setting (sketched in the main text and fleshed out in Appendix , 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 is 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, are able to perfectly smooth their consumption through storage. Their stable diet ensures the maximum possible fertility, so that they have the lowest consumption per capita possible in a population equilibrium.

In the model we will assume that the average level of productivity is fixed. What makes this assumption defensible is the fact that population levels can be expected to adjust to the average level of resources available. Therefore, two nomadic populations living in environments with different average level of resources will in expectation have different population levels, but the same consumption per capita. In the static version of the model (Section 4.2), this equilibrium is assumed to already have been reached. Further, it is easy to show that in the dynamic version multiplying all resource levels by a fixed constant (i.e. increasing the average availability of resources) affects only the equilibrium population levels, but not the equilibrium utility levels or the optimal switching points.

In fact, the direct effect of the natural food productivity of a given territory on the likelihood of agriculture being adopted is in principle ambiguous. Logically, a more fertile area will have higher agricultural productivity, but it will also have a 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: 1) below a certain level of average productivity, it becomes impossible to become sedentary at all, because the land will simply not produce enough food within a reasonable radius of daily travel, for even the smallest viable group size. These are the conditions in which we generally find nomads living today: very dry and very cold places, which effectively force their inhabitants to a life of wandering. 2) Higher population densities favor the exchange of ideas and early domesticated crops, so denser populations are more likely to achieve the initial set of starting techniques and seeds necessary to make agricultural progress self-sustaining.

The model is also silent on the impact of variability from one year to the next, or one decade to the next. Variation at these scales can certainly impact the viability of incipient agricultural communities (as documented in Ashraf and Michalopoulos (2015), but the effect is almost entirely separable from what I examine in this paper. Seasonality is by definition extremely predictable, and also takes place within a single year. These two characteristics make it possible for a population with a suitable storage technology to smooth their consumption essentially perfectly — so long as its members accept becoming sedentary. In contrast, variability across years is essentially unpredictable, creating uncertainty over how much storage would be necessary. Also, due to the longer timeframes involved, spoilage would necessarily take a much greater toll on the accumulated stores. In most cases, the appropriate response to higher level of variability *between years* would be to become more nomadic, to improve the population's ability to reap whatever uncorrelated food sources still exist during bad years, rather than to become more sedentary and store food.

It might seem counter-intuitive that farmers (whom, after all, received most of their calories from a single crop) would face less volatility than the apparently diversified hunter-gatherers. However, it's important to keep in mind that the farmers had storage on their side, while the apparent diversification of the hunter-gatherers was illusory in highly seasonal locations, where their available food sources were extremely correlated. It would have been safer for them to face the occasional weak harvest, which could to some extent be partly offset by carryover of stores from the previous year, than to face certain hunger and perhaps starvation during an entirely predictable winter or dry season.

4.1 Setup

The unit agent of the model is a band, which has exclusive control over a specific territory. There are two locations in the band's territory, the Hill and the Plain, 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 Plain provides no food in July and $1-\sigma+\gamma$ units of food in the December. The parameter σ indicates the amount of climate seasonality in the region, while γ represents how much extra food is available in the Plain in December.

Table 1: Endowments of each location in each season

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

For example, we could imagine that the general area has a warm but dry July, but is cold and rainy in December. Hills are usually colder than the surrounding plain, but they receive more rainfall. Therefore, we would expect that in July the hills 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 will provide much less food. In the plains, the lack of rainfall makes food extremely hard to find in July. But in December, the plains are warm and wet enough to provide more food than in the hills. 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

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

4.2 Static model

I first compare the outcomes from the two strategies 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 is most abundant at the time. It will therefore choose to spend July on the Hill, but will descend onto the Plain 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 in the Hill (which has the highest aggregate endowment), and it will be able to perfectly smooth its consumption through storage. However, it will no longer be able to access the resources of the Plain, so aggregate consumption will necessarily be lower.

Specifically, the Nomadic band will consume C_N, and the Settled band will consume C_S, where

$$C_N = \{1 + \sigma, 1 - \sigma + \gamma\} \quad (2)$$
$$C_S = \{1, 1\} \quad (3)$$

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

$$U(N) = \ln(1 + \sigma) + \ln(1 - \sigma + \gamma) \quad (4)$$
$$U(S) = 0 \quad (5)$$

The utility of the settlers is therefore always zero, but that of the Nomads depends on the environmental parameters. A higher σ will lower nomadic utility, while a higher γ will increase it. These relationships are represented in Figures 5 and 6.

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

$$\sigma = \frac{\gamma + \sqrt{4\gamma + \gamma^2}}{2} \quad (6)$$

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

Proposition 1. *In the static model we find that:*

1. *If the climate is not very seasonal (low σ, and the band has access to uncorrelated ecosystems (high γ), nomadism will be optimal.*
2. *An increase in seasonality can cause settlement to become optimal.*
3. *The higher γ is, the more seasonal the climate must be before settlement becomes optimal.*
4. *Consumption per capita will be lower after the transition.*

4.3 Dynamic Model

In the dynamic version of the model, I modify a standard Malthusian framework by specifying that population is an increasing function of average consumption, and a decreasing function of consumption seasonality, while all endowments and choices over settlement pattern remain as before. As detailed in Appendix C.1, this model generates essentially the same predictions as the static one, during both the short and long run.

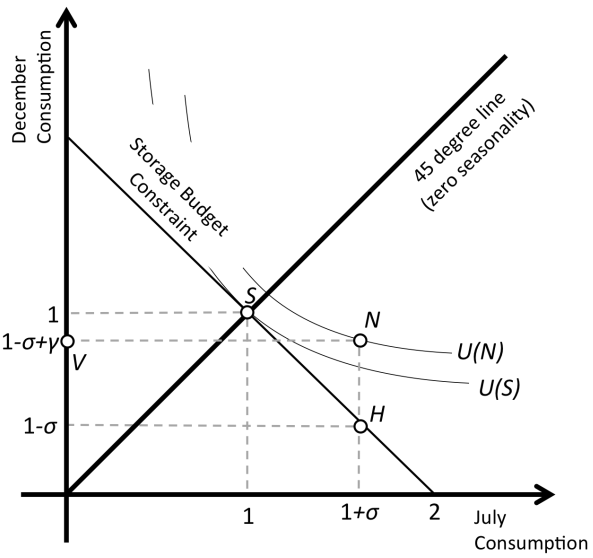

Figure 5: Circles H and V represent the endowments of Hill and Valley respectively. The Nomads are able to always reside in the best territory during each month, and therefore enjoy a consumption profile of N. The Settler can only harvest the resources of H, but can smooth consumption costlessly. It will therefore equalize its consumption across periods and achieve a consumption profile of S. In this case, seasonality σ is low, and the usefulness of mobility γ is high. The band, therefore, has a higher utility if it remains nomadic.

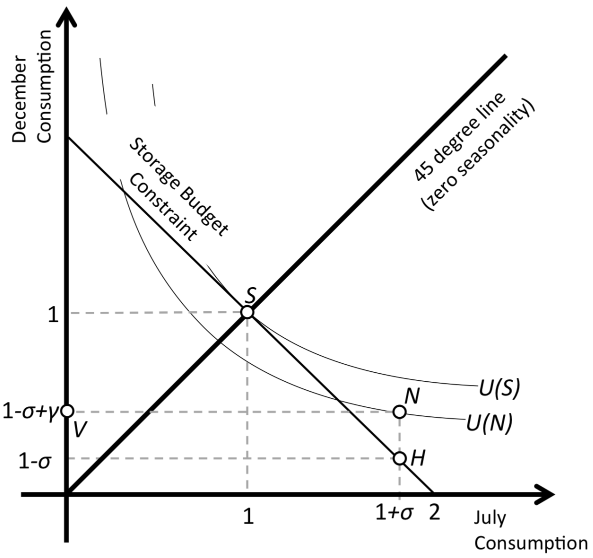

Figure 6: Now σ is higher, and γ is lower. A nomadic band would now be exposed to high consumption seasonality, so that utility is now higher if it switches to settlement. This is true despite settlement having a lower consumption per capita.

4.4 Predictions

The result of the models generate a number of empirical predictions, which can be verified using the archaeological and paleoclimatic record for the invention and spread of agriculture.

1. If a nomadic band becomes settled, average consumption per capita will immediately decrease due to the loss of access to the December Refuge endowment, but consumption seasonality will disappear.
2. In the long run, average consumption per capita of the settlers will remain lower than during nomadism (since consumption seasonality no longer depresses fertility).
3. For any level of γ, a sufficiently large increase in seasonality can make settlement optimal both in the short run and in the long run.
4. The higher γ is, the higher σ will have to be before settlement becomes optimal.

Thus we would expect settlement to be adopted en masse where seasonality is high and correlated across locations. These are precisely the conditions that became common shortly before agriculture appeared.

5 Overview of Empirics

The predictions of the model discussed in Subsection 4.4 now need to brought 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 one extra standard deviation of temperature seasonality is associated with adopting agriculture 1,500 years earlier. Second, I check whether the areas in the world where agriculture was *invented independently* where unusually seasonal, and I find that more seasonal locations did indeed invent agriculture earlier. And third, I check whether climate seasonality made agriculture spread faster, by measuring how long it took a particular location to adopt agriculture, once its neighbors had already begun farming. Indeed, I find that populations inhabiting seasonal climates adopted faster after being exposed to farming. I replicate the most important steps of this analysis on a higher resolution regional dataset for Western Eurasia, which confirms the earlier findings and also allows me to compare my results to those of Ashraf and Michalopoulos (2015), which use interannual volatility.

The preceding discussion establishes a strong and robust link between climate seasonality and the adoption of agriculture, but this association could be due to channels other than storage. For example, Diamond proposed that the invention of agriculture was caused by the availability of easily domesticatable plants, such as large seeded grasses. Did a short growth season favor the evolution of such plants? To avoid this threat to identification, I concentrate on a subsample consisting entirely of highly seasonal locations, but with heterogeneity in the ability of nomads to leverage their mobility (this investigates Prediction 4 from the model). I find that archaeological sites that had access to diversified environments within nomadic foraging range indeed show a delayed adoption of agriculture.

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

6 Data

Our ideal data source would be a panel dataset covering all population for every time period since the emergence of the first *Homo sapiens* 150k to 200k years ago, detailing the precise moment they adopt 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. Needless to say, such a dataset is not feasible, but the paper takes advantage of a variety of different datasets to investigate the most salient points.

6.1 The invention and spread of agriculture

Data on the invention of agriculture comes from two main sources: direct archaeological evidence of plant domestication, which are typically dated by ^{14}C; and DNA sequencing of large populations of modern crops, which are then compared to 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 between seven generally accepted primary (i.e. independent domestications centers) and a further seventeen potentially important secondary domestication centers. However this data provides dates *only* for these domestication centers, which are a very small minority of all land areas.

To overcome this limitation, I complement the Purugganan and Fuller (2009) dataset on invention location with data from Putterman and Trainor (2006), which provides the year of agricultural transition for 160 countries, where transition is defined as when the first local population in each country was obtaining half or more of its calories from domesticated plants and animals. Given the two different definitions (domestication of plants vs half of calories from agriculture) and the different sources used, it is not surprising that the two dates don't align exactly. To harmonize the two datasets, I assign to individual cells whichever adoption date is earliest: that of the country it belongs to (from Putterman and Trainor (2006)), or that of any domestication area it may be a part of (from Purugganan and Fuller (2009)). This means that within large countries that independently domesticated crops within their borders, the specific regions where domestication occurred could have dates that are earlier than the rest of the country. For example, the areas of the Northeastern United states that domesticated crops independently are coded as receiving agriculture 4500 years ago (following Purugganan and Fuller (2009), while the rest of the country is coded as adopting it 3500 years ago (following Putterman and Trainor (2006)).

While the Putterman dataset enables me to track the spread of agriculture on a global scale, the use of countries as a unit of analysis limits my ability to examine diffusion at the regional level. To obtain finer-grained data, I employ the data collected by Pinhasi et al. (2005), giving the dates for the first evidence of agriculture in 765 different archaeological sites in Western Eurasia. These sites chronicle the spread of the middle eastern set of crops (mainly barley and various types of wheat), which were domesticated in the so-called fertile crescent and diffused into Europe at an average speed of approximately one kilometer per year. The location of each archaeological site was checked against the literature, and the exact coordinates adjusted where necessary.

6.2 Climate data

My main source for climate data is the TraCE Dataset (He, 2011), which uses the CCSM5 model to simulate global climatic conditions for the entire planet for the last 22,000 years.

The model employs the orbital parameters of Earth, the extent of the glaciers in each hemisphere, the concentrations of various greenhouse gases, as well as changes to sea level. The model outputs average temperature and precipitation totals for each trimester, for 3.75x3.75 degree cells, at a yearly frequency. I aggregate the time dimension of the dataset into 44 periods of 500 years each. This data allows me to analyze the invention and spread of agriculture using climate conditions contemporaneous to the Neolithic rather than to proxy using modern datasets.

The TraCE data has the advantage of providing insight into past climates, but for regional-scale analysis, its spatial resolution is marginal. Therefore, in regressions using the higher resolution Pinhasi dataset on European adoption dates, I instead use present climate data from the BIOCLIM project (Hijmans et al., 2005), which is representative of average conditions between 1950 and 2000, and is available at 10km resolution. From this dataset, I employ 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.

The use of present data to proxy past weather could potentially be problematic, especially when comparing outcomes which are very distant in space or time (e.g. the fact that New Zealand has a similar climate to Western England today, does not mean this would be true in the distant past, especially before deglaciation. But in our case, 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 BC).

6.3 Other data sources

The altitude data used in the Elevation Range analysis were obtained from the Shuttle Radar Topography Mission (SRTM), as described in Farr et al. (2007). For part of the analysis, I limit the dataset to the subset of archaeological sites which had access to barley, emmer wheat or einkorn wheat. These are derived by digitizing the maps from Harlan (1998), from page 94 onwards.

6.4 Variable construction

The model predicts that agriculture will be adopted when nomadic hunter-gatherers have to suffer through periods of seasonal scarcity. This will tend to happen when a given region experiences high seasonality in temperatures, precipitation, or both. Under these conditions, plant growth will 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. But if this oscillation occurs between -10°C and -50°C, in practice there will never be any food, and resource seasonality will effectively be zero.

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

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

That is, I first censor the average temperatures of each quarter at zero degrees Celsius, and then take the difference between the two. The principle behind this measure is the same used by several commonly used measure of agricultural suitability, which 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 of the results. The baseline varies depending on the species being analyzed, but is always above 0° Celsius. The measure I employ will therefore be 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, i.e. 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 doesn't place unwarranted emphasis on areas that are very rainy to begin with. E.g. an area with 1000mm of rain in the "dry" season, and 3000mm during the wet season is unlikely to experience lack of food due to draught, while a region that has precipitations of 200mm in one season and 600mm in another almost certainly will. It is also preferable to the simple ratio of wettest to driest precipitation level because it doesn't go to infinity as dry season precipitation goes to zero, which otherwise would overpower all other variation in precipitation seasonality or require introducing arbitrary cutoffs. The two seasonality variable share a correlation coefficient of 0.24. [3]

I proxy for the average food supply by using 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 mm per day.

7 Results

7.1 Global-scale analysis

The climatic data from He (2011) consist of $48 \times 96 \times 22,000$ observations (Latitude$\times$ Longitude$\times$ Years). My first step is to contract the dataset along the time dimension by averaging the climatic variables by 500 year periods. The resulting dataset has $48 \times 96 \times 44$ observations, each representing the conditions present in a specific latitude and longitude, during a specific period. I drop all observations that are covered by water, Antarctica, and Greenland, leaving 1024 cells in each period.

To this dataset, I merge my data on agricultural invention, by generating a dummy that takes the value of 1 if agriculture was *invented* in a particular place and time, and 0 otherwise. This variable is coded from the map in Purugganan and Fuller (2009). I also generate another dummy – based on the Putterman and Trainor (2006) data on agricultural *adoption* – which takes the value of 1 if agriculture had already been adopted in a particular time and place (regardless of whether it was invented locally or adopted by neighbors).

I will begin by presenting some summary statistics for the Neolithic Revolution (Table 2) . I collapse the data to a cross-section of 1024 cells, by averaging all values of each variable for a given location through time. YearAdop is the date of the earliest evidence for agriculture in a given country, expressed in years before present. The very first farmers

[3]While it would be desirable to maintain the two seasonality measures symmetric, it does not make sense to normalize the temperature seasonality measure by the average temperature, since a) it would risk dividing by zero, b) the zero point of the Celsius scale is arbitrary, c) there is no sense in which going from 1 °C to 3 °C is a similar change to going from 10 °to 30 °C, and d) while normalizing using temperatures expressed in Kelvin degrees is possible, there is no particular biological justification for doing so.

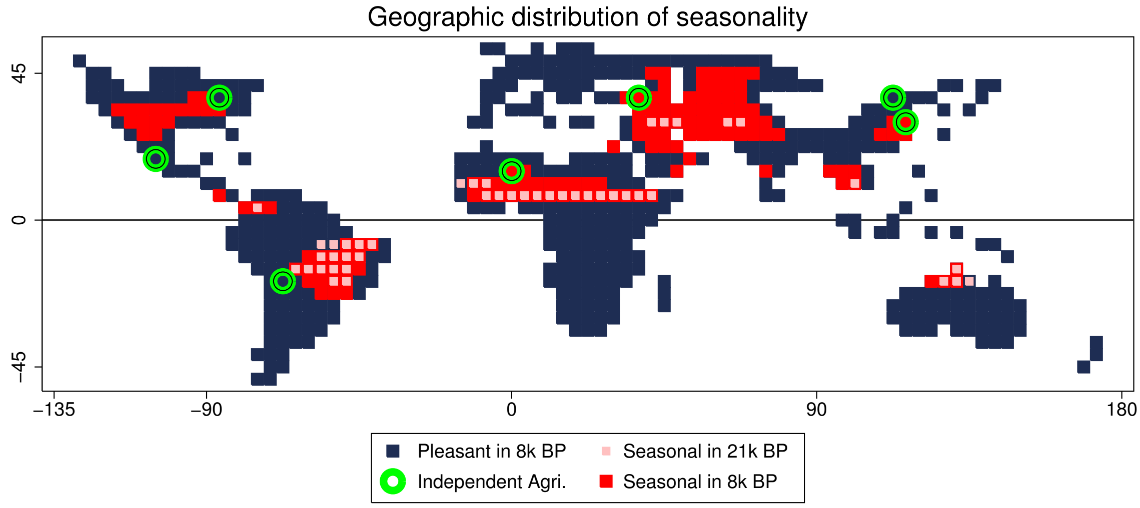

Figure 7: The map shows the global distribution of seasonal locations. Pink cells were already seasonal in 21k BP. Cells that were seasonal in 8,000 BP, are in red. Dark blue cells are hospitable in 8,000 BP (average temperature > 0 and annual precipitation > 100mm). Locations that were not hospitable in 8,000 BP are omitted. Most of the areas where agriculture was invented had recently become extremely seasonal.

appeared 11,500 years ago, while some locations are still populated by hunter gatherers today (e.g. Greenland). The average location on Earth started farming 4,500 years ago, had an average temperature of 2.5 °C, received 1.8mm/day of rainfall (approximately 650mm/year), had a temperature seasonality of 9 °C, and a precipitation seasonality of 1.3.

	mean	sd	min	max
Year Adop.	-4500.00	2500.43	-11500.00	0.00
Temp. Seas	8.85	7.26	0.00	28.98
Precip. Seas	1.35	0.67	0.16	3.58
Temp. Mean	2.49	17.44	-33.98	27.64
Precip. Mean	1.80	1.63	0.02	10.40
Seas. Index	625.13	225.53	84.37	993.60
Observations	1036			

Table 2: Summary statistics for the adoption cross-sectional dataset.

As Figure 7 shows, six out of seven independent inventions occurred precisely in areas where seasonality increased, or in very close proximity. The outlier is Mexico, where drylands with highly seasonal rainfall coexist in close proximity with tropical rain forests on the other side of the mountains. The spatial resolution of the climate dataset 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 3.1 and detailed in Appendix B, the specific archaeological sequences of all seven independent inventions show very high levels of seasonality, with spikes in close chronologitcal proximity to the actual invention events.

7.1.1 Impact of seasonality on date of adoption

A first obvious question to ask regarding this data is "did agriculture appear earlier in locations with higher seasonality?". Figure 8 shows binned scatterplots of date of adoption against measures of seasonality. The locations that adopted first were clearly much more seasonal than the late adopters.

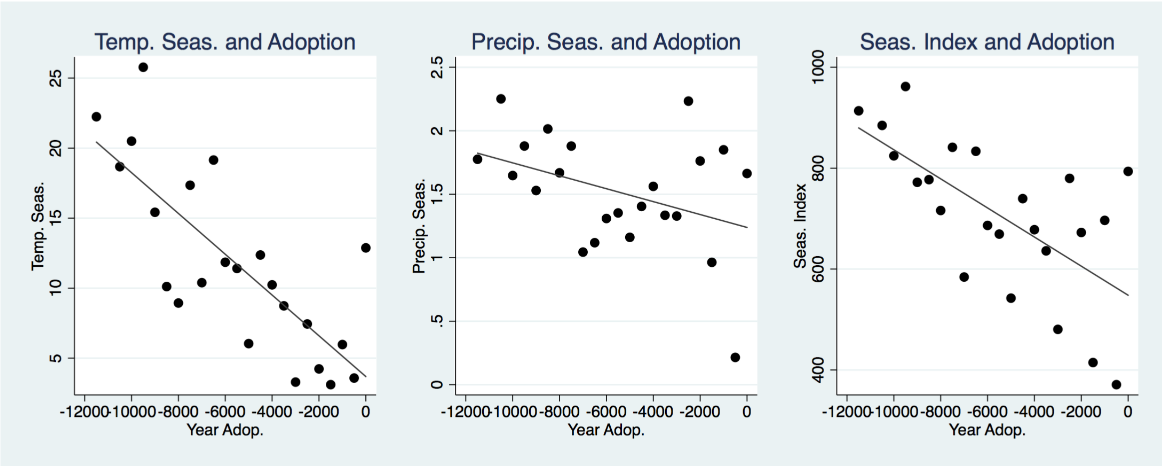

Figure 8: Binned scatterplots of different forms of climate seasonality vs the date of adoption. Locations exposed to more seasonal climates adopted agriculture ahead of more stable climates.

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 is given the value it had when agriculture was adopted in that location. Each observation is one 3.75x3.75 degree cell. The statistical specification, is:

$$Y_i = \alpha + \beta_1 \mathrm{T}_i + \beta_2 \mathrm{S}_i + \gamma[C]_i + \epsilon_i \tag{7}$$

Where Y_i is the date in which cell i adopted agriculture, in years Before Present (i.e. ten thousand years ago is represented as -10,000).

Table 3 Shows the results. A negative result implies that the given explanatory variable leads to earlier adoption of agriculture. Temperature Seasonality is statistically significant across all specifications, and Precipitation Seasonality is significant after the inclusion of the basic set of controls. All columns report clustered standard errors at the level of square neighborhoods of 4x4 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 Temperature and Precipitation Means (henceforth together referred to as Climatic Means) and Absolute Latitude, and the effect sizes actually increase. In Column (5), I include quadratic controls for Climatic Means and Latitude, and a dummy variable for the Americas, and in Column (6) I exclude all areas with less than 0 C average temperature, or less than 0.5mm day of rainfall. Results remain significant and broadly consistent in both of these specifications. In columns (7) and (8) I repeat the same analysis as the previous two columns, but this time including fixed effects for the 104 geographic neighborhoods. This causes the effect size to moderate (likely at least partly due to attenuation bias), but both columns have the right size and are significant in one or both measures of seasonality.

	(1) Temp Seas	(2) Precip Seas	(3) Basic	(4) Controls	(5) Quadratic	(6) No Arctic	(7) Neighbor FE	(8) Neigh. FE + Pleasant
Temp. Seas	-134.5***		-131.1***	-222.5***	-176.9***	-163.9**	-51.7*	-56.9
	(29.4)		(29.8)	(36.1)	(38.1)	(64.5)	(28.3)	(40.2)
Precip. Seas		-490.2	-152.2	-529.4*	-851.1**	-922.7**	-434.9**	-539.3**
		(308.3)	(277.4)	(299.5)	(331.2)	(406.3)	(182.8)	(265.1)
Temp. Mean				107.3**	95.5**	265.0*	9.5	37.7
				(47.6)	(37.4)	(135.6)	(24.7)	(55.6)
Precip. Mean				-464.3***	-95.6	5.9	-48.9	1.1
				(154.4)	(315.9)	(443.4)	(169.7)	(196.4)
Abs Lat				46.3	187.7***	146.0*	3.5	44.6
				(38.4)	(67.9)	(74.8)	(25.1)	(33.3)
Extra Controls	No	No	No	No	Yes	Yes	Yes	Yes
Geographic FE	No	No	No	No	No	No	Yes	Yes
r2	0.15	0.02	0.15	0.24	0.37	0.23	0.87	0.85
N	1024	1024	1024	1024	1024	482	1024	482

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Effect of seasonality on adoption (both invention and adoption from neighbors). Linear regression of date of adoption on time-averaged climatic variables for each cell. All columns: clustered errors for 104 geographic neighborhoods of 4x4 cells. Extra Controls are the squares of temperature mean, precipitation mean, and absolute latitude, and a dummy for the Americas.

If we take Column (6) as authoritative (i.e. all controls, no arctic or deser areas) the results imply that increasing Temperature Seasonality by one standard deviation (around 7 °C) will lead to agriculture being invented some 1,000 years earlier. While the locations with the most seasonal temperatures (around 28 °C) would be expected to adopt agriculture some 4,000 years earlier than locations with absolutely no temperature seasonality. Similarly, increasing precipitation seasonality by one standard deviation (around 0.7 points of the index), should cause agriculture to appear some 500 years earlier, while the areas with the greatest precipitation seasonality in the sample (with a precipitation seasonality index of 3.5) would be expected to start farming around 3,500 years ahead of a hypothetically identical location with perfectly uniform rainfall.

It is worth noting that while the measures of seasonality preserve their significance throughout the various specifications, the same cannot be said for the measures of climatic averages. This confirms the predictive weakness of linking agriculture to the end of the Ice Age. The results are similarly strong using a spatial lag model and Conley's geographically adjusted standard errors. The results from these robustness checks are presented in the Appendix A.4.

7.1.2 Independent invention

Having established that climate seasonality predicts the date of *adoption* of agriculture in the global sample, I will 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). Each observation is one 3.75x3.75 degree cell, during a specific 500-year period. The basic specification is:

$$Pr(I_i = 1|T_{it}, P_{it}, C_{it}) = \frac{1}{1 + e^{-(\alpha+\beta_1 \mathrm{T}_{it}+\beta_2 \mathrm{P}_{it}+\gamma C_{it})}} \tag{8}$$

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 C_{it} is a vector of controls. The adoption dummy I_{it} is 0 for all locations and periods representing times and places where agriculture was *not* invented, and has only seven 1s representing the times and places where agriculture *was* invented. As soon as each location in the dataset either invents agriculture or adopts it from neighbors, I drop it from the panel, since it is no longer possible for it to independently invent agriculture.

I use logistic regression to estimate the model and present the results in Table 4. All columns report clustered standard errors at the level of 104 square geographic neighborhoods of 4x4 cells. In columns (1), (2), and (3), I present my results with the baseline set of controls, first with temperature and precipitation seasonality individually, and then both together. Both coefficients show the expected sign, but only temperature seasonality is significant. The same pattern holds in column (4), where I add 500 yr FE, in column (5) where I include a New World dummy, quadratic terms for absolute latitude, and quadratic terms the two climatic averages. In column (6), I exclude locations that are colder than 0 °C on average, or have less than 0.5mm of rainfall per day. In column (7), I have both the extra controls and the 500 year fixed effects, and finally in Column (8) I add controls for the temperature and precipitation seasonality *today*, which confirms that the effect comes from climate conditions present at the time of invention, rather than today, avoiding the possibility that the effect comes through any correlation present-day climate might have with current population density, income per capita, and funds for archaeological exploration.

With the inclusion of fixed effects (Columns 7 and 8), the effect described in the previous paragraph reduced by about two thirds for temperature seasonality, and by about half for precipitations seasonality. It should however be noted that the implied effects are relative to other locations within the same local neighborhood of 15x15 degrees of latitude and longitude (an area roughly the size of Saudi Arabia).

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 1:30,000. At the sample mean of Temperature Seasonality of 10 C that probability would be 1:5,000, and one standard deviation above that (7 °C) the odds would be 1:1500. Finally, the very most seasonal locations, with a Temperature Seasonality of 30C, would see agriculture invented with a probability of 1:165, over 30 times as likely to invent agriculture compared to a location with average seasonality, and 200 times more likely than 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 1:13,000 to 1:1700, an eightfold increase across the observed range.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Temp+Basic	Precip+Basic	Both+Basic	Basic+500y FE	Extra Controls	No Arctic	Extra Controls + 500y FE	Modern Weather
Temperature Seas.	1.219***		1.218***	1.277***	1.193***	1.188**	1.192**	1.253*
	(0.065)		(0.065)	(0.077)	(0.078)	(0.089)	(0.095)	(0.171)
Precipitation Seas.		1.913	1.966	2.254	2.036	1.760	1.822	1.100
		(1.229)	(1.103)	(1.421)	(1.243)	(1.027)	(1.326)	(1.489)
Mean Temperature	1.032	1.097***	1.047	0.931	1.062	0.883	0.920	1.040
	(0.047)	(0.038)	(0.041)	(0.054)	(0.114)	(0.213)	(0.144)	(0.123)
Mean Precipitation	1.987***	1.590**	2.330***	2.240***	4.744**	2.813*	3.477*	4.459**
	(0.464)	(0.355)	(0.533)	(0.570)	(2.958)	(1.734)	(2.290)	(3.155)
Absolute Latitude	1.019	1.082***	1.052	0.967	1.120	1.140	1.133	1.127
	(0.037)	(0.030)	(0.038)	(0.039)	(0.087)	(0.100)	(0.137)	(0.109)
Temp. Seas. Today								0.936
								(0.203)
Precip. Seas. Today								2.106
								(2.773)
Extra Controls	No	No	No	No	Yes	Yes	Yes	Yes
500yr FE	No	No	No	Yes	No	No	Yes	No
Pseudo-R2	0.12	0.04	0.13	0.18	0.15	0.09	0.21	0.15
N	38533	38533	38533	4550	38533	16989	4550	38533

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: The table uses logistic regression to estimate the effect of climate on a dummy for the invention of agriculture. Each observation is a particular place during a particular 500 year period, and each location is dropped from the sample after they adopt agriculture. All columns report standard errors clustered at the level of 104 squares of 4x4 cells each.

These results are robust to a number of alternative specifications, as I show in the appendix. Specifically, I show that the results are not significantly affected by including dummies for periods of 500, 1000, 2000, and 5000 years (Table A5). I also show that results are robust to clustering based on geographic squares of 7, 15, and 30 degrees of latitude and longitude (Table A6), and to using Rare Events Logit, and Firth Logit, two alternative estimation techniques that are specifically designed to produce better estimates of standard errors in datasets with only a few positive observations (Table A7).

In principle, it would be desirable to include location fixed effects, to ensure that the effect of seasonality can be identified off of the time variation alone. Unfortunately doing so reduces the dataset to only the seven locations that invented agriculture independently, and places an excessive burden on the accuracy of the recovered archaeological record, and the precise timing of climate changes in each area. Nonetheless, as I show in Table A3, while culling all locations that never adopted removes significance of seasonality when using the dummy variable for invention of agriculture, the results carry through when using the date of transition to a sedentary lifestyle, for the cases where it's available in the sources consulted to compile Section 3.2.

To conclude, the dataset has obvious limitations due to the small number of locations which independently invented, and the high level of noise with which both the outcome and the independent variables are measured. Nonetheless, even in this challenging econometric setting, seasonality performs remarkably well in providing a single factor which the seven of the independent Neolithic transitions shared as a group, and which was 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.

7.1.3 Spread of farming

I now turn my attention to the process of agricultural diffusion, which saw farming and settlement expand from the handful of isolated pioneering outposts studied in the previous section, into becoming the dominant lifestyle for our species. For this part of the analysis, I construct a dataset consisting only of locations and time periods that are likely to receive agriculture soon. Specifically, from the full panel, I keep only observations that have hospitable climates [4], haven't already adopted agriculture, and have neighbors that are already farming. This sample represents the population which is "at risk" of adopting agriculture from neighbors.

The basic specification is:

$$Pr(A_i = 1|T_{it}, P_{it}, C_{it}) = \frac{1}{1 + e^{-(\alpha+\beta_1 \mathrm{T}_{it}+\beta_2 \mathrm{P}_{it}+\gamma C_{it})}} \tag{9}$$

Each observation represents a specific cell i, during a specific period t. I keep only observations which are on the agricultural frontier: i.e. cells that still haven't adopted agriculture themselves in a particular time period, even though at least one of their neighbors already has. The dummy variable A_{it} is coded as 1 if agriculture was first adopted in location i at time t and 0 in all other periods. Therefore, the dataset is empty for all periods preceding the first invention of agriculture (the Levant), at which point the cells neighboring it first enter the dataset, with a value of 0 for the dependant variable. They continue to be coded as 0s until they each adopt agriculture as well. In the period in which they adopt, they are coded as 1, and are subsequently dropped from the dataset from the next period onwards. Their *their* neighbors that were not already neighbors of the initial location now enter the dataset with a zero, and so on.

This approach is in many ways superior to simply including a control variable for the distance to the closest location of invention for two reasons. First, the independent inventions happened at different times, so simply using distance to the closest independent invention would have been 'unfair' towards locations that were close to later agricultural originators, such as Subsaharan Africa. Secondly, the simple distance measure does not take into account the geography of locations between the observation in question and the closest location of invention. The method used here measures how long it took agriculture to be adopted *after agriculture arrived in a particular neighborhood.* For completeness, I run the regression using distance to the closest independent invention of agriculture, and obtain very similar results (shown in the Appendix A.2).

This model is estimated using the logistic estimator, and the results are shown in Table 5. In Column (1) I regress adoption on Temperature and Precipitation Seasonality, Climatic Means, Absolute Latitude , the Calendar Year, and its square. In Column (2) I add controls for the Square of the Climatic Means, Absolute Latitude squared, and a dummy for the Americas. In Column (3) I run the same specification as in (2), but this time excluding all areas that have an average temperature below 0 °C or Mean Precipitation below 0.5 mm/day. In Columns (4) and (5) I repeat the analysis of Columns (2) and (3), but this time with the addition of the number of years a given location has been exposed to agriculture, its square, and its cube, thus forming a duration model. Finally, in column (6) I substitute the Calendar Year and its square with 500 year fixed effects. Across all specifications, both explanatory variables have the expected

[4] As in the previous sections, a location is considered hospitable if it has average temperatures above 0 ° C, and average rainfall of more than 0.5mm of rain per day.

sign, though only Temperature Seasonality is consistently economically and statistically significant, while Precipitation Seasonality is never significant and drifts in and out of irrelevance depending on the specification.

To quantify these results, I take Column (5) as a reference, i.e. the full duration model with quadratic controls for calendar year, and the cubic controls for number of periods exposed. With all other variables fixed to their sample means, the results s imply that a location with no seasonality would have only an 8% chance of adopting agriculture each period, while a location with a seasonality of 15 °C would have a 20% probability, and at 25 °C the probability would be 34%.

	(1) Basic	(2) Extra Controls	(3) No Arctic	(4) Duration	(5) Dur. + No Arctic	(6) 500yr FE
Temperature Seas.	1.076***	1.080***	1.078***	1.078***	1.075***	1.073***
	(0.020)	(0.022)	(0.028)	(0.019)	(0.024)	(0.025)
Precipitation Seas.	1.068	1.041	1.024	1.008	1.005	1.073
	(0.166)	(0.143)	(0.159)	(0.130)	(0.149)	(0.175)
Mean Temperature	0.992	0.923	0.957	0.911	0.936	1.069
	(0.028)	(0.075)	(0.084)	(0.057)	(0.062)	(0.072)
Mean Precipitation	1.172**	1.155	1.045	1.094	1.022	1.080
	(0.086)	(0.201)	(0.207)	(0.167)	(0.171)	(0.164)
Absolute Latitude	1.009	1.017	1.020	1.018	1.020	1.040
	(0.015)	(0.026)	(0.028)	(0.024)	(0.025)	(0.029)
Year	1.001***	1.001***	1.001***	1.001***	1.001***	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	
Year Squared	1.000**	1.000**	1.000*	1.000**	1.000**	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	
Exposed to Agriculture				0.315***	0.320***	0.314***
				(0.082)	(0.092)	(0.102)
Exposed Squared				1.204***	1.194***	1.216***
				(0.051)	(0.055)	(0.067)
Exposed Cubed				0.992***	0.992***	0.991***
				(0.002)	(0.002)	(0.003)
Extra Controls	No	Yes	Yes	Yes	Yes	Yes
Period FE	No	No	No	No	No	Yes
Pseudo-R2	0.10	0.10	0.11	0.14	0.15	0.27
N	1735	1735	1553	1735	1553	1537

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Effect of climate seasonality on spread of agriculture. The sample is composed only of location-period combinations on the Neolithic frontier (at least one of their neighbors is already farming, but they are not). The dependent value is a dummy for whether agriculture was adopted. Regression of adoption dummy on climatic variables. All columns report standard errors clustered at the level of 104 local neighborhoods of 4x4 cells.

7.2 Comparison with Interannual Seasonality in Western Eurasia

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

To verify the findings of the global-scale analysis in a setting free from these particular shortcomings, I now 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 are undoubtedly the most researched case of agricultural invention and expansion.

Specifically, Pinhasi et al. (2005) have collected a dataset of 765 archaeological sites for which they have compiled the dating for the earliest definite evidence of agriculture, as established through ^{14}C dating. The resolution of the TraCE climate dataset is far too low to be useful on this scale, so I substitute the BIOCLIM data of Hijmans et al. (2005), which is representative of average climatic conditions from 1950-2000, but has the advantage of being available at 10km resolution.

As Figure 9 shows, the earliest agriculture in this sample occurred in a wide arc joining the Eastern Mediterranean to the Persian Gulf. In fact, this area is currently believed to have been the earliest case of plant domestication anywhere in the world. From the flanks of the Zagros and Tauros mountains, farmers and their crops spread out onto the plains of Mesopotamia, and westwards across the Bosphorus, 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 so-called Fertile Crescent is only fertile when compared to the surrounding desertic and semidesertic 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 *a*nd 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 dataset is that it also allows me to directly test the validity of my theory alongside that of Ashraf and Michalopoulos (2015), who instead argues that agriculture was favored by intermediate levels of year-on-year 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 both a very high amount of seasonality and intermediate levels of 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 show that seasonality is a good predictor of the date of adoption.

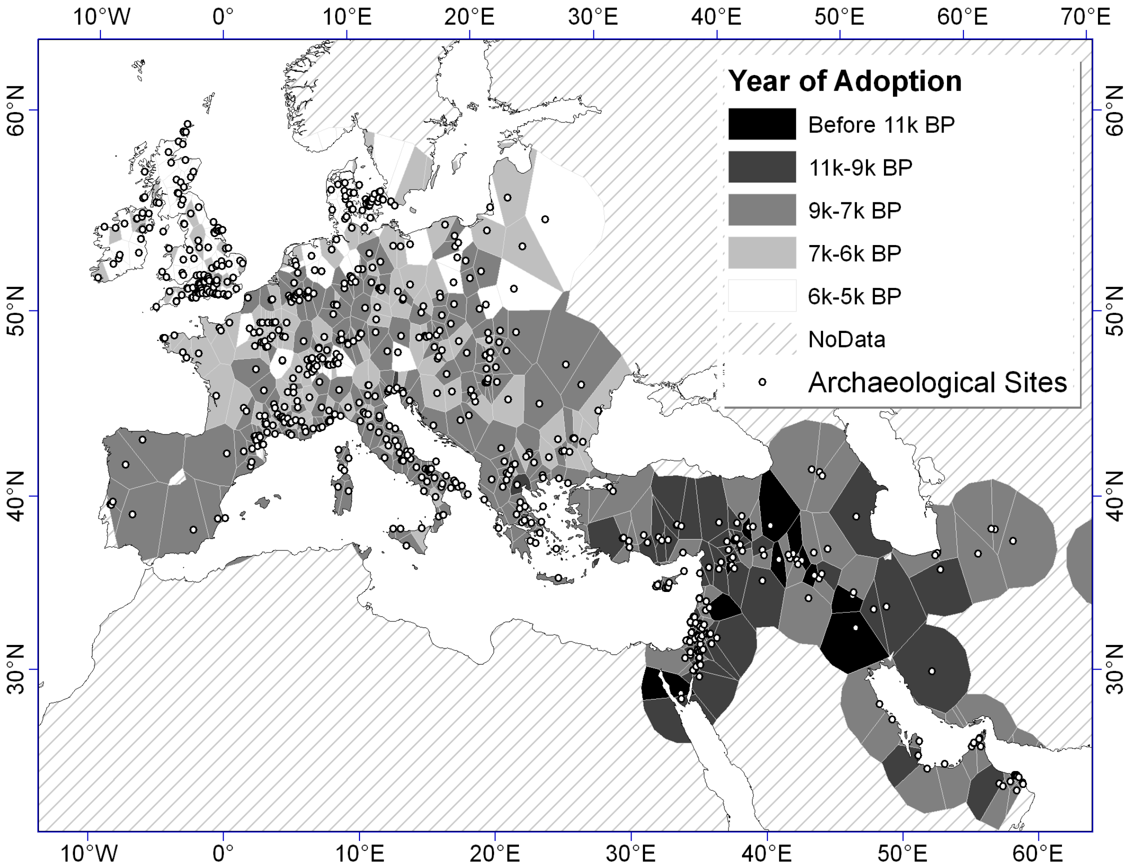

Figure 9: The Pinhasi et al. (2005) dataset provides ^{14}C dates for the onset of agriculture in 765 locations, chronicling the spread of agriculture from the Middle East into Europe.

The basic specification is the same as that of the basic linear model of Subsection 7.1.1:

$$Y_i = \alpha + \beta_1 T_i + \beta_2 P_i + \gamma C_i + \epsilon_i \tag{10}$$

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 Column (1) of Table 6, which once again shows that high seasonality is a strong predictor of early adoption, even when controlling for distance to the locations where agriculture originated, altitude, distance to the coast, and the usual controls from the previous regressions.

In Column (2) I replace the Seasonality variables with Interannual Average measures, and I find the same pattern as described in the Ashraf and Michalopoulos (2015) paper, with moderate levels of volatility promoting early adoption, while both extremes delay it.

Adding both the seasonality and interannual volatility measures to the same regression (Column 2), I find that temperature and precipitation seasonality measures both retain their explanatory power, and this is also true when using interannual variation for only spring, summer, or fall temperatures. The only partial failure occurs when using the interannual variation in winter temperatures, in which case precipitation seasonality remains significant, but temperature seasonality is no longer statistically significant (though it preserves it's sign and remains at similar magnitudes). It should be noted that in this specification the interannual variability measures are themselves insignificant. Further, across all specifications, the estimated effect of the seasonality when volatiltiy measures are included is consistent with what I obtained without those variables.

While the dataset on hand is not ideal for distinguishing between the two theories, on the whole we can exclude that the 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 would have the increase in seasonality creating the preconditions for the development of agriculture, while the interannual volatility determined how fast the progress was, once it had initiated. In the next section, I will further strengthen the case for seasonality causing the Neolithic, by showing that where the effect of seasonal food supply could be offset by geographic heterogeneity, agricultural adoption was delayed. This result is a direct prediction of my model, and is instead not derivable from Ashraf and Michalopoulos (2015).

	(1) Seasonality	(2) Interannual Average	(3) Both	(4) IA Spring	(5) IA Summer	(6) IA Autumn	(7) IA Winter
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 SD Avg		-5088.9*	-5162.9**				
		(2608.2)	(2388.7)				
IA SD Avg Sq.		2287.6**	2390.8**				
		(1070.0)	(962.0)				
IA SD Spr				-5935.1***			
				(2114.4)			
IA SD Spr. Sq.				3037.6***			
				(965.2)			
IA SD Summ.					-1087.0		
					(3518.5)		
IA SD Summ. Sq.					508.4		
					(2040.6)		
IA SD Aut.						-6930.3***	
						(2130.6)	
IA SD Aut. Sq.						3882.8***	
						(1158.6)	
IA SD Win.							-1793.0
							(1571.1)
IA SD Win. 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

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Comparison of seasonality variables with interannual variation as calculated by Ashraf and Michalopoulos (2015). All columns control for climate means and their squares, latitude, distance to origins of agriculture and altitude, and clusters residuals at country level. Column (1): results for Temperature and Precipitation Seasonality. Column (2): Results for the standard deviation of interannual temperature averages, and their squares. Column (3): Results for both sets of explanatory variables at the same time. Columns (4)-(7): Results using 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 clustered at the country level.

7.3 The impact of large seeded grasses

The analysis conducted so far has established that seasonality is strongly associated with the adoption of agriculture. These findings agree 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 might lead to the proliferation of plants that are somehow easier to domesticate. For example, Blumler (1992) showed that the Middle East has the largest concentration of large seeded grasses, which he argued made excellent targets for domestication. This theory was later popularized and expanded upon by Diamond (1997). Therefore, it is possible that the observed association between seasonality and the adoption of agriculture was not due to the decision to become sedentary in order to store, but rather to the abundance of easily domesticated plants which are found in such climates.

However, the large-seeded grass theory cannot account for all of the observed evidence. From an empirical standpoint, adding the presence of large seeded grasses to the invention locations does not eliminate the impact of seasonality, as shown in the Appendix (Table A1). Indeed, there are also good theoretical reasons to doubt that seed size of the local grasses was a decisive factor in determining whether agriculture would be invented or not.

As noted by Darwin (1868), it is very difficult to determine ex-post which plants were easiest to domesticate ex-ante. After thousands of years of human-crop coevolution, we have developed innumerable cultivation techniques that are specific to those particular crops, and it is only natural for us to assume that these particular species had insurmountable advantages even in their wild state, and before we had developed those complementary technologies. However, had our ancestors started off with an entirely different set of crops, we would have developed completely different technologies, that could well have made large seeded grasses largely irrelevant. For example, the usefulness of large seeds lies not in the fact that they produce larger harvests for a given unit area: smaller seeded species in general produce more individual seeds, so the total harvest size is not determined by the mean seed weight. Rather, a larger seed allows the plant to develop its shoots and root system more quickly, which allows the farmer to plant the seeds deeper (protecting them from birds and ants), and gives the plants a competitive advantage over weeds, particularly if a field has been plowed or hoed. We can therefore see how the supposed ex-ante advantage of a larger seed is only true because of the complementary techniques of planting seeds in holes, and uprooting competing vegetation.

Secondly, Blumler found that it was only precipitation seasonality that was associated with larger seed size, while regions with large temperature seasonality have grasses of normal size, presumably to increase the odds that one of these smaller seeds will find a fortuitous break in the canopy of trees, which cover most of the temperate areas of the world. The empirical analysis detailed in the previous section has shown that temperature seasonality has, if anything, a stronger predictive power than precipitation seasonality. It is of course entirely possible that highly seasonal temperatures select for entirely different adaptations, which have a similar effects on ease of domestication. But such a link is absent from the literature, and would be entirely coincidental. The storage hypothesis has the advantage of relying on something that is true of both temperature and precipitation seasonality: the presence of a season of food scarcity, which could be circumvented by becoming sedentary and storing food.

Third, the large seeded grass hypothesis cannot by itself explain why the adoption of agriculture would have reduced food availability for the populations that invented it, or what they received in exchange to make this trade-off acceptable. While plausible theories have been proposed, such as appropriation by greedy elites, or unforeseen population growth, the storage hypothesis has the advantage generating the reduction in average food availability organically, both in the short term (due to loss of distant food sources which can only be accessed nomadically), and in the long run (due to the removal of the population bottleneck during the scarce season, bringing equilibrium population levels closer to the ultimate Malthusian limit).

Fourth, not all original agricultural adoption had large seeded wild grasses to work with. In the Sahel, the earliest domesticates are grasses had very small seeds. In South America, the earliest domesticated plants were squashes, potatoes and legumes. In

Northern China, the earliest farmers grew a very small seeded millet. Meanwhile Southern Spain is home to two species of grass with exceptionally large seeds, but did not adopt agriculture until the arrival of the fully domesticated Middle Eastern crops.

It is indeed plausible that large seeded grasses were a useful aid in the development of agriculture, particularly in determining the speed of development after its invention. show that plants However they were clearly neither necessary nor sufficient for agricultural invention itself. In Appendix A1 I add the Blumler (1992) data popularized by Diamond (1997) and used *inter alia* by Olsson and Paik (2013), and found no significant effect either for the number of large seeded grasses themselves, or for their interaction with the climatic variables.

Besides the above theoretical and large-scale observations, the next section will develop and independent line of evidence supporting the Nomadism-Storage decision as central to the adoption of agriculture.

7.4 Geographic Heterogeneity

I will now show that the seasonality-storage hypothesis generates predictions for the adoption of agriculture even at scales of tens of kilometers. In this section I focus on those areas of the Middle East where cereals are known to have grown wild, i.e. areas that had very similar endowments of domesticable species. As all of these locations are extremely seasonal and close to each other, the accidents of proximity and local conditions dominate over both temperature and precipitation seasonality. These variables are no longer significant, though they have the expected sign and comparable magnitude to the results from the full sample. The prediction from the model is that settled agriculture should be adopted earlier where mobility is less useful — i.e. where all locations in practical migratory range experience correlated seasonal food shocks.

To test this prediction empirically, I first limit the analysis to the subset of locations from the Pinhasi et al. (2005) dataset that are within 100km of known concentration of wild cereals as described in Harlan (1998). I then construct a series of proxies, each measuring the difference between minimum and maximum altitude present within a specified distance from the location under observation. The reasoning is that areas with different altitudes will experience different temperature and precipitation regimes, are likely to have slopes with different exposures to the sun, and will generally possess a wide variety of microclimates. In short, it is highly unlikely that areas at widely differing altitudes will suffer the type of perfectly correlated seasonal food shocks that make nomadism pointless. This measure is a better proxy for abundance of different microclimates than ruggedness or average slope, since a landscape could be quite rugged but still be uniform, for example because it is entirely composed of a succession of very similar steep hills.

The behavior of the band will differ based on the scale on which these variations occur. If great altitude variability can be found within a small distance – say, 5km – then the band will be able to access this variation from a single location, and we expect settlement to actually occur faster than if no variation had been present. Altitude heterogeneity at larger radii ($\approx$ 50km) will instead lie beyond the grasp of the settler, while still remaining easily accessible to the nomad. Locations with such a topography will create an incentive to remain nomadic. Eventually, at very large distances, the uncorrelated food sources will be beyond the annual migratory ability of even the most mobile nomads, and therefore irrelevant.

In Figure 10, I show the locations in the Pinhasi dataset that are close to known concentrations of wild wheat and barley. I will use four sites in particular to illustrate how topography affects the incentives to remain nomadic or transition to settled storage. These are all within a 250km-radius circle at the border of Iraq, Syria and Turkey, and all had access to the same domesticable species. However, they differ greatly in local topography, as shown in Figure 11. Location (1) is Jerf el Ahmar, which lies on the banks of the Euphrates river, in the middle of a flat plain. Location (2) is Qermez Dere, on the southern flanks of a steep mountain, surrounded by an extensive and homogeneous plain. Location (3) is Girikiacian, which lies on a flat stretch of land close to some mountains. Finally, location (4) is Gawra, which is right next to some reasonably tall mountains, but has some truly impressive peaks around 40kms away. For each archaeological site, I plotted a line originating at the site's location, in the direction of the greatest changes in altitude.

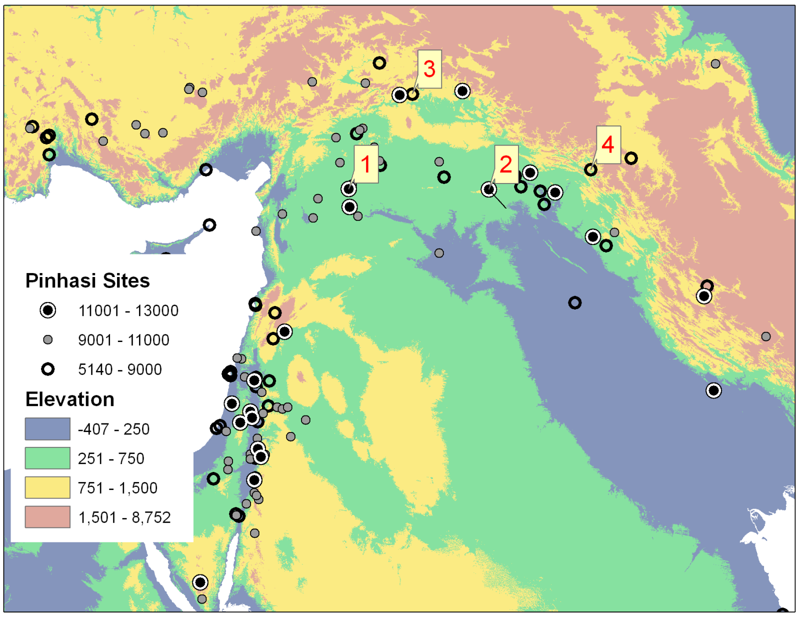

Figure 10: The map shows the Neolithic sites in the Middle East from the Pinhasi dataset that are within 100km of known concentrations of wild cereals. The sample is divided in locations that adopted before 11,000 years ago, between 11,000 and 9,000 years ago, and after 9,000 years ago. The four example sites discussed in Figures 11 and 12 are highlighted.

In Figure 12, I show elevation profiles taken along these lines, allowing us to better appreciate the differences in local topography. Locations (1) and (3) both have only moderate changes in altitude within 5km of the site, but the land around (1) is flat in all directions for at least another 100km, while (3) has significant peaks within the assumed nomadic radius of 50km. In contrast, Locations (2) and (4) both have large changes in elevation within their immediate neighborhood, but (2) is surrounded by a flat plain, while (4) has even larger mountains within the migratory radius of nomads.

As predicted by the theory, locations (1) and (2) – which had little to lose from abandoning nomadism – were amongst the first locations to adopt farming, while locations (3) and (4) – where the opportunity cost of abandoning nomadism was high – adopted only more than 2,000 years later. The local topography was not crucial: the areas within 5km of the two early adopters look very different from each other. What mattered was that the prospective settlers could find a location from which they could access the same variety of ecosystems which they could exploit as nomads.

This pattern is not specific to these four locations but is found generally within the Middle-Eastern sample. Defining $r(x)$ as the range in altitude present within x kilometers, Figure 13 shows that the early adopters of agriculture have a significantly lower $r(50)$, compared to late adopters with similar levels of $r(5)$. In particular, note that the seven locations with the highest $r(50)$ all adopted agriculture very late.

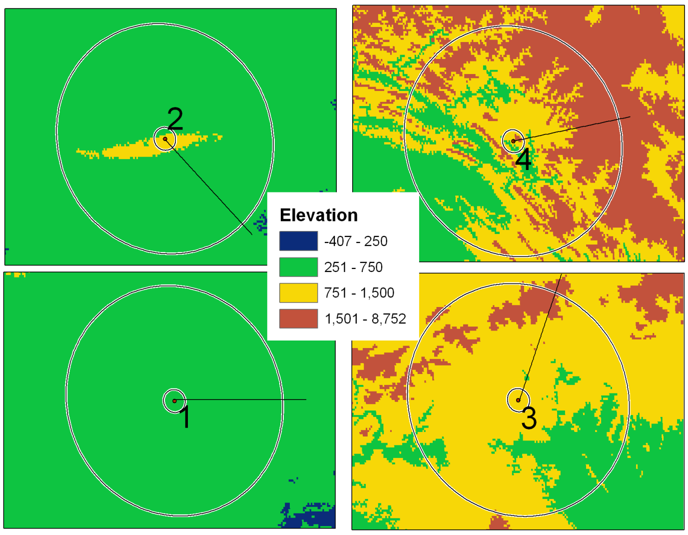

Figure 11: The four graphs show the local topography for the four examples sites, shown in Figure 10. The small circles have a 5km radius and are indicative of the area that could be accessed by a settled community occupying the site. The large circles are 50km in radius and shows the area that would have been available to a nomadic band.

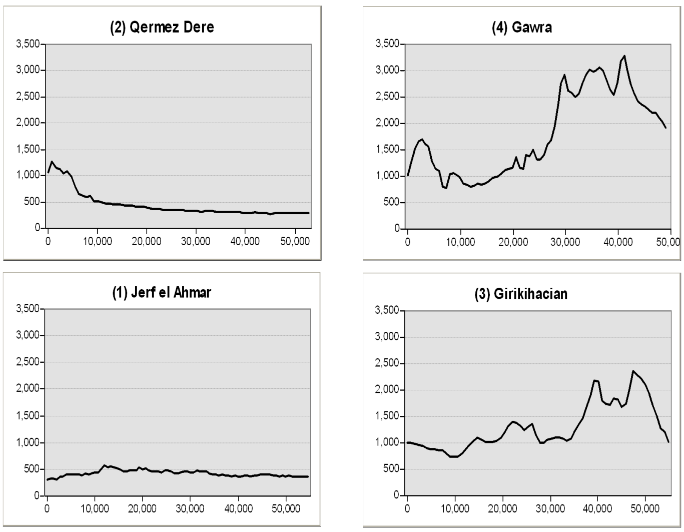

Figure 12: The four graphs show altitude profiles for the four lines shown in Figure 11. (1) has virtually no altitude variation in the local area. (2) Has a lot of variation close by, but nothing in the wider area. (3) has little variation close by, but a lot in the wider area. (4) has a lot of variation close by, but even more variation within the local area. Locations (1) and (2) adopted early, while locations (3) and (4) adopted later on.

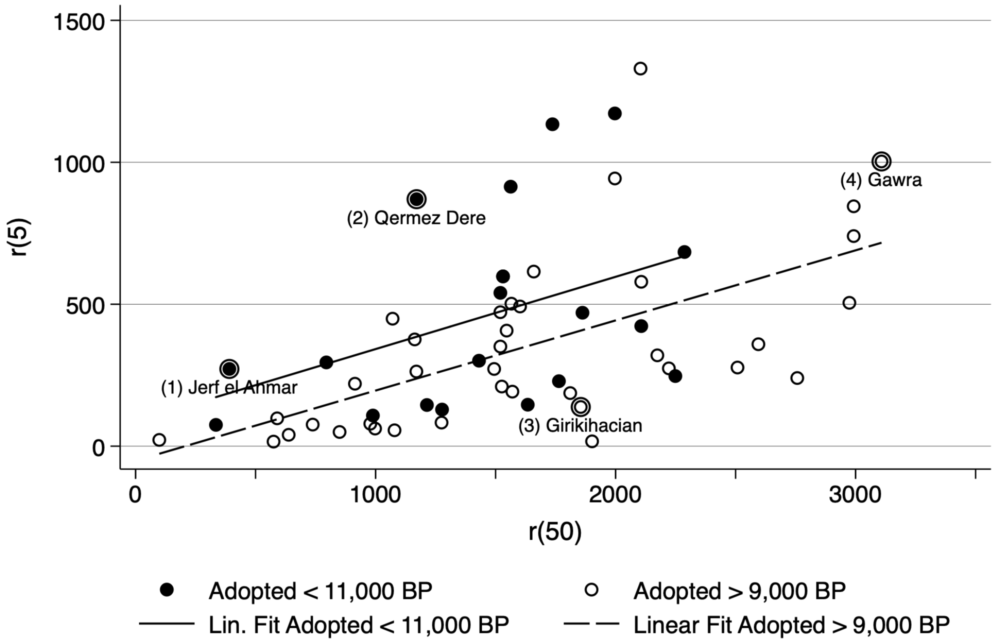

Figure 13: The graph shows how, irrespective of the altitude range immediately available to settlers (the $r(5)$), locations with a lot of altitudinal range available to nomads (the $r(50)$) adopted agriculture later than those with a low $r(50)$. The examples presented in Figure 11 are highlighted and labeled, and follow the general pattern.

I now investigate these relationships systematically using linear regression and a sample of 101 archaeological sites from the Pinhasi et al. dataset that are within 100km of known stands of wild cereals. The basic specification is:

$$Y_i = \alpha + \beta_1 r(5) + \beta_2 r(50) + \gamma C_i + \epsilon_i \tag{11}$$

Where Y_i is the year in which agriculture was adopted in archaeological site i, $r(5)$ is the range of elevations present within 5km of the site, $r(50)$ is the range of elevations present within 50km of the site, and C_i is a vector of controls. The model predicts that farming will be adopted first where nomadism does not materially improve the variety of ecosystems the band can access, i.e. where $r(50)$ is low, and $r(5)$ is high. The model is estimated through a straightforward linear specification, and the results are presented in Table 7.

Column (1) shows the direct effect of $r(5)$ and $r(50)$ on adoption. The sample is limited to sites which are within 100km of known dense cereal stands. Altitude variety within settled range (5km) led to earlier adoption of farming. Conversely, altitude variety which could be exploited by nomads (i.e. located 5 to 50km away) resulted in later adoption. The measured effect is large and statistically significant. Adding a 1000m mountain within 50km of a given site delayed adoption by approximately 500 years. In Column (2) I add controls for climatic seasonality, average climate, altitude, latitude, distance from the Neolithic epicenter, and distance from the coast. In this highly homogeneous environment, the coefficients on climatic variables are not significant, but those on the altitude ranges are effectively unchanged. In Column (3) I show that these estimates are not sensitive to particular cutoffs in the radii of the circles, by substituting my measures for sedentary-radius and nomadic-radius altitude variety with two smoothed versions:

$r(5:8)$, which is the average of $r(3)$,$r(5)$ and $r(8)$; and $r(50:100)$, the average of $r(50)$, $r(75)$, and $r(100)$. Column (5) shows that, while these measures are less predictive, the magnitudes of the coefficients is not affected, and that of $r(50:r100)$ is statistically significant. Finally, I add a control for $r(200)$, the range in altitude present within a 200km radius. I find that at these extreme distances, far outside of the comfortable range for nomads without livestock, altitude range ceases to have any impact on adoption of agriculture, while the variation at distances relevant to nomads continues to delay the onset of agriculture by about the same amount as before, and is still significant at the 10% level.

	(1) Baseline	(2) Controls	(3) Smoothed Measures	(4) r200
r(5)	-0.990*	-0.986*		-0.970*
	(0.454)	(0.537)		(0.513)
r(50)	0.517**	0.587**		0.540*
	(0.231)	(0.193)		(0.252)
r(3:8)			-0.774	
			(0.590)	
r(50:100)			0.436***	
			(0.131)	
r(200)				0.111
				(0.312)
Temp. Seas.		-161.6	-152.6	-158.0
		(126.4)	(98.59)	(130.6)
Precip. Seas.		737.9	-396.6	471.2
		(4771.8)	(3518.1)	(5062.2)
Controls	No	Yes	Yes	Yes
Observations	101	101	110	101
R^2	0.051	0.110	0.134	0.111

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Effect of local topography on the timing of agricultural adoption. Each observation is an individual archaeological site in the Middle East for which the date of the first evidence of agriculture is known. Linear regression of year of adoption of agriculture on the range of altitude within various radii. More variation in altitude within 50km (greater opportunity cost of abandoning nomadism) delayed the adoption of agriculture.

These findings are in principle compatible with one other interpretations. It could be that mountainous areas could provide a refuge for raiding parties that plundered the harvests of any farming band within range. Therefore, the negative coefficient on r(50) could represent potential farmers being deterred by the higher prevalence of raiders. To address this concern, I conduct an additional test. If higher raiding pressure was indeed the reason agriculture was delayed by distant mountains, we would expect that the effect of a higher r(50) would be highest for those locations that have the lowest r(5) (i.e. the most vulnerable to raids). A farming village high on an impregnable plateau could be expected to farm in peace no matter how ravenous and impregnable the neighbors might be, while doing the same in a featureless plain would be extremely dangerous.

To test this prediction, I re-run the regression of Column 3 (using all the controls) of Table 7, but add an interaction term between r(5) and r(50). Figure 14 plots the marginal effects of r(50). It is clear that there is no attenuation of the effect of r(50) as r(5) increases, indeed we instead observe the opposite pattern, and the coefficient on r(50) when r(5)=100 is significantly *larger* than at r(5)=0, with a p-value of 0.018. This allows us to discount the possibility that the impact of r(50) comes mainly from raiding.

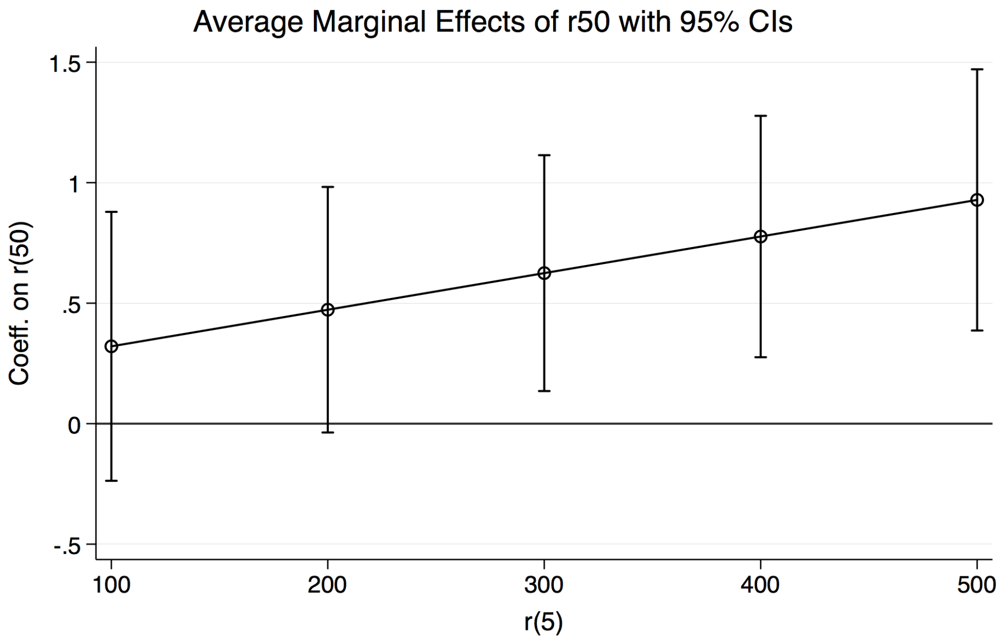

Figure 14: The graph shows the marginal effects of r(50) for different values of r(5), as derived from a regression of year of adoption on r(5), r(50), an interaction term between the two, and the same controls for climate, altitude, and distances from the coast the earliest agricultural locations latitude. Most of the effect of r(50) comes from locations with a lot of variations in altitude within 5km, which would have been easier to defend. This suggests the effect of r(50) was not primarily due to the threat of raiders in the mountains.

To further explore robustness at different radii, I show in Appendix **??** a number of robustness checks around my preferred measures of heterogeneity available to settlers (5km, variable r5) and nomads (50km, variable r50) heterogeneity. Specifically, I use r(3), r(8), and r(10) as measures for local heterogeneity, and r(40), r(50), r(75) and r(100) as the main explanatory variable.

All specification that keep r(50) as the main explanatory variable have point estimates remain within one standard error of the main specification, and are still significantly different form zero at the 5% level. I then keep r5 as the control for local heterogeneity, and vary the nomadic measure. and I find that the only insignificant specification is that with r(40). While I don't have a reason why 40km should be the specific radius at which this effect disappears, clearly at some point the distance has to become so short that a settled population could take advantage of peripheral food resources, e.g. via short "camping trips". In this specific sample, this appears to happen at 40km.

8 Consumption seasonality and human health

The model predicts that the transition from nomadic hunting and gathering to sedentary agriculture should be associated with a lower average food consumption but much greater stability. In this section, I will detail how chronic malnourishment and acute starvation differ in their effects on the human body, and how the evidence from the Neolithic Revolution compares to the the welfare outcomes predicted by the model.

Healthy adults carry fat reserves, the body's primary long-run energy store, which generally allows them to survive periods of acute malnourishment. These are complemented by the body's energy conservation strategies, such as reducing body temperature, decreasing fidgeting and unnecessary movement, and generally lowering the basal metabolism (Keys et al., 1950). Unless starvation is prolonged, lost weight can be regained when conditions improve, and the individual need not suffer significant long term consequences. However, fat reserves can only last for so long. Eventually, if the body is unable to reduce its energy requirements to fit the available resources, death by starvation will ensue.

As discussed in the introduction, in most of the locations for which data exist, consumption per capita decreased when farming replaced hunting and gathering. Achieved adult height is one of the most commonly used proxies for health, and as Figure 15 shows, this parameter declined drastically as agriculture became the dominant lifestyle (Cohen and Armelagos, 1984). Similar declines in health are evident from a host of other indicators, such as measures of skeletal robustness, tooth wear, joint diseases due to overwork, and evidence of disease and infection. These are the findings that prompted Diamond to title his famous article "the worst mistake in the history of the human race" (Diamond, 1987).

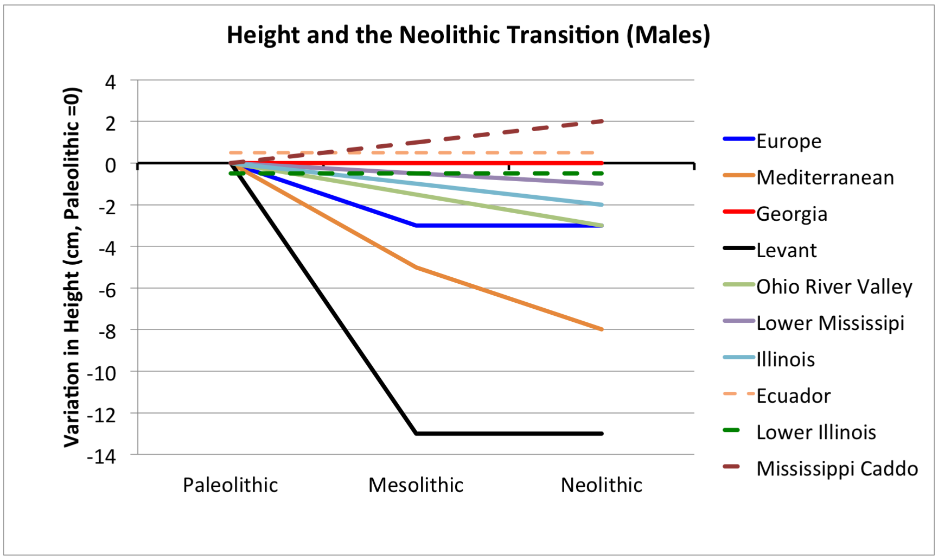

Figure 15: Achieved adult height across the Neolithic sequences reported in Cohen and Armelagos (1984). Each line represents the progression in observed heights in one location, expressed as a difference from its value during the Paleolithic (nomadic hunting and gathering). The sedentary farmers (Neolithic) 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.

These basic findings have since been confirmed by subsequent research, as detailed in a review article by Mummert et al. (2011), which found that out of 17 studies conducted after the publication of Cohen and Armelagos (1984), ten found a decrease in adult stature following the introduction or intensification of agriculture (Portugal, Scandinavia, Southern Europe, Levant, Bahrain,China, Japan, Peru, Georgia Bight, and California Channel Islands), three found no significant change (Ecuador, West Central Illinois, and Florida), Egypt and Britain saw an initial increase followed by decrease, and only Thailand and the US Southeast saw an increase in adult stature. It should further be noted that in the case of the Southeastern US, the local inhabitants were already largely sedentary and storing food on a vast scale for almost three thousand years before the agriculture was introduced, which would mean that in this region the consumption smoothing would already have been present.

The height decrease was unlikely to be entirely due to the transition from a more meat-based diet of hunter-gatherers to a cereal-based diet during the Neolithic. In many cases, late Paleolithic communities were already highly dependent on the plants that were eventually cultivated and domesticated, and most of the early farmers were still hunting significant amounts of game from their surroundings (Humphrey et al., 2014). Further, in some cases (e.g. the Natufian in the Middle East), height was seen to decrease as soon as the population became sedentary and started to store food, even though cereals were still not a dietary staple.

These observations are in agreement with the welfare implications of the model, which predicted that average consumption should decrease as soon as a population becomes sedentary and starts to store, and should thereafter remain relatively constant, even as farming is adopted.

Measuring consumption seasonality is more difficult: height overwhelmingly reflects the *average* nutritional status an individual experienced through childhood, while *volatility* in food intake is only marginally recorded. Acute starvation episodes in children can in fact pause skeletal growth entirely, but if sufficient nutrition is provided thereafter, the child will experience faster than normal growth. This catch-up growth will generally result in the child rejoining its original growth curve and achieving virtually the same adult height as if the starvation episode had not occurred (Williams, 1981). Similar considerations hold for other skeletal disease markers, which also tend to show accumulation of stress factors over time (e.g. tooth wear and joint disease inform us of the average grittiness of food and the amount of labor expended in procuring it, rather than the time pattern of these factors). Thus, the most commonly used health markers are woefully inappropriate for assessing the degree of seasonality in consumption.

However, catch-up growth leaves telltale signs along the length of the bones themselves. Long bones (such as those of the leg) grow from their end outwards. If a growth-arrest episode is ended by a rapid return to favorable conditions, the body will deposit a layer of spongy bone in the normally hollow interior. These layers, called Harris lines, will form a permanent record of the number of growth disruption suffered by an individual before the end of adolescence (Harris, 1933). Harris lines can be examined by sectioning the bone lengthwise, or non-destructively through x-rays (see Figure 16).

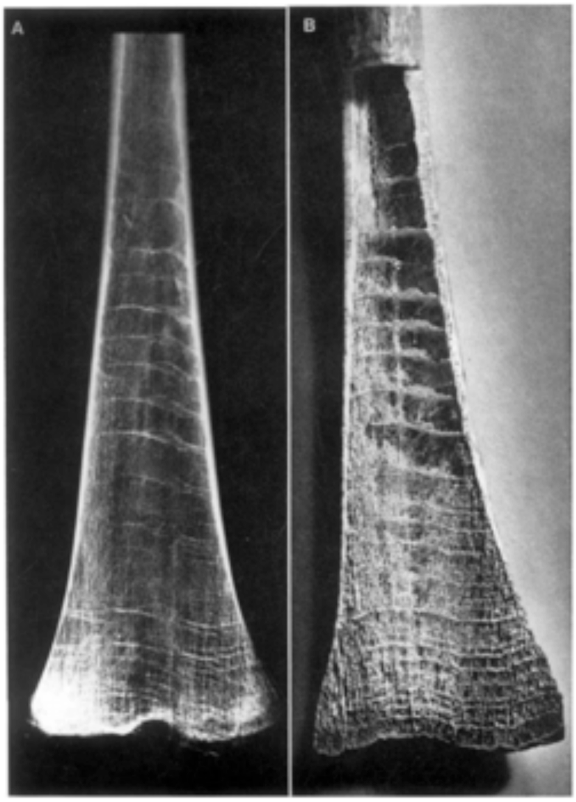

Figure 16: Example of Harris lines in a 19th century Inuit adult. The regular spacing of the Harris lines show that each winter, food intake would drop low enough to arrest bone growth. Each spring, the arrival of migratory species would rapidly increase food intake, a catch-up growth spurt would occur, and a line for more calcified bone would be deposited (whiter in the x-rays). Such a regular pattern is extremely unlikely to occur due to illnesses. Source: Lobdell (1984)

In most locations where Harris lines were counted before and after the transition, they were found to be numerous during the nomadic-hunting and gathering stage, while comparatively rare during 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, no significant movement in one case, and a slight increase in the last. For example, nomadic hunter-gatherers in the Central Ohio Valley were 165cm tall on average and had an average of eleven Harris Lines each. When they started to farm, they became about three centimeters shorter but had only four lines on average.

The evidence from Harris lines, together with that from height suggests that hunter gatherers ate well on average, but were forced to starve during part of the year.

9 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 in order to store food, thereby preadapting them to develop farming.

Using archaeological and paleoclimatic data, I find that agriculture appeared earlier in areas characterized by high seasonality, and that this effect can be further decomposed into both a higher probability of invention, and a faster spread of agriculture from one location to the next. This explanation can further account for the fact that early farmers were shorter than their hunter and 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 data on the local topography of early sites, and the comparative absence of growth arrest lines in the bones of early farmers.

This paper also 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 that are very similar to those where agriculture originated. Why didn't these southern temperate areas invent agriculture during the Neolithic? Because the shock to seasonality that triggered the transition only happened in the northern hemisphere Berger (1992). As a result, these areas never experienced the extreme seasonality experienced by the populations which 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 paper has a further desirable charachteristic, in that 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[5], 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 that specific population domesticated that specific plant, at that specific point in time.

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

This paper 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 all share as a species.

[5] Due to the prevailing winds blowing west to east, areas like Northern Europe and the US Pacific Northwest tend to enjoy a less seasonal, maritime climate, compared to areas that are either landlocked or on the eastern coast of land masses, like New England or China)

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A Econometric robustness

A.1 Presence of domesticable plants

In Table A1 I show that the results for the date of adoption are robust to the inclusion of the number of domesticable plant species. For this I use the date compiled by Hibbs and Olsson (2004). Their data covers approximately half of our sample (most of the missing countries are in Africa and Central Asia), though in fact it consists of only six macro regions for the whole world. The results of the estimation show that while having domesticable species available has a measurable effect on adoption, it does not materially impact the coefficient and signficance levels for our variables of interest.

A.2 Distance from independent invention centers

Table A2 shows an alternative approach to analyzing the spread of agriculture, specifically by repeating the regression for date of adoption (Table 3), but controlling for distance to the closest location where agriculture was invented. The results are not materially affected.

A.3 Using Location Fixed Effects with Timing of Sedentarism

Adding location fixed effects by themselves leads to all variables being statistically insignificant. The reason for this is simple: adding these fixed effects drops all locations except the seven that actually invented agriculture. Further, my model predicts that seasonality should lead populations to become sedentary, and that this should *eventually* lead to agriculture being developed. This works reasonably well at simultaneously predicting the cross sectional and time variation simultaneously, but is not precise enough

	(1) Plants	(2) Seas. Interactions	(3) + Means Interactions
Temperature Seas.	-139.5***	-134.4***	-128.7***
	(35.7)	(37.2)	(39.2)
Precipitation Seas.	-792.5***	-758.3**	-720.6**
	(293.9)	(323.1)	(337.4)
Mean Temperature	80.6**	78.9**	75.7**
	(35.6)	(35.7)	(37.0)
Mean Precipitation	52.1	48.0	132.8
	(270.5)	(271.2)	(295.0)
Absolute Latitude	198.6***	198.1***	197.7***
	(59.5)	(59.6)	(59.4)
Dom. Plants	-87.1***	-62.1**	-4.4
	(15.0)	(26.1)	(61.3)
Temp. Seas. * Plants		-0.9	-2.9
		(2.0)	(3.5)
Precip. Seas. * Plants		-11.9	-22.3
		(30.7)	(32.6)
Temp. Mean * Plants			1.4
			(2.2)
Precip. Mean * Plants			-20.6
			(17.6)
Extra Controls	Yes	Yes	Yes
r2	0.45	0.46	0.46
N	1024	1024	1024

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A1: Effect of seasonality on date of agricultural adoption, controlling for the presence of domesticable plant species (Columns 1), adding interactions between plants and the climate seasonality variables (Column 2), and finally adding interactions between plants and the climate means variables as well. All columns report clustered errors at geographic neighborhood level.

	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Basic+Clust	Quadratic	Quad+Clust	Americas	Americas+Clust
Temp. Seas	-157.9***	-157.9***	-135.0***	-135.0***	-32.50**	-32.50*
	(15.47)	(18.88)	(19.09)	(22.71)	(16.35)	(18.40)
Precip. Seas	-436.5***	-436.5***	-974.0***	-974.0***	-599.8***	-599.8***
	(125.6)	(163.9)	(139.2)	(174.6)	(116.8)	(147.5)
Distance	509.6***	509.6***	484.7***	484.7***	823.9***	823.9***
	(56.04)	(71.64)	(52.11)	(65.23)	(48.92)	(59.94)
Temp. Mean	47.51***	47.51**	32.95**	32.95	-36.72**	-36.72**
	(16.80)	(20.68)	(16.37)	(20.03)	(14.31)	(17.25)
Precip. Mean	-397.2***	-397.2***	245.3	245.3	189.3	189.3
	(70.61)	(82.45)	(152.2)	(189.6)	(122.7)	(148.9)
Abs Lat	-3.473	-3.473	161.4***	161.4***	125.6***	125.6***
	(15.03)	(18.43)	(21.95)	(26.03)	(20.71)	(24.73)
GeoControls	No	No	Yes	Yes	Yes	Yes
Climate^2	No	No	Yes	Yes	Yes	Yes
Observations	1024	1024	1024	1024	1024	1024

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Effect of seasonality date on agricultural adoption, with distance from the closest independent invention. All columns report standard errors clustered by 104 geographic neighborhoods.

to identify the timing alone when looking only at the locations that actually invented agriculture. This is mainly because adding time fixed effects forces each location that adopted agriculture to compete with its past self, and most locations reached the peak in seasonality sometime before agriculture was invented, as shown in Figure A1. Given that the theory predicts that higher seasonality should lead to sedentarism, and to agriculture only after some time, this lag is actually in line with my theory.

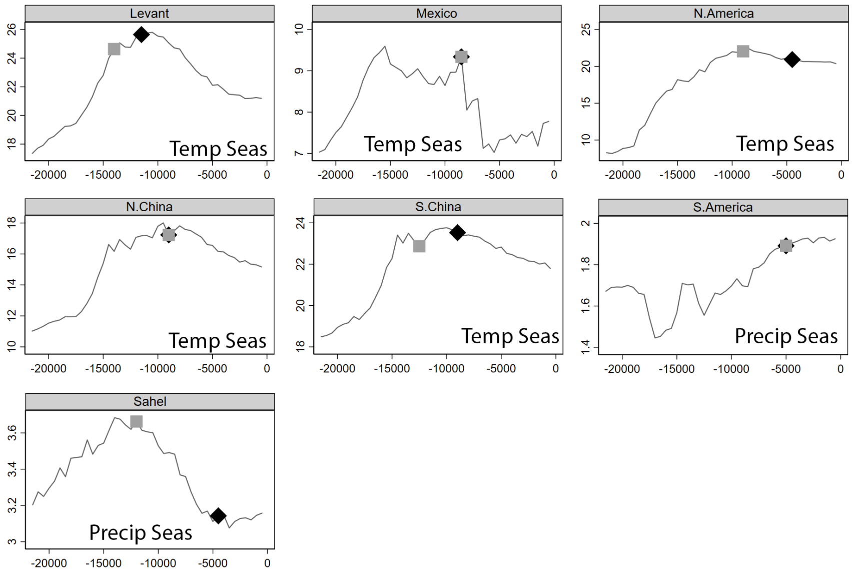

Figure A1: The graph shows the evolution of climatic seasonality (either temperatures or precipitation depending on which was more significant), and it's relation to the adoption of agriculture (dark diamond) or sedentarism (when it is known, light square).

To show the broad compatibility of the data with my theory, I have replaced the date of adoption of agriculture with that of the appearance of sedentarism, for the cases in which it was known (four out of the seven cases), based on the articles included in my review of the archaeological literature. The results are presented in Table A3. I prefer to use the agricultural invention data for my main specifications, since that data is more complete and easier to compare to the results for the global spread of agriculture.

A.4 Spatial Robustness

I further check whether the regressions of year of adoption on seasonality are robust to taking into account spatial correlation. Table A4 contrasts the results from three approaches. The first two columns show the results with simple robust standard errors. Columns (3) and (4) show the results for the spatial lag model. Columns (5) and (6) use Conley spatial standard errors. The coefficients on temperature seasonality are weaker when spatial lags are added to the model, but overall the estimates are remarkably consistent and significant.

	Dependent variable: sedentary dummy					
	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Controls	Controls2	Basic SI	SI+Controls	SI+Controls2
Temp. Seas.	2.406***	2.326**	3.286**			
	(0.730)	(0.832)	(1.956)			
Precip. Seas.	0.296	0.343	1.481			
	(1.614)	(1.576)	(4.814)			
Seas. Index				1.022	1.017	1.027**
				(0.016)	(0.017)	(0.013)
Temp. Mean		1.452	0.746		1.507	1.733
		(0.885)	(0.734)		(0.919)	(1.594)
Precip. Mean		1.325	468.472*		0.556	57.866
		(2.531)	(1715.447)		(1.209)	(194.323)
Abs Lat		0.525	0.001		0.762	0.120
		(0.235)	(0.004)		(0.268)	(0.177)
Abs Lat 2			1.093			1.004
			(0.081)			(0.029)
America			16.818			15.542
			(58.199)			(31.682)
Temp Mean 2			1.031			0.989
			(0.061)			(0.045)
Precip Mean 2			0.198			0.193
			(0.305)			(0.279)
CellID	Yes	Yes	Yes	Yes	Yes	Yes
N	169	169	169	169	169	169

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3: I repeat the analysis of Table 4, but adding cell level fixed effects, and replacing the dummy timing for the invention of agriculture with one for the transition to sedentarism.

	Dependent variable: year of adoption					
	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Controls	Basic Spat.Lag	Controls Spat. Lag	Basic Conley	Controls Conley
Temp. Seas	-222.5***	-143.8***	-65.8***	-62.5***	-222.5***	-143.8***
	(13.4)	(38.4)	(14.3)	(15.5)	(24.7)	(29.0)
Precip. Seas	-529.4***	-936.5***	-645.8***	-668.0***	-529.4**	-936.5***
	(131.1)	(249.2)	(93.5)	(101.7)	(245.5)	(243.4)
Temp. Mean	107.3***	71.5**	-15.0	-14.6	107.3***	71.5***
	(15.9)	(29.6)	(9.3)	(13.5)	(33.0)	(26.3)
Precip. Mean	-464.3***	90.0	-525.7***	-462.0***	-464.3***	90.0
	(71.2)	(235.8)	(40.4)	(111.8)	(122.3)	(231.9)
Abs Lat	46.3***	207.6***	-49.9***	-79.0***	46.3*	207.6***
	(13.6)	(64.9)	(4.9)	(18.0)	(27.8)	(44.4)
Extra Controls	No	Yes	No	Yes	No	Yes
r2	0.24	0.40			0.82	0.86
N	1024	1024	1024	1024	1024	1024

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A4: Regression of date of adoption of climate seasonality. Columns (1) and (2): robust standard errors. Columns (3) and (4): spatial lag model. Columns (5) and (6) Conley spatial standard errors.

A.5 Time Fixed Effects

These results are robust to introducing a variety of time period fixed effects, as shown by Table A5. The sign and magnitude of the coefficients on temperature seasonality is not materially affected, despite the reduction in sample size (due to the fact that all the observations in periods that did not experience any original invention were dropped). This is as expected, since it is in any case difficult to imagine any factor besides climate that could simultaneously affect the adoption of agriculture on multiple continents.

	Dependent variable: invention dummy				
	(1)	(2)	(3)	(4)	(5)
	NO FEs	500Y FEs	1000Y FEs	2000Y FEs	5000Y FEs
Temperature Seas.	1.193***	1.192**	1.191**	1.185**	1.210**
	(0.078)	(0.095)	(0.093)	(0.096)	(0.107)
Precipitation Seas.	2.036	1.822	1.778	1.788	1.791
	(1.243)	(1.326)	(1.294)	(1.293)	(1.294)
Mean Temperature	1.062	0.920	0.916	0.923	0.900
	(0.114)	(0.144)	(0.144)	(0.136)	(0.149)
Mean Precipitation	4.744**	3.477*	3.526*	3.469*	3.412*
	(2.958)	(2.290)	(2.325)	(2.285)	(2.382)
Absolute Latitude	1.120	1.133	1.136	1.138	1.116
	(0.087)	(0.137)	(0.136)	(0.125)	(0.148)
Extra Controls	Yes	Yes	Yes	Yes	Yes
Period FE	No	Yes	Yes	Yes	Yes
Pseudo-R2	0.15	0.21	0.19	0.20	0.21
N	38533	4550	9084	11260	23273

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A5: Results for independent invention using fixed effects for periods of various lengths.

A.6 Changing Clustering Levels

Table A6 demonstrates how the main findings on the effect of seasonality on invention are robust to variations in the size of the neighborhoods used for clustering the standard errors. The table reports the results obtained by using robust standard errors, and by clustering the errors within within geographic neighborhoods of 7, 15 , and 30 degrees square. This was done both for a basic set of controls, and the full set of controls available.

	Dependent variable: adoption dummy					
	(1)	(2)	(3)	(4)	(5)	(6)
	Clust.7deg	Clust.15deg	Clust.30deg	Ctrl+7deg	Ctrl+15deg	Ctrl+30deg
Temperature Seas.	1.218***	1.218***	1.218***	1.193***	1.193***	1.193***
	(0.062)	(0.065)	(0.049)	(0.078)	(0.078)	(0.067)
Precipitation Seas.	1.966	1.966	1.966	2.036	2.036	2.036
	(1.217)	(1.103)	(1.326)	(1.289)	(1.243)	(1.404)
Mean Temperature	1.047	1.047	1.047	1.062	1.062	1.062
	(0.052)	(0.041)	(0.052)	(0.125)	(0.114)	(0.102)
Mean Precipitation	2.330***	2.330***	2.330***	4.744**	4.744**	4.744**
	(0.532)	(0.533)	(0.524)	(3.298)	(2.958)	(3.060)
Absolute Latitude	1.052	1.052	1.052*	1.120	1.120	1.120
	(0.038)	(0.038)	(0.030)	(0.085)	(0.087)	(0.089)
Extra Controls	No	No	No	Yes	Yes	Yes
Pseudo-R2	0.13	0.13	0.13	0.15	0.15	0.15
N	38533	38533	38533	38533	38533	38533

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Column (1) 7 degree squares, (2) 15 degree squares, (3) 30 Degree Squares. Columns (4) to (6), same as (1) to (3), but with a dummy for the Americas and the squares of Absolute Latitude, Temperature Mean and Precipitation Mean.

A.7 Rare Events and Firth Logit

Given the small number of independent inventions, it is appropriate to check whether results are biased by the rarity of the event. For this reason I employ two alternative approaches designed to correct for severely unbalanced dependent variable, the Rare Events Logit procedure from King and Zheng (2001), and the approach proposed by Firth (1993). In both cases the main results are essentially unchanged.

	(1) RELogit	(2) REL + Controls	(3) REL + Controls2	(4) FirthLogit	(5) FL + Controls	(6) FL + Controls2
Temperature Seas.	1.126***	1.191***	1.197***	1.126***	1.192***	1.214***
	(0.050)	(0.063)	(0.079)	(0.051)	(0.066)	(0.080)
Precipitation Seas.	1.301	1.898	1.649	1.298	1.918	1.712
	(0.614)	(1.065)	(1.007)	(0.606)	(1.144)	(1.056)
Mean Temperature		1.034	0.911		1.032	0.985
		(0.040)	(0.098)		(0.095)	(0.063)
Mean Precipitation		2.274***	2.897*		2.268***	3.075*
		(0.520)	(1.806)		(0.655)	(1.892)
Absolute Latitude		1.050	1.040		1.049	1.114
		(0.038)	(0.081)		(0.087)	(0.170)
Extra Controls	No	No	Yes	No	No	Yes
r2						
N	38533	38533	38533	38533	38533	38533

Exponentiated coefficients; Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A7: The results of Table 4 (effect of seasonality on invention), with standard errors re-estimated to take into account the very rare nature of agricultural invention. Column (1) Rare Events Logit, (2) RE Logit and controls, (3) Rare Events Logit + Quadratic Controls ,Columns 4 to 6, same as (1) to (3), but with Firth Logit instead of Rare Events Logit. All columns using RE Logit are clustered at the level of 104 grid squares of 4x4 observations. The Firth Logit command I used does not allow a clustering option.

A.8 Effect of elevation range for different

In Section 7.4 I show that nomadism persisted longer where there was significant variation in altitude just outside of the comfortable foraging range for a settled band, but within a reasonable seasonal migratory radius for nomads. My measure of geographic heterogeneity available to settlers was the range in altitude within 5km, which I denote r(5), while the heterogeneity available to nomads was the r(50). While these are plausible values, I now investigate the robustness of the analysis to choosing different values for each. I use Column (2) of Table 7 (all controls added) as my starting point, and first keep r(50) as my nomadic heterogeneity measure, while changing the sedentary heterogeneity measures to r(3), r(8) and r(10), and then I keep r(5) as the sedentary measure, and change my nomadic measure to r(40), r(75), and r(100).

The results are presented in Table A8: in each case the measure of nomadic seasonality is significant, except for the case of r(40), shown in Column (5). As discussed in the main text, this is not particularly surprising, since of course at some point distances must be small enough that food could be accessed through short multi-day expeditions from the main settlement, and in this sample it appears this effect begins to mask the main one at around 40km.

	(1) Baseline	(2) r3	(3) r8	(4) r10	(5) r40	(6) r75	(7) r100
r(3)		-1.227					
		(0.811)					
r(5)	-0.986*				-0.860	-0.708	-0.649
	(0.537)				(0.553)	(0.516)	(0.532)
r(8)			-0.906*				
			(0.450)				
r(10)				-0.858*			
				(0.440)			
r(40)					0.373		
					(0.333)		
r(50)	0.587**	0.540**	0.664**	0.713**			
	(0.193)	(0.185)	(0.220)	(0.241)			
r(75)						0.348*	
						(0.176)	
r(100)							0.350**
							(0.156)
Temp. Seas.	-161.6	-153.7	-156.6	-154.8	-155.6	-141.4	-143.8
	(126.4)	(130.3)	(124.2)	(127.1)	(127.9)	(134.7)	(132.3)
Precip. Seas.	737.9	861.3	1067.4	538.7	-445.7	-954.6	-1659.1
	(4771.8)	(4998.5)	(4773.0)	(4547.0)	(5473.2)	(4519.5)	(4434.4)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	101	101	101	101	101	101	101
R^2	0.110	0.108	0.109	0.112	0.085	0.090	0.095

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A8: The results of Table 7 are replicated using the range in altitudes calculated for different radii from 3km to 100km. Column (1): baseline results. Columns (2), (3), and(4): keeping r(50) as the measure of heterogeneity accessible to nomads, and varying the heterogeneity accessible to settlers from 3km to 8km. Columns (5), (6), and (7): keeping r(5) as measure of settled heterogeneity, and using 40km, 75km, and 100km to measure nomadically accessible heterogeneity.

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B History Background

B.1 Archaeological evidence from each independent invention

B.1.1 Near East

In the Near East, the Epipaleolithic developed between 23,000 and 11,500 cal BP. During this phase, multiple cultural traditions have been identified based on studies of stone artefacts (Pirie, 2004; Olszewski, 2006), namely the so-called Nebarian, Kebarian, Nizzanian and Mushabian cultures. These groups coexisted in the Levant region (Syria, Jordan, Lebanon and Israel) and despite their technological differences are all considered to be part of the Pre-Natufian complex (Maher et al., 2012). During these millennia, there is evidence of incipient semi-permanent seasonal settlement, stone architecture, multi-seasonal hunting and fishing, intensified plant use, storage and long-distance trade and exchange (Asouti and Fuller, 2012; Diaz et al., 2012), especially after 13,000 BP (Hayden et al., 2012). The Mesolithic population that emerged from them were the Natufians, which appear for the first time in the archaeological record in ca. 14,500 BP (Weinstein-Evron et al., 2012; Barzilai et al., 2017).

Although hunting-gathering activities were still present, Early Natufian sites have shown increased exploitation of the site catchment and decreasing mobility (Belfer-Cohen and Goring-Morris, 2011; Yeshurun et al., 2014), as well as evidence of intensive storage (Kuijt, 2011; Hayden et al., 2012; Saulieu and Testart, 2015). This shift coincided with a greater seasonality of climate (Abbo et al., 2010)and increased aridity (Caracuta et al., 2016; Yeomans et al., 2017). Eventually, Natufian groups were replaced by early Pre-Pottery Neolithic communities. During PPNA (12,500 - 10,600 BP), there is increasingly accumulating evidence of pre-domestication cultivation of barley, emmer and pulses, though the first fully-domesticated crops date from PPNB, ca. 10.600 BP (Asouti and Fuller, 2012). Animal exploitation also would have experienced a pre-domesticated phase until ca. 10,000 BP, when domesticated goats have been identified in various sites (Zeder, 2011; Makarewicz and Tuross, 2012).

The Near East is the most thoroughly excavated Neolithic transition, and provides the best evidence for the sequence of events implied by the model: increased climatic seasonality followed by a transition to a more sedentary lifestyle with storage, and culminating in the adoption of widespread agriculture and the domestication of plants.

B.1.2 Eastern North America

In general, it is accepted that Eastern North America was occupied at least 15,000 years ago, even though some authors find an earlier date of 20,000 BP likely (Lavallée, 2000; Dillehay, 2001), or even earlier. These Paleo-Indian communities inhabited the region of the Eastern Woodlands, encompassing essentially the entirety of the United States west of the Mississippi River (Dancey, 2005). They had a highly mobile subsistence strategy, with short-term encampments and a diet based on big-game hunting, fishing and plant collection (Anderson, 2012).

During the abrupt climatic changes associated with the Pleistocene-Holocene transition at circa 10,000 BP (Carbonell, 2005), the Paleo-Indian way-of-life was replaced by a less mobile subsistence strategy with only a few movements per year, the so-called Archaic Period (Munoz et al., 2014). Archaic peoples exploited a variety of wild resources, constructed storage facilities (Dancey, 2005) and developed or adopted tools such as grinding stones to maximize the effective yield of undomesticated foods (Styles and McMillan, 2009). As shown in the archaeological record, these communities appear to have begun plant domestication after the Hypsithermal (8,500-5,000 BP), mostly of species of starchy- and oily-seed bearing annual plants (Munoz et al., 2014). The earliest evidence of agriculture appears associated witbh small settlements and situated in resource-rich environments such as Hayes (Marshall County, TN), Phillips Springs (Hickory County, MO) or Napoleon Hollow (Pike County, IL) among others (Smith, 2011). These have yielded evidences of domesticated squash (*Cucurbita pepo*) dated from 4,440 BP, sunflower (*Helianthus annus*) at 4.265 BP, marsh-elder (*Iva annua*) at 3,920 BP and goosefoot (*Chenopodium berlandieri*) at 3,400 BP (Smith and Cowan, 2003; Smith, 2006; Smith and Yarnell, 2009). It is still not entirely clear whether these sites were occupied year-round on a permanent basis or annually during certain seasons of the year (Smith, 2011). As such, the mainstream view is that these domesticated plants were gradually integrated into their seasonally mobile way-of-life and would have become increasingly important as they began to develop fully-sedentary occupations (Munoz et al., 2014) and pottery production (Tache and Hart, 2013) during the second half of the IV millennium BP.

The North American case is therefore only partially in agreement with the theory. While the evidence does suggest that an increase in climate seasonality preceded the appearance of a a less mobile hunting and gathering culture with evidence of storage, there is no definite evidence that these storing foragers had in fact completed the transition to full sedentarism before advancing to the domestication of plants. The crucial aspect is to understand exactly how residential mobility and intensive storage were compatible strategies in this specific case.

B.1.3 Mesoamerica

The oldest human remains found in Mesoamerica date back to circa 13,000 BP (Stinnesbeck et al., 2017). These Paleo-Indian communities were semi-sedentary and survived of hunting megafauna, plant gathering and fishing in the highland areas of Chapala, Sayula-Zacoalco, Zacapu, Cuitzeo, Mexico and Puebla-Valsequillo (Zizumbo-Villarreal and Colunga-Garcia, 2010). An important migration from North America into the area occurred around 10,600 BP (Dixon, 2001). These groups were mobile hunter-gatherers, specializing in small game hunting using domesticated dogs (Wayne et al., 2006) and wild plant gathering for direct consumption or after processing (Ranere et al., 2009). This has led some authors (Landon, 2008; Piperno et al., 2009; Ranere et al., 2009; Zizumbo-Villarreal and Colunga-Garcia, 2010) to consider these communities to be the precursors of agriculture in the area.

Climate began to change after 12,000 BP with a gradual rise in temperature, rainfall and a greater seasonality (Zizumbo-Villarreal and Colunga-Garcia, 2010), specifically an increasingly long drought period before a rainy season (Piperno, 2006; Cunniff et al., 2008). This was followed in the archaeobotanical record by proof of domesticated *Cucurbita sp.* and *Lagenaria sp.* from 10,000 BP (Piperno, 2011), and around 9,000-8,5000 BP by the domestication of different species of squash (Pickersgill, 2016). However, cereal agriculture is much more debated since the first domesticated maize dates from about 6,250 BP (Pickersgill, 2016). In fact, palaeoecological records show an increased presence of Asteraceae family weed species and maize pollen accumulations (Piperno et al., 2007), pointing to an agricultural intensification during the 7th millennia BP that seems to have triggered a meaningful growth in population as well as semi-sedentary settlements, not to mention the appearance of common storage of agricultural surplus (Zizumbo-Villarreal and Colunga-Garcia, 2010). This process culminated during the so-called Formative Period (c. 4.500-1.750 BP) with the emergence of the Olmec Culture, when sedentism and the production of pottery became nearly universal throughout the area (Nichols, 2015; Pickersgill, 2016).

The Mesoamerican case is another example of partial agreement with the theory: domestication followed closely a large increase in climatic seasonality, but the evidence for sedentary life and dedicated storage facilities only becomes conclusive after the adoption of cereal agriculture. The lack of evidence for dedicated storage facilities could potentially be explained by the fact that properly treated squashes store for months without the need of any specific infrastructure.

B.1.4 South America

South America has been inhabited by humans since at least 13,000 BP (Steele and Politis, 2009) and probably before 20,000 BP (Lahaye et al., 2013; Prates et al., 2013; Boëda et al., 2014). Nonetheless the first conclusive evidence encountered in the Andean regions dates back to 12,000 BP (Lavallée, 2000). These Late Pleistocene communities known as Paleo-Indians were mobile hunter-gatherers, featuring broad spectrum economies similar to those of their counterparts in North- and Meso-America (Piperno, 2011). From 9,000 to

7,000 BP people formed more settled communities, living near scarce water sources where they continued hunting, fishing and gathering, but also began gardening and storing (Dillehay et al., 2007). Such resource abundance would have allowed them to maintain year-round fully-sedentary settlements such as Las Vegas-80 (Ecuador) o Paloma (Perú) (Lavallée, 2006).

The adoption of this new way-of-life overlaps in time with a period of increasing aridity that started at circa 8.500 BP and lasted until at least 6,000 BP (Craig et al., 2010) as shown in the palaeoecological record of the area, enhancing the already natural seasonality of the Andean region due to its monsoonal climate (Abbott et al., 1997; Bustamante et al., 2016). Eventually, these communities would have developed agriculture, probably as a result of intensive gardening of roots, tubers and tree crops (Pearsall, 2008) even though there is still debate about the exact timing of such domestications. During the 80s, it was argued that the Guitarrero Cave (8,500-7,000 BP) holds the earliest known remains of domesticated plant species such as *Capsicum chinese* (Lynch, 1980) tough this viewpoint has recently been called into question. Instead, many specialists now favor 5,000-4,500 as the earliest confirmed evidence of domestication, mainly different species of *Cucurbita sp.* and maize (Pearsall, 2008; Piperno, 2011), though this viewpoint is still being debated. Be that as it may, the importance and richness of this crop complex did not peak until at least 4,000 BP (Pearsall, 2008) or even later in some areas (Diaz-Zorita et al., 2016) when the number of cultivated species starts to grow exponentially and pottery production is introduced (Lavallée, 2006).

The evidence from the South American case therefore broadly overlaps with the predictions of my theory: an increase in climatic seasonality is closely followed by a more settled lifestyle and eventual domestication. The main problem is the lack of any definitive evidence of intensive food storage, though the above mentioned Guitarrero cave contained basketwork of unknown function.

B.1.5 North China

The North China Late Paleolithic is characterized by mobile hunter-gatherers who inhabited small open-air sites, featuring a broad range of technological strategies such as microblade production or grinding stones; possibly reflecting specific adaptations to the unstable conditions of the region during the late Terminal Pleistocene (Cohen, 2011). Most scholars agree that these resource intensification technologies began in China during the Last Glacial Maximum (24,500 - 18,300 BP) and that their presence would have been crucial to the later development of food production and agriculture (Elston et al., 2011).

The Younger Dryas (12,900-11,300 BP) brought about greater aridity and climate seasonality (Wang et al., 2001). Around the same time, the production of pottery in sites such as Nanzhuangtoy (12.500-10.900 BP, Henan), Zhuannian (11,300-10,300 BP, Beijing) or Donghulin (11,000-9,300 BP, Beijing) points to newly-sedentary forager communities who show important transitional steps towards the subsequent Neolithic period (Yang et al., 2015). Around 10,000 BP, the archaeological record points to a further increase in sedentism, population agglomeration and intensive storage (Cohen, 2011) . Their subsistence, however, was still based on hunting, gathering and fishing activities (Barton et al., 2009) accompanied by intensive exploitation of the animals (e.g. pigs) and plants (e.g. millet) which will be domesticated and exploited after 9,000 (Larson et al., 2010) and 8,000 BP respectively (Zhao, 2011; Liu et al., 2012). In fact early farming in North China has been found to occur in at least five separate areas, associated to distinct, but roughly contemporary cultures (Xinglongwa, Houli, Cishan, Peiligang, and Laoguantai), distributed over diversified environments from the northeast China Plain to the western Loess Plateau (Bettinger et al., 2010) . As such, there is still debate about the role of the climate change in the emergence of food production (An et al., 2004; Zhang et al., 2010; Zhuang, 2015) and the issue needs to be revisited (Bar-Yosef, 2011).

North China can therefore be classified as perfectly reflecting the predictions of the theory: an initially mobile hunting and gathering population responds to a large increase in climatic seasonality by becoming sedentary and storing food, followed later by the adoption of agriculture and the domestication of both plant and animal species.

B.1.6 South China

Late Upper Paleolithic South China communities were hunter-gatherers who subsisted on the exploitation of both terrestrial and aquatic fauna and plant collection (Prendergast et al., 2009). They lived mainly in caves, most of them located around the Nanling Mountains (Chi and Hung, 2012). They feature the typical cobble-tool industries of the area (cores, flakes and choppers) (Bar-Yosef and Wang, 2012) since the so-called Chinese Acheulian. Mesolithic communities had a more intensified and diversified economy (Prendergast et al., 2009), featuring large quantities of shell midden (mostly riverine gastropods) and 20-30 types of food animal, specially deer who represent the main food income along with various edible plant seeds (Prendergast et al., 2009; Chi and Hung, 2012). However, no proof of food production has been discovered so far.

Instead, it was about 11,000 years ago when the initial pre-domestication of rice cultivation began in the region between the Yellow and Huai rivers (Chi and Hung, 2008). As in the northern case, this intensification coincides with a greater aridity and climate seasonality (Wang et al., 2001) during and after the Younger Dryas (12,900-11,300 BP) (Prendergast et al., 2009)— though somewhat less extreme than in the North. Although the number of identified sites for this period is not large, the overall cultural sequence is fairly well understood (see Chi and Hung, 2008). The so-called Middle Neolithic communities (10,000 - 7,000 BP) lived outside caves, usually on river terraces in relatively sedentary settlements which could have supported cultivation: in fact, a great amount of domesticated rice husks have been found in different archaeological sites such as Shangshan (10,000 BP) (Jiang and Liu, 2006). Also, incipient domestication of pigs and chicken was underway, as documented in Kuahuqiao site (Jing et al., 2008; Cucchi et al., 2011). The subsequent Early Late Neolithic phase (7,000 - 5,500 BP) witnessed the definitive establishment of food production economies and, as a result, rapid geographical expansion due to population growth and cultural diversification (Chi and Hung, 2008, 2012).

The South Chinese Neolithic is therefore another case where the match with the predictions of the theory can be described as only partial. As in Northern China, agriculture followed a period of increased seasonality, though unfortunately there is no evidence of an intermediate stage with sedentism and storage, but without agriculture. One possibility might be that the populations in question had already accumulated some familiarity with rudimentary agricultural techniques while remaining nomadic. Therefore, they would have begun farming very soon after increased seasonality pushed them to become sedentary. Given the very small number of excavated sites for the period in question, it is plausible that a short sedentary hunter-gatherer stage would not be observed. Of course this is merely compatible with the theory I propose, rather than diagnostic of it.

B.1.7 The Sahel

Plant domestication in Africa occurred relatively late compared to the rest of the world. In this sense, the first evidence of properly African cultigens are concentrated in the sub-Saharan area of the so-called Sahel. This region was inhabited by various Late

Stone Age communities, featuring pottery production since 12,000 BP (Huysecom et al., 2009). They subsisted on small game hunting (Linseele, 2010) and aquatic resources exploitation (Holl, 2005), varying in relative importance depending on the region in question. They also used plant foods, some of them requiring more preparation such as grinding (Finucane et al., 2008). Eventually, these communities engaged in animal domestication, mainly cattle at circa 10,000-9,500 BP (Gautier, 2007). As nomadic pastoralists, they continued hunting, gathering and fishing (Kuper and Kroepelin, 2006) but started their sedentarization process (Phillipson, 2005). In this sense, the climatic benevolence of the African Humid Period (9,000-6,000 BP) (Menocal et al., 2000; Tierney and de Menocal, 2013) — which would have allowed an important increase of population size (Manning and Timpson, 2014) and the success of this mixed subsistence strategy (Neumann, 2003, 2005) could have slowed down the domestication of local African crops for several millennia.

However, the abrupt end of such humid period around 6,000-5,000 BP and the subsequent aridification process after 4.500 BP (Renssen et al., 2003) would have given way to a seasonal semi-arid environment (Cremaschi et al., 2014). In this context, the Sahel witnessed the appearance of the first indigenous African crop, that is, pearl millet (*Pennisetum glaucum*) (Kahlheber and Neumann, 2007; Linseele, 2010). The earliest evidence has been found in the Tilemsi Valley (Manning et al., 2011) in association with diversified pastoral communities that had already develop storage facilities and became almost fully sedentary (Phillipson, 2005).

The Sahel is an example of a completely different path to plant domestication, which is nonetheless broadly compatible with the predictions of the theory. The main difference with the other Neolithic sequences considered is that in the Sahel, the populations in question developed advanced pastoral societies based on herding of cattle and smaller animals before any significant move towards sedentarism or storage developed. However, in agreement with the basic theory I propose, when these pastoral nomadic communities experienced an increase in rainfall seasonality, they responded by becoming increasingly sedentary, adopting storage, and later agriculture.

C Model Extensions

C.1 Dynamic Model

I now modify the simple static model described in Section 4.2, by adding endogenous population growth to show that the instantaneous results of the static model also hold in the long run. The population dynamic of the band is determined by its consumption profile. Specifically, net individual fertility ϕ is a weighted average of consumption per capita in both months, with the weighting favoring consumption per capita in the scarcest period:

$$\begin{aligned} &\phi = \alpha \max(c_J, c_D) + (1-\alpha)\min(c_J, c_D) \qquad (12) \\ &0 < \alpha < 0.5 \end{aligned}$$

If α were equal to 0, then fertility would be equal to the minimum of consumption per capita in both months (the production process for children would have a Leontief form), while if α were equal to 0.5 fertility would only depend on average consumption per capita, and the entire model would collapse to the standard Malthusian case. I assume that the fertility dynamic lies somewhere in between these two extremes: higher average consumption per capita will increase fertility, but for any average consumption per capita, higher consumption volatility will depress fertility (Almond and Mazumder,

2008) [6]. This dynamic could arise from either biological constraints on a population reproducing *ad libitum*, or else be the result of optimizing behavior by a population that has control over its fertility, and prefers more children when food supply is abundant and stable.

In any case, even if the two populations had the same number of live births, it is almost inevitable that the one that was malnourished for part of the year would have a lower number of children reaching reproductive age, even they did have as much to eat on average. This would have the same effect of reducing the effective fertility rate of the population.

The first step is to calculate the equilibrium levels of population for each lifestyle. Population size will be stable if:

$$\begin{aligned} 1 &= \phi \qquad (13) \\ 1 &= \alpha \frac{C_J}{P_N} + (1-\alpha)\frac{C_D}{P_N} \end{aligned}$$

Where C_X is aggregate consumption of the band in month X, and P_N is the population of the band. By substituting the appropriate values we find that the equilibrium level of population for the two lifestyles will be:

$$P_N^\star = 1 - \sigma(1-2\alpha) + \gamma(1-\alpha) \qquad (14)$$

$$P_S^\star = 1 \qquad (15)$$

dividing the endowments by the equilibrium level of population, we can thus derive consumption per capita in the long run for both strategies in equilibrium:

$$c_N^\star = \left\{ \frac{1-\sigma+\gamma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}, \frac{1+\sigma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)} \right\} \qquad (16)$$

$$c_S^\star = \{1, 1\} \qquad (17)$$

Settlers, irrespective of environmental parameters, will always consume one unit of food per capita, per month: their ability to smooth consumption ensures that the standard Malthusian result prevails. In contrast, Nomads suffer a population penalty due to the seasonality in their diet. This ensures that consumption per capita is an increasing function of their diet seasonality.

The consumption profiles for both strategies allow us to derive the respective equilibrium levels of utility:

$$U_N^\star = \log\left(\frac{1-\sigma+\gamma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}\right) + \log\left(\frac{1+\sigma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}\right) \qquad (18)$$

$$U_S^\star = 0 \qquad (19)$$

Nomadism will be optimal *in the long run* whenever $U_S^\star > U_N^\star$, leading to the long run threshold condition:

[6] Unfortunately I was unable to source studies comparing fertility outcomes in two populations with the same *average* food consumption, but different *seasonal* patterns. This is partly because such cases are rare in modern times, thanks to the very storage technologies that I examin in this paper. However, the cited study showed that even brief periods of daily fasting have measurable and significant negative outcomes for the viability of pregnancy, and long run health after birth.

$$\sigma = \frac{1 + \gamma(1 - 2\alpha + \alpha^2) - 2\alpha}{1 - 2\alpha + \alpha^2} \tag{20}$$

The higher γ is, the higher σ must be for settlement to provide a higher utility than nomadism.

However, the long-run equilibrium outcomes of settlement could not be guessed by the populations that abandoned nomadism. For this adaptation to become widespread, it is important that settlement is also better than nomadism soon after the transition, i.e. before population size adjusts to the new equilibrium. In the short run we find:

$$c_S^- = \frac{C_S}{P_N^\star} c_S^- \qquad = \left\{ \frac{1}{1 - \sigma(1 - 2\alpha) + \gamma(1 - \alpha)}, \frac{1}{1 - \sigma(1 - 2\alpha) + \gamma(1 - \alpha)} \right\} \tag{21}$$

Settlement will increase utility in the short run if $c_S^- > c_N^\star$. This disequation is simply the condition for optimality derived for the static model, scaled by a constant (the equilibrium population size of nomads). Since preferences are homothetic, we know that the optimality condition will be the same as in Equation 6.

$$\sigma = \frac{\gamma + \sqrt{4\gamma + \gamma^2}}{2} \tag{22}$$

These results can be condensed in the following proposition, which parallels the statements of Proposition 1

Proposition 2. *In the dynamic model we find that:*

1. *If the climate is not very seasonal (low σ), and the band has access to uncorrelated ecosystems (high γ), nomadism will be optimal both in the short run and in the long run.*
2. *An increase in seasonality can cause settlement to be better than nomadism both in the short and long run.*
3. *The higher γ is, the more seasonal climate must be before settlement becomes optimal.*
4. *Consumption per capita will be lower after the transition and will remain lower even after population adjusts.*

C.2 Explaining the spread of agriculture

So far I have shown that an increase in environmental seasonality will make it optimal for a nomadic population of hunter gatherers to become sedentary, even though doing so might decrease their average diet. In this subsection, I will sketch a model extension that shows how the initial transition is likely to result in the adoption of agriculture, and just as importantly, to precipitate its spread. To do so, I will make only superficial modifications to the model outlined in the previous sections, by introducing some new assumptions. These are:

1. All populations possess some rudimentary level of agricultural technology, which grants them an extra amount of food c in Summer, provided that they reside constantly in the same environment.

2. This extra amount of food c is large enough to be measurable, but so small as to be insufficient to motivate transition to settlement if environmental seasonality remains low.
3. Agricultural technology is subject to large gains from learning by doing, so that c will increase as the population practices farming longer.
4. Gains in agricultural technology eventually diffuse to neighboring areas.

Assumption 1) is justifiable due to the fact that even very obvious activities such as deterring grazers from destroying a particularly productive vegetable patch will have an immediate effect on realized productivity. Assumption 2) is essentially by construction: if nomads had already acquired a sufficiently large level of technology to motivate settlement even in the absence of a seasonality shock, agriculture would have already been adopted. Since it hadn't been adopted, we know they hadn't developed it to that point yet. Assumption 3) reflects the fact that many rudimentary agricultural activities are fairly straightforward when presented with the actual problem. Field guards can be economically replaced by fences; weedy plants can be identified and removed; and where feasible, water can be diverted away from areas prone to flooding. Once deliberate seed planting is initiated, plants will begin to coevolve with humans, leading to selection for traits that improve the chances of a plant's seed being gathered and replanted. This process will inexorably lead to plant domestication, and unlock further increases in productivity. Finally, assumption 4) takes into account the fact that cultivation techniques can be transmitted by word of mouth or imitation, more productive domesticated seeds can be traded, or populations that don't take advantage of agriculture kicked off their land and replaced.

Given these assumptions, consumption of the Nomadic and Settler bands in the static model will simply be

$$C_N = \{1 + \sigma, 1 - \sigma + \gamma\} \tag{23}$$

$$C_S = \left\{1 + \frac{\chi}{2}, 1 + \frac{\chi}{2}\right\} \tag{24}$$

Where χ is the extra level of food coming from agriculture, which starts from some low base level, and is an increasing function of the cumulative amount of agriculture which has been carried out by the band an all of neighboring populations within cultural contact. The utilities for the two subsistence strategies will therefore be:

$$U(N) = \ln(1 + \sigma) + \ln(1 - \sigma + \gamma) \tag{25}$$

$$U(S) = 2\log(1 + \chi) \tag{26}$$

How do these assumptions bode with what we have seen previously? The analysis proceeds very similarly. We will begin from a situation in which there are two neighboring populations, both of which are experiencing low environmental seasonality, and therefore find it optimal to remain nomadic hunter gatherers. Then, one of them experiences an increase in seasonality, which pushes the utility from nomadism below what they would achieve if they became sedentary, motivating them to transition. The newly settled population now finds it optimal to begin employing their rudimentary agricultural technology, leading to slight improvements in their diet and utility.

More importantly, by engaging in agriculture, their farming technology begins to improve, leading to very gradual increases in their utility (or population size, if we take into account increased fertility). Eventually, these gains will lead to hunting and gathering being relegated to a secondary source of food. Just as importantly, the improved technology will diffuse to their neighbors who did not experience the seasonality shock.

At some point the imported technology will be so effective as to make it worthwhile for them to transition to sedentarism and agriculture, even though they did not themselves experience an increase in seasonality. However, higher seasonality will still lower the threshold of agricultural technology above which case it makes sense to make the switch, so all things being equal we expect that if two otherwise identical locations are simultaneously exposed to a farming neighbor, the more seasonal locations will transition to agriculture sooner.

Another important implication of this extension is that agricultural technology creates a ratchet effect. Once farming is sufficiently established and productive, sedentary agriculture will remain optimal even if the increase in seasonality that motivated the original transitions is reversed (which in fact is evident from the data). This would explain the near absence of examples of reverse transitions from agriculture to hunting and gathering.

The introduction of agriculture could be expected to increase the year-on-year risk experienced by the band, since an increasing fraction of the food supply would depend on the climate conditions favoring the growth of only few species. However this kind of uncertainty would still have been preferable to the certain hunger that would befall a nomadic band in winter, if it lacked both food stores, and refuge locations within plausible migratory range.

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