Climate-driven technical change: seasonality and the invention of agriculture

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Abstract

During the Neolithic Revolution, seven populations independently invented agriculture. In this paper, I argue that this innovation was a response to a large increase in climatic seasonality. Hunter-gatherers in the most affected regions became sedentary in order to store food and smooth their consumption. I present a model capturing the key incentives for adopting agriculture, 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 amongst the major determinants of the present day global distribution of crop productivities, ethnic groups, cultural traditions, and political institutions.

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1 Introduction

Why was agriculture invented? The long run advantages are clear: farming produced food surpluses that allowed population densities to rise, labor to specialize, and cities to be constructed. However, we still don't know what motivated the transition 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 (the Neolithic Revolution). Moreover, the first farmers were shorter and had more joint diseases than the last hunter-gatherers, suggesting that they ate less, and worked more (Cohen and Armelagos, 1984). Why would seven different human populations decide to adopt remarkably similar technologies, around the same time, if it resulted in a lower resulting standard of living?

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 made it hard for hunter-gatherers to survive during part of the year. Some of the most affected populations responded by becoming sedentary in order to smooth their consumption through storage. While these communities were still hunter-gatherers, sedentarism and storage made it easier for them to adopt farming.

To guide the empirical analysis, I develop a simple model which 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 consumption seasonality reduces fertility. I find that a large increase in seasonality can cause agents to switch from nomadism to settlement, even if they still don't know how to farm. Despite consuming less on average, the ability to smooth consumption through storage more than repays this loss, meaning that the settlers are now better off both in the short and long run.

The theory suggests that more seasonal locations should receive agriculture sooner. To test this prediction, I employ a panel dataset of reconstructed climates, covering the entire world for the past 22,000 years. My results are summarized in Figure 1. I find that both temperature and precipitation seasonality are strong predictors of the date of adoption. In the global sample, increasing the yearly temperature range by 10 °C causes the local population to start farming approximately 1,000 years earlier. I show that this result comes through two channels. First, higher seasonality made the invention of agriculture easier: all seven locations where 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.

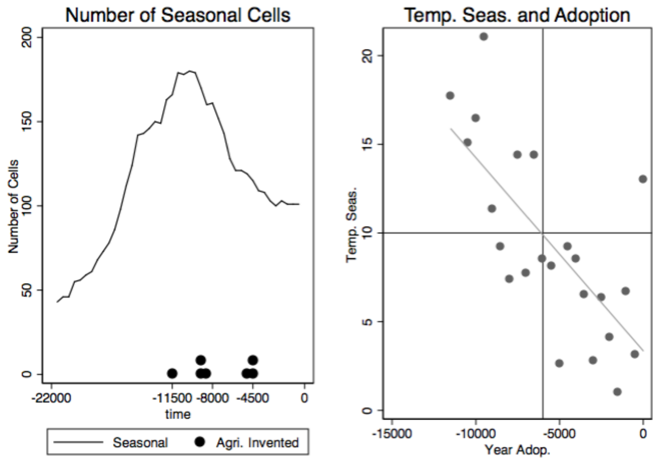

Figure 1: Right panel: climate became more seasonal shortly before agriculture was invented multiple times. Left panel: binned scatterplot of temperature seasonality and adoption; early adopters tend to be highly seasonal, and vice versa.

The statistical relationship between climate seasonality and agricultural adoption is significant and robust, but could be unrelated to the incentives to store food. For example, a short growth season might favor the evolution of plants which are exceptionally easy to cultivate (Diamond, 1997). To help separate these two channels, I look at a subsample of sites which had the same seasonality and domesticable species, but which differed in the opportunities they offered to a nomadic band. Some sites were close to large changes in elevation, which meant that nomads could migrate seasonally to areas with uncorrelated foodshocks. Other sites were surrounded by areas of similar altitude to their own, making 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 approximately 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 (Testart, 1982). Further, taking storage into account allows us to understand why agriculture was adopted in spite of the reduction in consumption per capita: the first settlers accepted a worse 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 setting of the Neolithic Revolution is unique, in that very similar technologies were developed multiple times by different groups. Unlike e.g. the Industrial Revolution, it is therefore possible to draw parallels between different adoptions, and identify what all of them had in common. Many contributions have focused on changes in average climate. The Neolithic started shortly after the end of the Late Pleistocene glaciation, which lasted from 110,000 to 12,000 years ago. This has led some researchers to hypothesize that either warmer weather made farming easier (Bowles and Choi, 2013), or else drier conditions made hunting and gathering more difficult (Childe, 1935). Ashraf and Michalopoulos (2013) propose a variant on the climatic theme, and argue that intermediate levels of inter-annual climate volatility led to the gradual accumulation of latent agricultural knowledge. The problem with these explanations is that they assume that the first farmers wanted to eat more. The fact that they ended up eating less suggests that greater food consumption is unlikely to be the motive.

Other contributions have focused on explaining the reduction in consumption per capita. This loss has been variously attributed 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 all have been contributing factors, they do not explain why agriculture was invented in particular places and at particular times. The key contribution of this paper lies in proposing a unified theory for the origins of agriculture, which can explain both of these puzzles: the geographic pattern of adoption, and the resulting decrease in consumption per capita. The model I propose generates clear empirical predictions, which I test against the paleoclimatic record, the local topography of early adoption sites, and the 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. (2013) provide an extensive review. I argue that increased climatic seasonality presented a challenge to the established way of life of humans, which responded by adopting a novel life strategy — sedentary storage— to mitigate the negative consequences of this change in climate. This new lifestyle was already a big change, but it would be soon overshadowed by the incredible technological and social innovations which it facilitated: agriculture, 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 tried to explain why humans started to farm. Early contributions (Darwin, 1868) focused on the greater abundance of food which agriculture allowed, but the decrease in standard of living suggests that this was not the primary reason. Climate change is arguably the only factor capable of explaining simultaneous invention on different continents Richerson et al. (2001), and indeed agriculture was invented after the end of the last Ice Age. This suggested that warmer climates may have made farming more productive (Diamond, 1997; Bowles and Choi, 2013), or else 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, improving climates allowed population density to rise, but a later return to near-glacial conditions forced hunter-gatherers to concentrate in the most productive environments. The problem with all these stories is that 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 (2013) propose that intermediate levels of inter-annual volatility favored 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, I focus on seasonality, rather than on inter-year volatility, and I argue that the crucial step was the decision to become sedentary and store food.

Other contributions have focused on the role of population growth. One possibility is that overexploitation decreased the productivity of hunting and gathering (Olsson, 2001; 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 becoming settled, 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 nomadic usefulness came from highly seasonal climate, which made all locations within migratory range similarly unproductive at the same time.

A large 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 which transitioned early gained an early technological lead, which largely predetermined which continents would eventually inflict colonialism, and which would suffer 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 which 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., 2013).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 but risky lifestyle, in exchange for one that had lower returns, but was more stable. 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 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 contributions, risk-aversion is seen as an economically costly trait. I show that a desire for stability can also promote economic growth, if the risk mitigating strategies adopted happen to make innovation 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 can 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, 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 which encouraged higher mortality (Voigtländer and Voth, 2013b), and lower fertility (Voigtländer and Voth, 2013a). Wu et al. (2014) 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 consumption seasonality.

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 by slaving incursions. Michalopoulos (2012) documented the role of ruggedness in forming ethnolinguistic groups. Fenske (2014) noted that regions with more varied ecosystems have greater incentives to trade, and showed that the more successful African governments benefit 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, worse 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. Since latitude and seasonality are highly correlated, the findings of this paper suggest that part of the association between latitude and development outcomes might be due to the different amount of time humans have been performing agriculture at various distances from the equator.

3 Historical background

For the first 200,000 years of our species existence, our ancestors relied exclusively on wild foods for survival. The hunting and gathering lifestyle sustained them from the plains of Africa, throughout their successive migrations. By 14,000 BP, humans had colonized all continents except Antarctica, and hunted and gathered from the tropical rainforest to the arctic tundra. The incredible versatility of this lifestyle was partly due to nomadism. By constantly moving to temporarily more abundant areas, humans could survive even where no single location provided a reliable food supply. Hunter-gatherers managed to develop rich and unique cultures and technologies, adapted to the opportunities and requirements of their specific surroundings. These trends solidified approximately 60,000 years ago, when humans acquired behavioral modernity: they developed languages, made art, decorated their bodies, and buried their dead.

After this milestone, however, further progress had been comparatively modest. Our ancestors continued to refine their techniques, and to adapt them to changing environments, but the basic pattern remained unchanged. In particular, no population is known to have domesticated crops until about 12,000 years ago.

The Neolithic transition is now understood to have occurred gradually, starting from relatively minor actions - such as pulling up weeds, and culminating in highly complex endeavours - such as the excavation of massive irrigation channels. These activities changed the selective pressures operating on cultivated species, which soon evolved to take advantage of human assistance — they became domesticated (Harlan, 1992). This resulted in crops which were more productive, easier to harvest, and able to grow in a wider range of conditions.

The very earliest farmers belonged to the Pre-Pottery Neolithic B culture, which domesticated wheat and barley in the hills of the Fertile Crescent approximately 11,500 years ago (Belfer-Cohen and Bar-Yosef, 2002). Within seven thousand years, agriculture would be invented independently at least six more times, in the Andes, North and South China, Mexico, Eastern North America, and Sub-Saharan Africa (Purugganan and Fuller, 2009). Each of these locations had different climates and available plant species, and was inhabited by populations who had not been in contact for tens of thousands of years. Figure 2 shows the independent farming inventions and their dates.

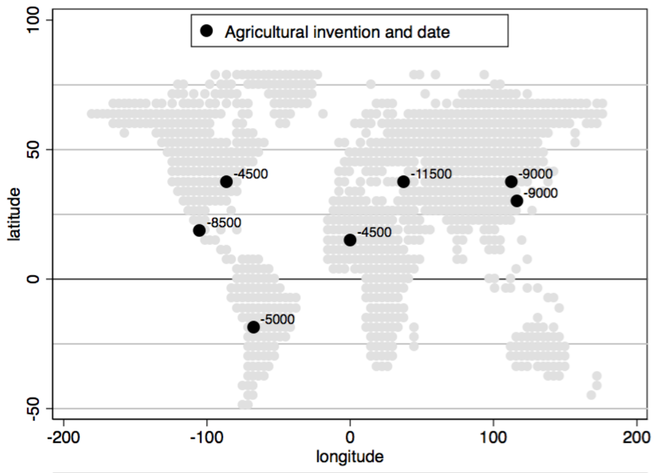

Figure 2: The locations where agriculture was invented, and their respective dates in years before present.

Thanks to farming, the same amount of land could feed more stomachs. The increased population density led to the rise of the first cities, with their 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). 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 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 requires constant interaction with the plants under cultivation, it was very difficult for a nomadic population to discover agricultural techniques. First, nomads would typically never witness the same individual plant growing throughout the year. They were thus less likely to understand how their actions affect 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.

I argue that the rise of the Neolithic was ultimately caused by unprecedented climate seasonality. What caused these conditions? The patterns of climatic seasonality experience on Earth depend chiefly on the shape of Earth's orbit, as described by three parameters: axial tilt, eccentricity, and precession. During the Ice Age, Earth's axis of rotation was less tilted and its orbit was less elliptic. Moreover, when the Northern hemisphere 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 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, 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 risked starving in the harsh winters. Conversely, tropics 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, and then become barren during the dry one. In fact, all confirmed independent inventions of farming occurred within these two absolute latitude bands: 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, the Andes and Mexico are all within the tropical area of rainfall seasonality.

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. 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 start the current warm period (the Holocene) it is tempting to assume that agriculture was a response to change climate averages. 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.

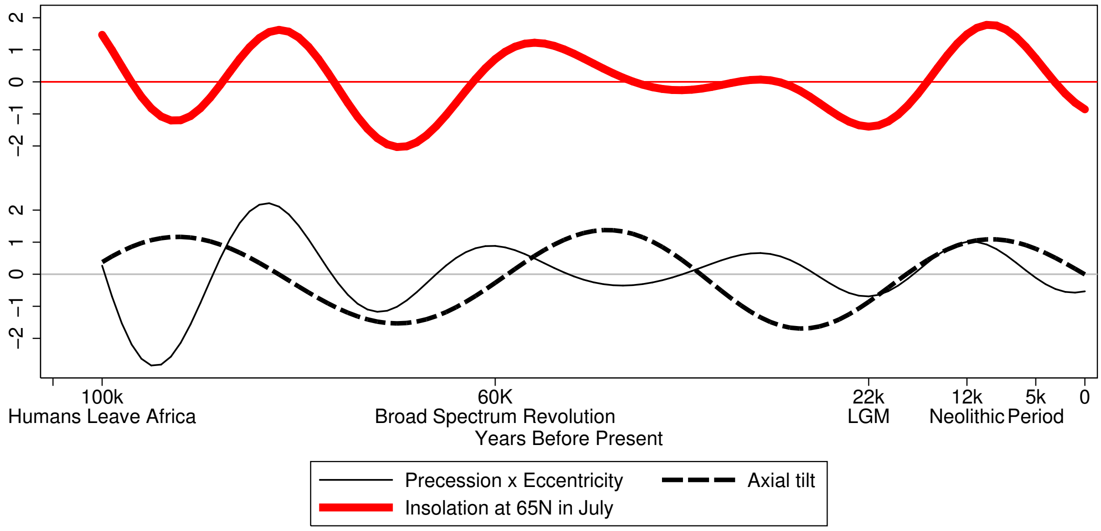

Figure 3: Three parameters combine to determine insolation seasonality in the northern hemisphere. During the Early Neolithic, these three cycles peaked simultaneously for the first time in over 100,000 years (black, I show the effects of axial tilt, and the combined effect of precession and eccentricity). 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.

These narrow confines would have provided the right incentives for agricultural adoption. 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 elsewhere had experienced similarly pleasant conditions for tens of thousands of years.

4 Model

In this section I model the incentives faced by a single band of hunter-gatherers, as it adapts its 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 looses 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, in which population evolves endogenously. I modify the basic Malthusian setup by assuming that fertility is increasing in consumption per capita, but 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 in contrast are able to perfectly smooth consumption through storage. Their stable diet ensures the maximum possible fertility, so that in equilibrium they have the lowest consumption per capita possible.

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 territory of the band, the Hill and the Valley, and two months in the year, December and July. The Hill provides an endowment of $1+\sigma$ in July, and $1-\sigma$ in December, while the Valley provides no food in July and $1-\sigma+\gamma$ units of food in the Winter. 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 summer, but a cold and rainy winter. Hills are usually colder than the surrounding plain, but receive more rainfall. Therefore we would expect that in the summer, the hills will be hot and wet, plants will grow well, and food availability will be very high. In winter however, the hill is too cold and will provide much less food. In the plains, the lack of rainfall make food extremely hard to find in summer. But in winter, the plains are warm enough and wet enough, and temporarily provide more food than the hills. This general pattern can be adapted to model a variety of resource availability regimes.

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

$$U = \log(c_J) + \log(c_D) \tag{1}$$

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. The settled band will instead settle in the Hill (which has the highest aggregate endowment), and will be able to perfectly smooth its consumption through storage. However, it will no longer be able to access the resources of the 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

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

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

Each consumption profile shows first consumption July, and then consumption in

December. Utilities from the two strategies are simply:

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

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

Utility of the settlers is 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 4 and 5.

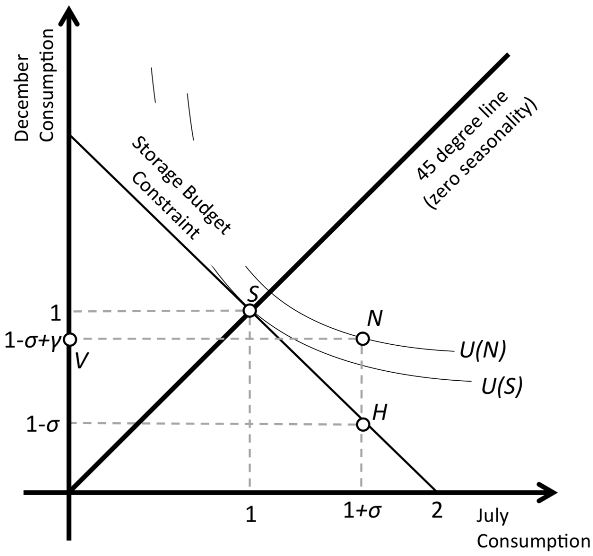

Figure 4: Circles H and V represent the the endowments of Hill and Valley respectively. The Nomads are able to always reside in the best territory during each month, and therefore enjoys a consumption profile of N. The Settler can only harvest the resources of H, but can smooth consumption costlessly. 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.

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

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

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

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

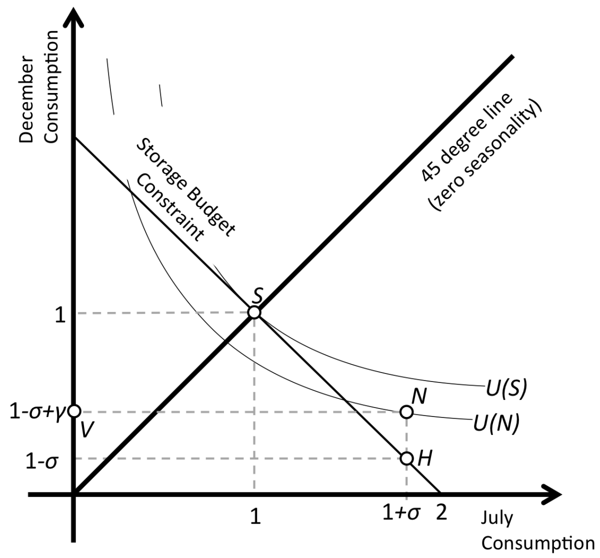

Figure 5: Now σ is higher, and γ is lower. A nomadic band would now be exposed to high consumption seasonality, so that utility is now higher if it switches to settlement. This is true despite settlement having a lower consumption per capita.

1. *If the climate is not very seasonal(high 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 climate must be before settlement becomes optimal.*
4. *Consumption per capita will be lower after the transition.*

4.3 Dynamic Model

I now add 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:

$$\phi = \alpha \max(c_J, c_D) + (1 - \alpha) \min(c_S, c_D) \tag{7}$$

$$0 < \alpha < 0.5$$

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 seasonality will depress fertility (Almond and Mazumder, 2008). This dynamic could indifferently 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.

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

$$\begin{aligned} 1 &= \phi \qquad (8) \\ 1 &= \alpha \frac{C_J}{P_N} + (1-\alpha)\frac{C_D}{P_N} \end{aligned}$$

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:

$$P_N^\star = 1 - \sigma(1-2\alpha) + \gamma(1-\alpha) \qquad (9)$$

$$P_S^\star = 1 \qquad (10)$$

By 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:

$$c_N^\star = \left\{ \frac{1-\sigma+\gamma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}, \frac{1+\sigma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)} \right\} \qquad (11)$$

$$c_S^\star = \{1, 1\} \qquad (12)$$

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:

$$U_N^\star = \log\left(\frac{1-\sigma+\gamma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}\right) + \log\left(\frac{1+\sigma}{1-\sigma(1-2\alpha)+\gamma(1-\alpha)}\right) \tag{13}$$

$$U_S^\star = 0 \tag{14}$$

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

$$\sigma = \frac{1+\gamma(1-2\alpha+\alpha^2)-2\alpha}{1-2\alpha+\alpha^2} \tag{15}$$

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. The short run

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

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.

$$\sigma = \frac{\gamma + \sqrt{4\gamma + \gamma^2}}{2} \tag{17}$$

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(high 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.*

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 Data

My analysis requires information on where and when agriculture was invented independently, the dates in which it reached particular areas, and information on the climate prevalent at the time.

5.1 The invention and spread of agriculture

Data on the invention of agriculture comes from two main sources: direct archaeological evidence of domesticated plants or farming implements, 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 generally accepted primary (i.e. independent domestications centers), and potentially important secondary domestication centers.

The previous dataset has information on the time and place of domestication, but does not track the gradual spread of the Neolithic to neighboring areas. Putterman and Trainor (2006) provides data on the earliest date for which there is evidence of agriculture for 160 countries. This dataset compiles for each country the year for which agriculture first appears in the archaeological record. Note that while the Purugganan and Fuller dataset is compiled mainly from genetic evidence (the number of generations which separate modern crops from their wild cousins), the Putterman dataset is based entirely on archaeological reports. As such, the dates are not always in perfect agreement. To harmonize the two datasets, I assign to individual cells whichever adoption date is earliest: that of the country it belongs to, or that of any domestication area it may be a part of.

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), which gives 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.

5.2 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. To complement the 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 is potentially problematic, especially when comparing outcomes which are distant in space or time. In this 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).

5.3 Other data sources

The altitude data comes 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. I use the maps from Harlan (1998), from page 94 and onwards.

5.4 Variable construction

The model predicts that agriculture will be adopted when nomadic hunter-gathered 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.

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

It would prove useful in the analysis to have a single measure reflecting both types of seasonality. Combining these two variables is problematic: water and temperature affect the food availability in complex ways. In the absence of an obvious candidate which can be calculated directly with the data at hand, I define the following Seasonality Index:

$$\text{SeasIndex} = \max(Quantile(TempSeas), Quantile(PrecipSeas))$$

That is, for each cell and period, I transform the two seasonality measures into quantiles (1000 categories). The seasonality index is equal to whichever of the two measures has the highest score. For example, if a location has a Seasonality Index of 900, it must either have more temperature seasonality than 90% of the cell-period observations, or more precipitation than 90% of the cell-period observations. I choose the minimum rather than the average because plant growth is limited mainly by the least abundant factor. For example, Sub-Saharan Africa is never cold, but the presence of a long dry season is sufficient to make food supply highly seasonal.

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.

6 Results

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 the areas in the world where agriculture was invented where unusually seasonal, and find that in all seven, a warm and moist season alternated with either very harsh winters, or a very dry season. Second, I show that farming spread faster in highly seasonal locations. Third, I estimate the combined effect of invention and spread on the timing of adoption, and find that one extra standard deviation of temperature seasonality is associated with adopting agriculture

1500 years earlier. I replicate the most important steps of this analysis on a higher resolution regional dataset for Western Eurasia, which confirms the earlier findings.

The preceding establishes a strong and robust link between climate seasonality and the adoption of agriculture, but does not identify the channel. For example, Diamond proposed that the invention of agriculture was caused by the availability of plants that were easy to domesticate, such as large seeded grasses. Perhaps a short growth season favored 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 part of the analysis

Further verification for the model's findings come from the paleopathological record of the Neolithic. Analysis of skeletal remains shows that consumption per capita decreased after the invention of farming, but the absence of growth-arrest line confirms that consumption seasonality decreased as well.

6.1 Global-scale analysis

The climate data consists 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, and Antarctica, leaving 1036 cells.

To this dataset, I merge my data on agricultural invention, by generating a dummy that takes the value of 1 if agricultural was invented in a particular place and time, and 0 otherwise. This variable is based on the Purugannan and Fuller data. I also generate another dummy -based on the Putterman and Trainor 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. I collapse the data to a cross-section, 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 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 4500 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, a precipitation seasonality of 1.3, and a seasonality index of 625 (out of 1000).

	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-section dataset.

How well does my story fit the basic features of the data? Figure 6 shows how many cells were seasonal during each period of the last 22,000 years. A location is considered seasonal if it has a Seasonality Index above 925. Seasonal locations were rare during the Ice Age, but became increasingly common in the lead up to the adoption of agriculture, more than tripling in frequency. This trend was driven by the simultaneous peaks in the three orbital parameters influencing seasonality (as discuss in Section 3 . Figure 7 shows how six out of seven of the independent inventions occurred precisely in these areas, or nearby. 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 average 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.

6.1.1 Independent invention

I will first check whether higher seasonality made invention more likely. I examine this prediction in the global context, 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, and I drop each location after it adopts agriculture. The basic specification is:

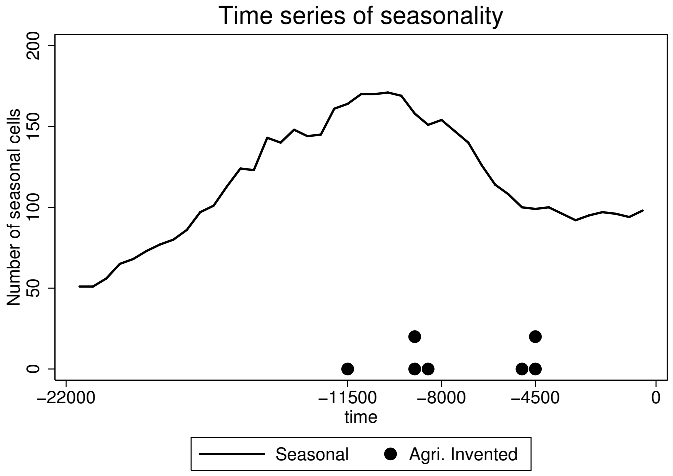

Figure 6: The number of cells with seasonal climates (Seasonality Index > 925), through time. The black dots mark the timing of the independent adoptions. At the start of the Neolithic, there were more than three times as many seasonal locations as during the Ice Age. This was primarily driven by the changes in orbital parameters described in Figure 3.

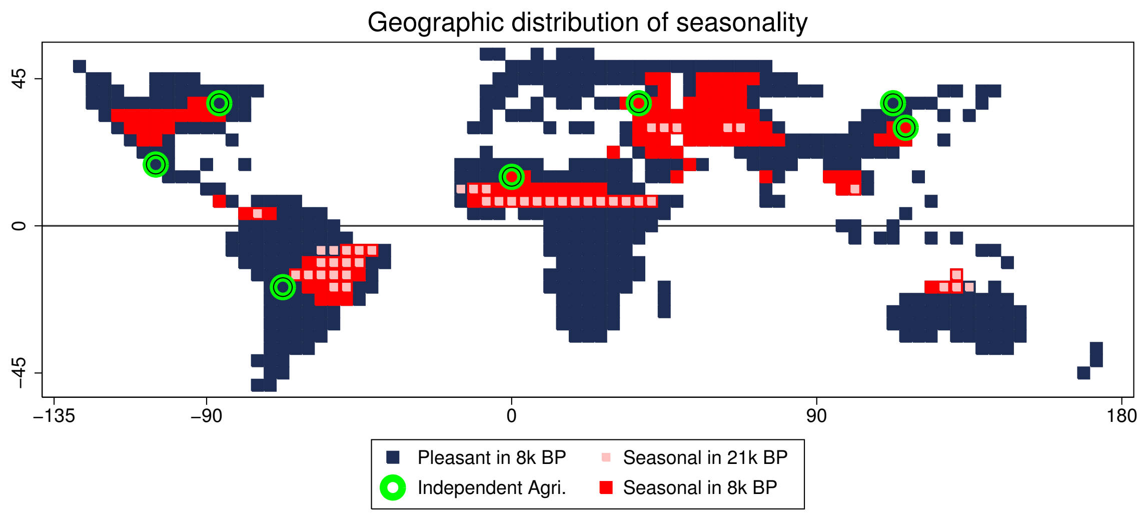

Figure 7: The map shows the global distribution of seasonal locations. Pink cells were already seasonal in 21k BP. Cells that were seasonal in 8,000, are in Red. Dark blue cells are hospitable in 8,000 BP (average temperature ¿ 0 and annual precipitation ¿ 100mm). Locations that were not hospitable in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

$$I_{it} = \alpha + \beta_1 \mathrm{T}_{it} + \beta_2 \mathrm{P}_{it} + \gamma C_{it} + \epsilon_{it} \tag{18}$$

$$\tag{19}$$

Where I_{it} is a dummy for whether agriculture was invented 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, except for seven 1s representing the times and places where agriculture was invented. As each location invents agriculture or adopts it from neighbors, I drop it from the panel.

I use logistic regression to estimate the model, and present the results in Table 3. In column (1), the only explanatory variables are the two individual seasonality measures. The coefficient on temperature seasonality is positive and statistically significant, while precipitation seasonality is not significant. In column (2) I add controls for mean temperature, mean precipitation, and absolute latitude. The coefficient on both types of seasonality increases, and the coefficient temperature seasonality remains significant. The same pattern holds in column (3), where I include a New World dummy, and quadratic terms for absolute latitude and the two climatic averages. In column (4), I add controls for the modern level of temperature and precipitation seasonality. This confirms that the effect comes from climate conditions present at the time, and not through correlation with present conditions. Finally, column (5) shows that the Seasonality Index is also a good predictor of independent invention. Very similar result are obtained using the Rare Events Logit estimation described by King and Zeng (2001), by clustering standard errors at the location level, or if different measures of seasonality are used. These results are in line with the predictions of the model: the places that invented agriculture were all extremely seasonal.

	Dependent variable: invention dummy				
	(1)	(2)	(3)	(4)	(5)
	Basic	Controls	Controls2	ModernSeas	SI
Neol7					
Temp. Seas.	0.197***	0.188***	0.232**		
	(0.051)	(0.063)	(0.106)		
Precip. Seas.	0.676	0.683	0.015		
	(0.633)	(0.679)	(1.339)		
Seas. Index				8.525**	6.571*
				(4.021)	(3.879)
Temp. Mean	0.046	0.050	0.028	0.053	0.091
	(0.050)	(0.125)	(0.129)	(0.038)	(0.149)
Precip. Mean	0.846***	1.639***	1.591**	0.812***	1.036
	(0.216)	(0.625)	(0.713)	(0.301)	(0.713)
Abs Lat	0.051	0.128	0.128	0.083	0.206***
	(0.034)	(0.088)	(0.101)	(0.050)	(0.065)
Temp. Seas. Today			-0.055		
			(0.207)		
Precip. Seas. Today			0.819		
			(1.265)		
Seas. Index Today					-0.280
					(2.021)
Extra Controls	No	Yes	Yes	No	Yes
p	0.00	0.00	0.00	0.00	0.00
N	38533	38533	38533	38533	38533

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

Table 3: The effect of climate on adoption. Dependent variable is a dummy which is 1 if agriculture was invented in a particular cell and period, and 0 otherwise. Each location is dropped from sample after they adopt agriculture. Logistic regression on climate variables and controls.

6.1.2 Spread of farming

I now turn my attention to the process of agricultural diffusion, which saw farming grow from a handful of isolated outposts to becoming the dominant lifestyle on Earth. For this part of the analysis, I construct a dataset consisting only of locations that are are likely to receive agriculture soon. Specifically, from the full panel, I keep only observations that have hospitable climates [1], 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:

$$A_{it} = \alpha + \beta_1 \mathrm{T}_{it} + \beta_2 \mathrm{P}_{it} + \gamma C_{it} + \epsilon_{it} \tag{20}$$

[1] A location is considered hospitable if it has average temperatures above 0 ° C, and more than 100mm of rain a year.

Each observation represents a specific cell i, during a specific period t. I keep only observations which are on the agricultural frontier: they still haven't adopted agriculture, 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. This model is estimated using the logistic estimator (first tree columns of Table 4, and then with the linear probability model (last three columns). In both cases I find that seasonality is associated with a higher probability of adopting agriculture from neighbors. Clustering residuals at the level of 123 geographic neighborhoods preserve the significance of temperature seasonality and the seasonality index, but precipitation seasonality becomes less significant.

	Dependent variable: adoption dummy					
	(1)	(2)	(3)	(4)	(5)	(6)
	Linear	Linear Geog.Cluster	LinearSI	Logit	Logit+ Geog.Cluster	LogitSI
main						
Temp. Seas.	0.005**	0.005*		0.027**	0.027*	
	(0.002)	(0.003)		(0.011)	(0.015)	
Precip. Seas.	0.035*	0.035		0.174*	0.174	
	(0.019)	(0.029)		(0.092)	(0.144)	
Seas. Index			0.168*			0.861*
			(0.096)			(0.506)
Temp. Mean	-0.007***	-0.007*	-0.007***	-0.032***	-0.032*	-0.034***
	(0.002)	(0.004)	(0.003)	(0.010)	(0.017)	(0.012)
Precip. Mean	0.023***	0.023	0.017	0.113***	0.113	0.086
	(0.008)	(0.015)	(0.012)	(0.038)	(0.071)	(0.058)
Observations	1735	1735	1735	1735	1735	1735

Standard errors in parentheses

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

Table 4: 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. Models 1 is Logit with robust s.e., models 2 and 3 Logit with geographic clustering. Model 4, linear probability with robust s.e., models 5 and 6 linear probability with geographic clustering.

I also estimate a continuous time duration model with Weibul distribution, and plot the resulting survival curves for various climate types (Figure 8). The more seasonal a location was, the sooner the locals would adopt agriculture from farming neighbors. For example, 2,000 years after being exposed to agriculture, a location with zero temperature seasonality still has a 40% change of being occupied by hunter-gatherers. An otherwise equivalent location with a temperature seasonality of 25 C has only a 20% chance. Very similar results are obtained for precipitation seasonality. In the Appendix, I show that these results also hold when using a parametric survival model.

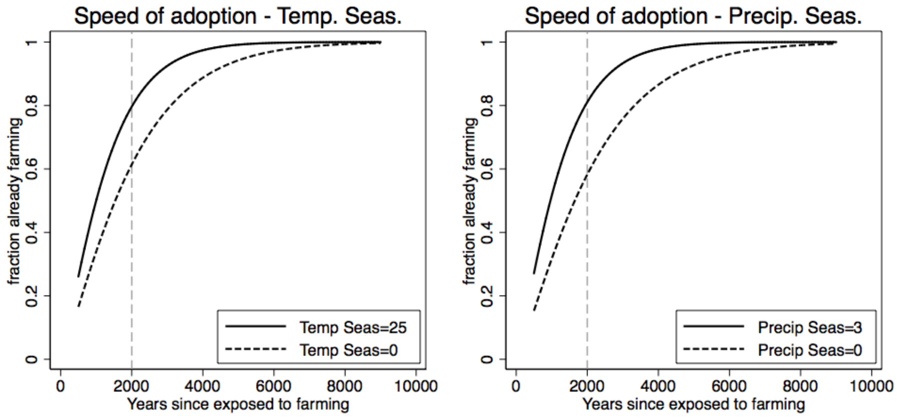

Figure 8: Fraction of locations expected to already farm, after a given number of years of being exposed to farming neighbors. Solid lines: high seasonality locations. Dashed lines: unseasonal locations. Left panel: temperature seasonality. Right panel: precipitation seasonality.

6.1.3 Impact of seasonality on date of adoption

The next step of my analysis is to estimate the cumulative effect of climate seasonality on the timing of the Neolithic. Figure 9 shows binned scatterplots of date of adoption against measures of seasonality. The early adopters were unremarkable in their average climates, but were clearly highly seasonal.

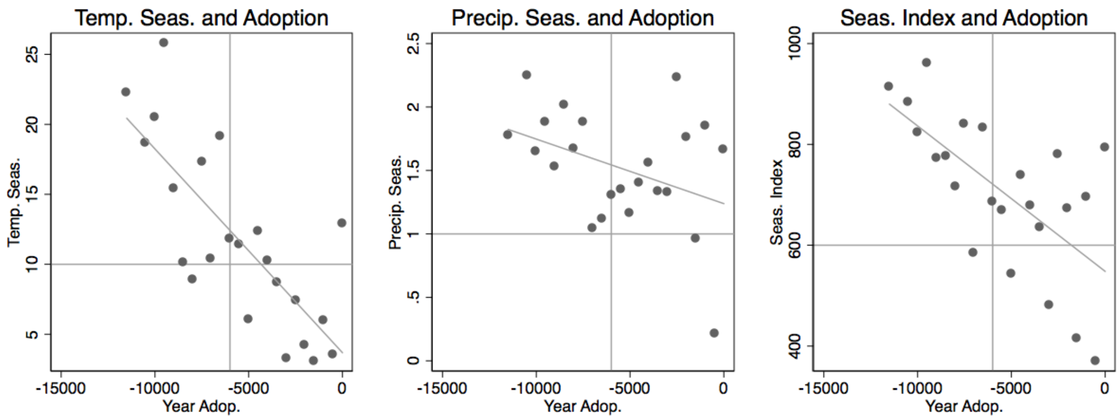

Figure 9: Binned scatterplots of different forms of climate seasonality vs the date of adoption. Locations exposed to more seasonal climates adopted agriculture ahead of more stable climates.

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. The basic specification is:

$$Y_i = \alpha + \beta_1 \mathrm{T}_i + \beta_2 \mathrm{S}_i + \gamma[C]_i + \epsilon_i \tag{21}$$

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).

The results of this analysis are presented in Table 5. Both Temperature and Precipitation Seasonality are associated with earlier adoption of agriculture, across a wide range of specifications. The effect is large and statistically significant for both factors, as well as for the combined Seasonality Index. Column (1) reports the direct effect of temperature and precipitation seasonality on adoption, without controls. The point estimate suggests that one extra standard deviation of Temperature Difference will result in agriculture appearing approximately 1000 years earlier than would otherwise have been the case. One extra standard deviation of rainfall seasonality will instead result in adopting agriculture 300 year earlier. Column (2) inserts basic geographic controls (climatic means and absolute latitude). These help discriminate the seasonality story from the most obvious correlates. When these controls are included, the point estimates of the effect of both types of seasonality increase, to 1500 and 400 years respectively. Column (3) adds controls for the squares of climatic means and latitude, as well a dummy for the New World, and clusters the standard errors The results are very similar to those from column (1). Column (4) removes all the controls except for mean temperature and mean precipitation, and instead uses fixed effects for 123 geographic regions taken from an evenly spaced grid. This approach removes most of the variation in the sample, and results in weaker (but still significant) point estimates. Column (5) and Column(6) substitute temperature and precipitation seasonality with the Seasonality Index, and replicate the first two columns. One extra standard deviation of the index is associated with adopting agriculture between 1000 and 1250 years earlier.

	Dependent variable: year of adoption					
	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Controls	Controls2	GeoFE	SI	SI+Controls
Temp. Seas	-131.1***	-222.5***	-143.8***	-51.6***		
	(10.1)	(13.4)	(38.4)	(17.5)		
Precip. Seas	-152.2	-529.4***	-936.5***	-435.3***		
	(110.4)	(131.1)	(249.2)	(112.3)		
Seas. Index					-3.3***	-5.1***
					(0.3)	(0.4)
Temp. Mean		107.3***	71.5**	9.5		42.7***
		(15.9)	(29.6)	(15.8)		(15.2)
Precip. Mean		-464.3***	90.0	-51.1		-257.2***
		(71.2)	(235.8)	(113.6)		(72.4)
Abs Lat		46.3***	207.6***	3.4		4.7
		(13.6)	(64.9)	(15.3)		(12.6)
Extra Controls	No	No	Yes	Yes	No	No
Geographic FE	No	No	No	Yes	No	No
r2	0.15	0.24	0.40	0.87	0.09	0.12
p	0.00	0.00	0.00	0.00	0.00	0.00

Standard errors in parentheses

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

Table 5: Effect of seasonality on the date of adoption (both invention, and adoption from neighbors). Linear regression of date of adoption on time-averaged climatic variables for each cell. Column 3: clustering for 123 geographic neighborhoods. All other columns: robust standard errors.

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.

6.2 Results from the Western Eurasia dataset

The preceding analysis has established that seasonality can account for a significant fraction of the variation in the date of agricultural adoption observed in the world sample, and that the effect can be observed both in the selection of places that originally invented farming, as well as in the speed with which these new techniques spread throughout the globe.

However, the data employed present certain limitations in geographic resolution that cannot be overcome easily. 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 archeological sites for which the date of earliest agriculture has been 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 10 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 are clearly inappropriate. However, the so-called Fertile Crescent is in fact not *particularly* fertile. Many locations on the Northern shore of the Mediterranean enjoy similar conditions of high average temperatures and adequate rainfall. What seems to set the area apart is the fact that it is simultaneously a pleasant environment, and a seasonal one. Thus, the Western Eurasian story of invention conforms to the general pattern observed globally, which saw the most seasonal locations adopt agriculture sooner.

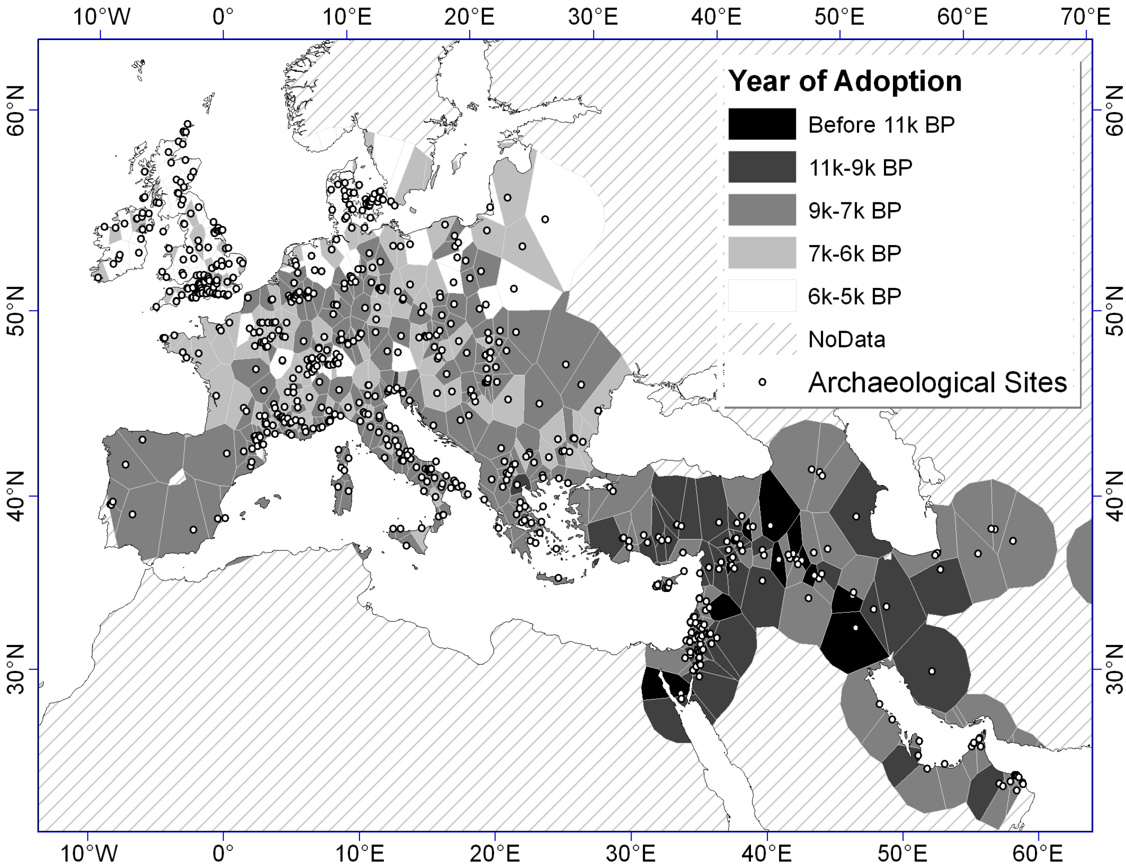

Figure 10: The Pinhasi et al. (2005) dataset provides ^{14}C dates for the onset of agriculture in 765 locations, chronicling the spread of agriculture from the Middle East into Europe.

	mean	sd	min	max
Year Adop.	-7218	1424	-12811	-5140
Temp. Seas.	15.2	3.2	6.9	25.1
Precip. Seas.	.23	.18	.038	.72
Temp. Mean	12.0	4.7	4.4	30.2
Precip. Mean	1.84	.73	.04	4.77
Observations	765			

Table 6: Summary statistics for the Western Eurasian dataset.

This relationship is also apparent from the analysis of the raw data on the diffusion of farming techniques through the archaeological sites in the sample, and their date of adoption. As the scatterplots in Figure 11 show, the locations which adopted early had high seasonality of temperature and precipitation, while locations with stable climates adopted agriculture much later.

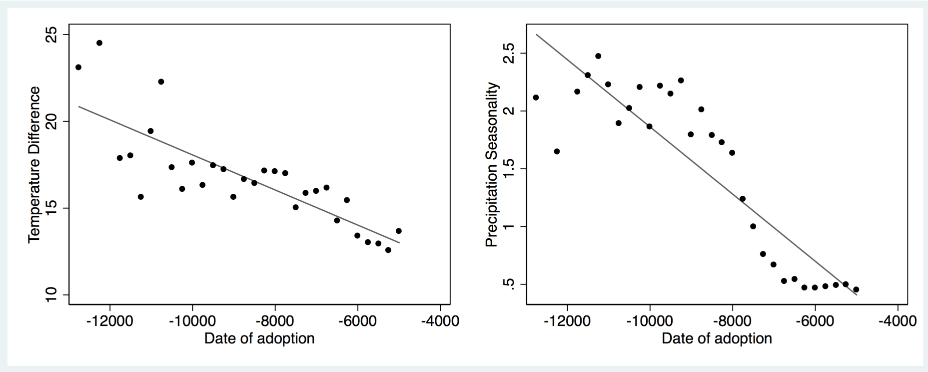

Figure 11: Binned scatterplot of climate seasonality and adoption dates. More seasonal locations adopted earlier, while less seasonal climates adopted later.

The basic specification is the same that for the basic linear model of Subsection 6.1.3:

$$Y_i = \alpha + \beta_1 T_i + \beta_2 P_i + \gamma C_i + \epsilon_i \tag{22}$$

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. The results are presented in Table 7, which once again shows how 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.

Column (1) shows the direct effect of temperature and rainfall seasonality on the date of adoption. One extra standard deviation of temperature seasonality results up adoption by about 400 years, while an equivalent change in rainfall seasonality is associated with adopting agriculture approximately 900 years later. These two variables alone account for over 60% of the variance in date of adoption observed in the sample. In Column (2) I add controls for climatic averages which slightly increases my point estimate for temperature seasonality, while reducing the one for precipitation seasonality. Column (3) adds controls for latitude, altitude, and distance from the Fertile Crescent (where agriculture started, for this dataset). In Column (4) I add a control for distance from the coast, and Column (5) concludes by adding quadratic terms for the climatic means. As more controls are added, the magnitude of the estimated coefficients falls, but all retain statistical and economic significance, as well as the correct sign.

	(1) Basic	(2) +Means	(3) +Geo	(4) +Geo2	(5) +Mean2
Temp. Seas.	-136.8***	-148.6***	-72.80***	-75.06***	-46.22**
	(12.25)	(13.11)	(20.15)	(22.59)	(23.48)
Precip. Seas.	-5102.7***	-3711.5***	-2042.6***	-2060.2***	-2028.4***
	(226.4)	(350.7)	(346.8)	(355.3)	(387.3)
Temp. Mean		-74.19***	19.76	21.00	-195.8***
		(14.73)	(20.02)	(22.32)	(43.26)
Precip. Mean		-90.87	-124.1**	-123.4**	239.3
		(68.41)	(61.74)	(62.47)	(245.5)
Dist Coast				5.703	-32.77
				(26.62)	(28.02)
Temp Mean 2					7.068***
					(1.375)
Precip Mean 2					-71.14
					(48.93)
GeoControls	No	No	Yes	Yes	Yes
Observations	765	765	765	765	765
R^2	0.610	0.627	0.692	0.692	0.706

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

Table 7: Climate seasonality and adoption in the Western Eurasia dataset, linear model, robust standard errors.

6.3 Geographic heterogeneity

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 the farming was invented in locations where the incentive to store food was high.

However, the association between seasonality and agriculture could also be due to the availability of easily domesticable plants, in the spirit of Diamond (1997). Plants have adapted to highly seasonal environments react by conducting their own forms of storage, either by storing energy in their roots, or by producing large amounts of seeds during the short growth season. Both of these adaptations create plants that are easier to cultivate, and which are in some sense pre-adapted to domestication. It is therefore possible that agriculture was first developed in highly seasonal locations not because of the incentives to store available food, but because these conditions were the only ones in which suitable plants thrived. Once these plants had been domesticated, it is only natural that the spread should have been faster in locations with similar climates, thus providing a potentially plausible explanation for the observed pattern of invention, and spread.

While these factors could have further assisted the development of agriculture, I can show that the nomadism-storage tradeoff retains independent explanatory power. To this end 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. All of these locations are extremely seasonal, so that both temperature and precipitation seasonality lose their explanatory power. The model shows that settled agriculture should be adopted earlier where mobility is less useful — i.e. where all locations in practical migratory range lack food at the same time.

To test this prediction empirically, I first limit the analysis to the subset of locations from the Pinhasi et al. (2005) dataset which are within a specified radius of known concentration of wild cereals. I then construct a series of proxies, each measuring the range in altitudes present within a specified distance from the location under observation. 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 makes nomadism pointless.

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, but will be 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 migratory ability of even the most mobile nomads, and therefore irrelevant. Table 8 presents the summary statistics for the sites in the Pinhasi dataset that are within 100km of known concentrations of wild cereals. Note that all of these places are quite seasonal.

	(1)			
	mean	sd	min	max
Years Ago	-9520	1336	-12811	-7276
r(5)	366.7	297.8	16	1330
r(50)	1485.3	666.4	99	3108
Temp. Seas.	18.1	4.12	11.4	24.7
Precip. Seas.	.54	.10	.21	.67
Temp. Mean	17.9	3.3	8.1	24.1
Precip. Mean	1.03	.60	.10	3.26
Latitude	34.2	3.01	29.5	41.4
Longitude	37.9	4.25	26.11	49.63
Altitude	487.2	523.5	-405	2376
Dist Coast	1.80	1.58	0	5.86
Observations	101			

Table 8: Summary statistics for the subsample of the Western Eurasian dataset which had access to wild cereals.

In Figure 12, I show the locations in the Pinhasi dataset that are close to known concentrations of wild cereals. 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 13. 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.

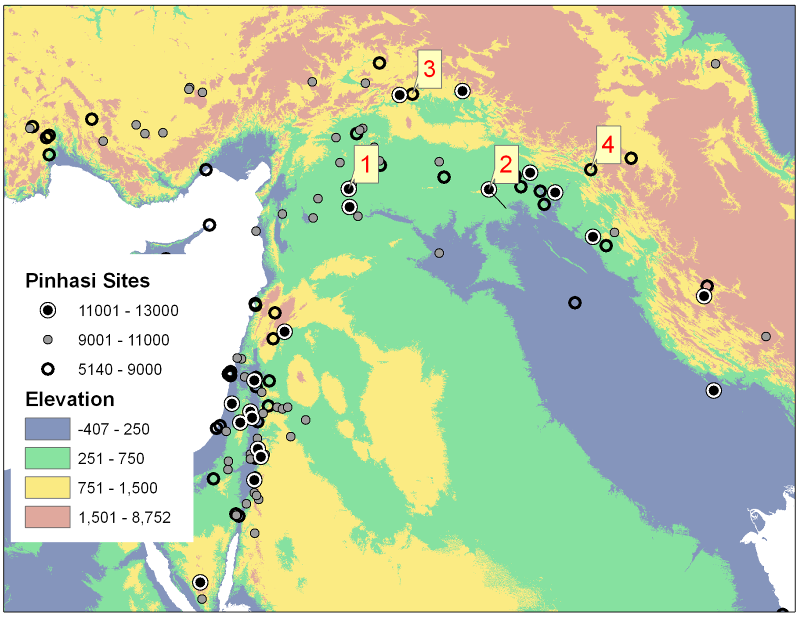

Figure 12: The map shows the Neolithic sites in the Middle East from the Pinhasi dataset, that are within 100km of known concentrations of wild cereals. The sample is divided in locations that adopted before 11,000 years ago, between 11,000 and 9,000 years ago, and after 9,000 years ago. The four example sites discussed in Figures 13 and 14 are highlighted.

In Figure 14 I show elevation profiles taken along these lines, which allow 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 loose 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. As Figure 15 shows, the early adopter 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.

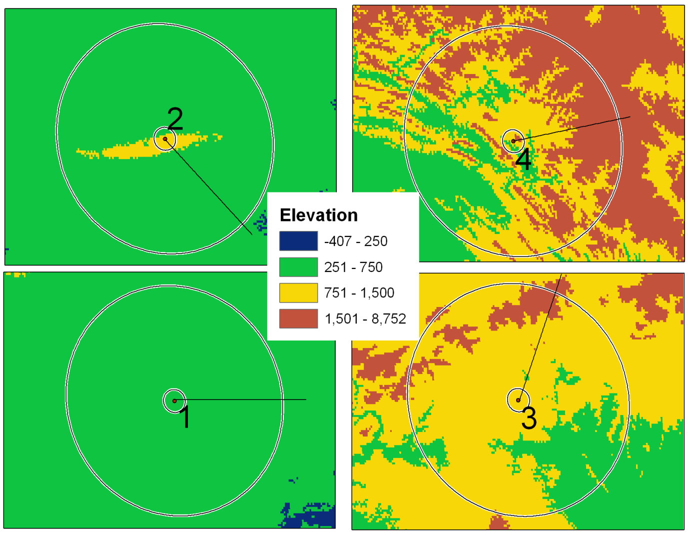

Figure 13: The four graphs show the local topography for the four examples sites, shown in Figure 12. The small circles have a 5km radius, and are indicative of the area that could be accessed by a settled community occupying the site. The large circles are 50km in radius, and shows the area that would have been available to a nomadic band.

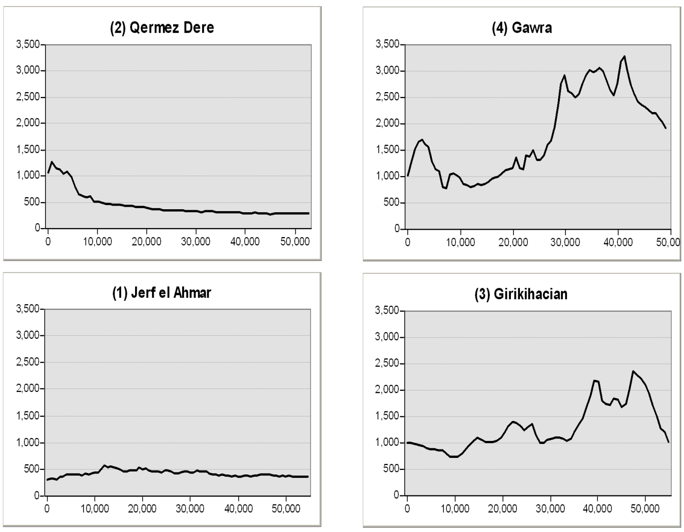

Figure 14: The four graphs show altitude profiles for the four lines shown in Figure 13. (1) has virtually no altitude variation in the local area. (2) Has a lot of variation close by, but nothing in the wider area. (3) has little variation close by, but a lot in the wider area. (4) has a lot of variation close by, but even more variation within the local area. Locations (1) and (2) adopted early, while locations (3) and (4) adopted later on.

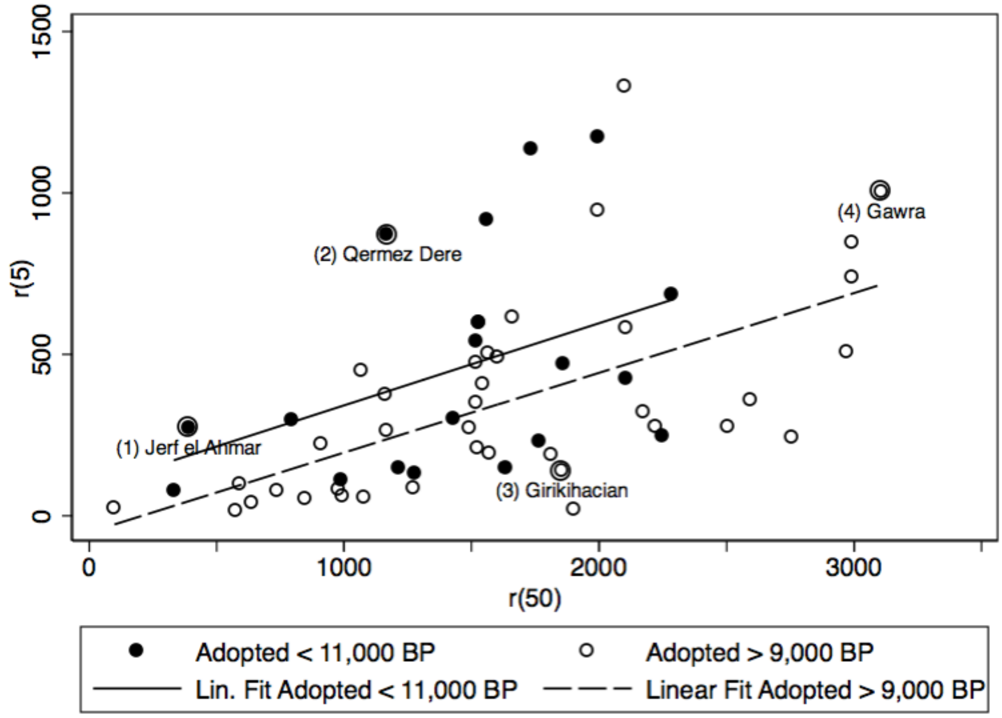

Figure 15: The graph shows how, irrespective of the altitude range available to settlers ($r(5)$), locations with a lot of altitude range available to nomads ($r(50)$) adopted agriculture later than those with a low $r(50)$. The examples presented in Figure 13 are highlighted and labeled, and follow the general pattern.

I now investigate these relationships systematically using linear regression. The basic specification is:

$$Y_i = \alpha + \beta_1 r(5) + \beta_2 r(50) + \gamma C_i + \epsilon_i \tag{23}$$

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 9.

Column (1) shows the direct effect of $r(5)$ and $r(50)$ on adoption. The sample is limited to sites which are within 250km of known dense cereals. 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 restrict the analysis to sites within 100km of known wild cereal distributions. Concentrating on the core areas increases the magnitude and significance of the coefficients. Column (3) keeps the 100km restriction and adds 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(4) I add a control for $r(200)$. I find that if variations in altitude happened outside of comfortable nomadic radii they are no longer predictive of date of adoption. Finally I substitute 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.

	Dependant variable: date of adoption				
	(1)	(2)	(3)	(4)	(5)
	<200km	<100km	Clim. Means	r(200)	Smooth Meas.
r(5)	-0.772*	-0.990**	-0.986*	-0.970*	
	(0.414)	(0.496)	(0.580)	(0.579)	
r(50)	0.414**	0.517**	0.587**	0.540*	
	(0.179)	(0.221)	(0.267)	(0.306)	
r(3:8)					-0.858
					(0.597)
r(50:100)					0.500*
					(0.254)
r(200)				0.111	
				(0.266)	
Temp. Seas.			-161.6	-158.0	-144.5
			(114.1)	(116.4)	(116.1)
Precip. Seas.			737.9	471.2	-442.4
			(4268.1)	(4417.6)	(4040.5)
Controls	No	No	Yes	Yes	Yes
Observations	129	101	101	101	101
R^2	0.037	0.051	0.110	0.111	0.101

Standard errors in parentheses

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

Table 9: Effect of local topography on the timing of agricultural adoption. 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.

7 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 a 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 reserves, which generally allow 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 exists, 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 16 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).

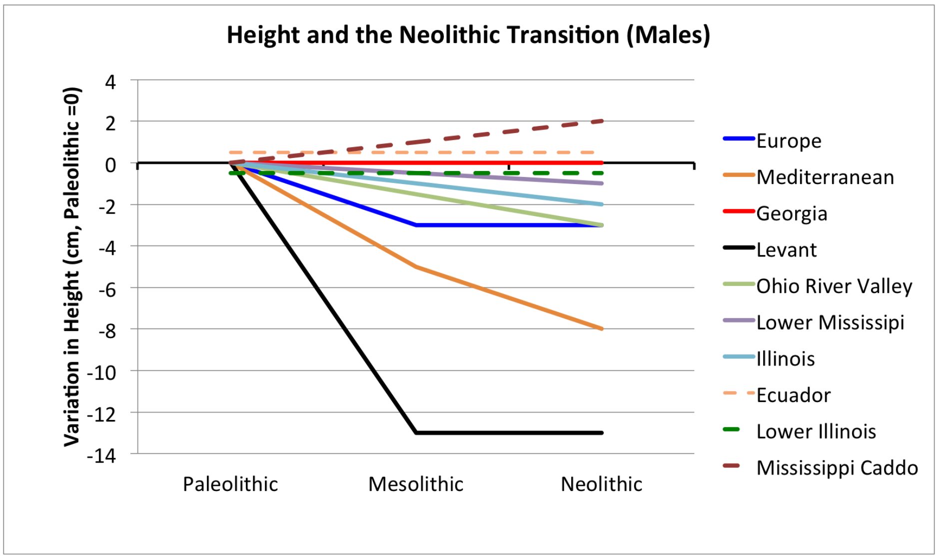

Figure 16: Achieved adult height across the Neolithic sequences reported in Cohen and Armelagos (1984). Each line represents the progression in observed heights in one location, expressed as a difference from its value during the Paleolithic (nomadic hunting and gathering). The sedentary farmers (Neolithic) were clearly shorter than their nomadic ancestors. In the cases for which independent data was independently recorded for the Mesolithic (settled hunter-gatherer) phase, the decrease in standard of living can be seen to have predated the Neolithic.

It should be noted that 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 17).

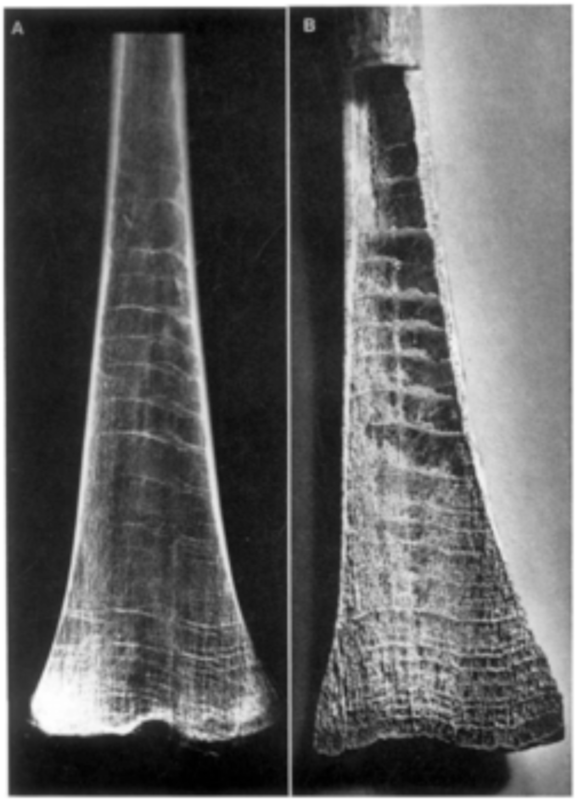

Figure 17: Example of Harris lines in an Inuit adult. The regular spacing of the Harris lines show that each winter, food intake would drop low enough to arrest bone growth. Each spring, the arrival of migratory species would rapidly increase food intake, a catch-up growth spurt would occur, and a line 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 it appears that hunter gatherers ate well on average, but were forced to starve during part of the year.

8 Conclusion

What caused the Neolithic Revolution? I examine the invention and early spread of agriculture, and find that increased climatic seasonality was the most likely trigger. Using data on both invention and adoption, I find that higher seasonality made the invention of agriculture more likely, and the spread of farming faster. The channel I propose — increased incentives for storage — explains why the farmers accepted a decrease in the standard of living. This interpretation is also supported by the data on the local topography of early sites, and the absence of growth arrest lines in their bones.

This paper also helps explain the technological advantage historically enjoyed by the Northern Hemisphere. Today, New Zealand, Australia, South Africa and Argentina have very similar climates to some of the areas where agriculture originated. Why didn't they invent agriculture? The shock to seasonality which triggered the invention of farming only happened in the Northern Hemisphere Berger (1992). As a result, these areas never experienced the extreme seasonality which was common where agriculture was invented.

The intuition of the model is relevant to a wide range of settings. Many human societies are subject to seasonal resource availability. If such conditions coexist with inefficient storage technologies, the local inhabitants would experience the same fertility-reducing fasting suffered by hunter-gatherers. The model predicts that such a society would have a lower population density, but higher consumption per capita.

Appendix: econometric robustness

Though seven locations show strong evidence of having independently invented agriculture, at least seventeen more are believed to have been important domestication centers (Purugganan and Fuller, 2009). Almost certainly, some of these centers also invented agriculture independently, but archaeologists disagree over which ones. The small number of sites which are universally accepted as independent originators of agriculture, leads to a highly skewed distribution of the dependent variable in the panel of agricultural invention: 38,853 zeros to only seven ones. I address this limitation in two ways: first I repeat the analysis of Table 3, using the Rare Events Logit model proposed by King and Zeng (2001). This is shown in the first four columns of Table 10. Then, I repeat the analysis of Columns (2) and (3), but using the sample of 24 domestication centers, rather than only the seven confirmed adoptions. The inclusion of locations of uncertain invention weakens the power of the analysis considerably, but the signs are preserved and the coefficient on temperature seasonality is significant.

	Dependent variable: adoption dummy					
	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Controls	Controls2	SI	Neol24	Neol24 SI
Temp. Seas.	0.118***	0.174***	0.199***		0.0898*	
	(0.0443)	(0.0515)	(0.0630)		(0.0462)	
Precip. Seas.	0.263	0.641	0.454		0.0852	
	(0.532)	(0.633)	(0.679)		(0.479)	
Seas. Index				7.219*		2.415
				(4.021)		(1.841)
Temp. Mean		0.0338	-0.133	0.0336	0.0515	0.0542
		(0.0500)	(0.125)	(0.0382)	(0.0446)	(0.0388)
Precip. Mean		0.822***	1.162*	0.784***	0.479**	0.498**
		(0.216)	(0.625)	(0.301)	(0.237)	(0.214)
Abs Lat		0.0487	0.0685	0.0699	0.00912	0.0255
		(0.0344)	(0.0878)	(0.0504)	(0.0409)	(0.0366)
Extra Controls	No	No	Yes	No	No	No
N	38533.00	38533.00	38533.00	38533.00	38533.00	38533.00

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

Table 10: The effect of climate on invention. Dependent variable is a dummy which is 1 if agriculture was invented in a particular cell and period, and 0 otherwise. Each location is dropped from sample after they adopt agriculture. All columns: Rare Events Logistic regression on climate variables and controls. Columns 5 and 6: using the 24 possible Neolithic sites instead of the 7 certain ones.

Next, I will explore the robustness of my analysis of the spread of agriculture to changes in the econometric specification. To this end, I collapse the Neolithic Frontier dataset to a cross-section, in which each observation is one location that adopted agriculture from a neighbor. The dependent variable is the number of years that elapsed from when they were first exposed to farming, and when they started to farm themselves. For each cell I assign the average of the values of each explanatory variable during the period the location spent in the frontier. The effect is estimated using a parametric survival model with Weibul distributions, and the results are presented in Figure 11.

Temperature and precipitation seasonality both hasten the adoption of agriculture. Increasing temperature seasonality by one standard deviation results in agriculture being adopted 250 years earlier, while doing the same for precipitation seasonality is associated with adopting 200 years earlier. This is equivalent to saying that one extra standard deviation of climatic seasonality made agriculture advance approximately 0.5 km/year faster.

	Dependent variable: no. of periods until adoption				
	(1)	(2)	(3)	(4)	(5)
	Seasonality	Controls	Controls2	Index	Index+Controls2
Temp. Seas.	-33.600***	-36.305***	-17.660		
	(8.335)	(11.015)	(16.856)		
Precip Seas	-22.771	-271.235***	-307.552**		
	(80.707)	(104.015)	(130.880)		
Seas. Index				-1.416***	-1.008*
				(0.478)	(0.581)
Temp. Mean		38.271***	4.223	39.189***	10.740
		(11.272)	(44.643)	(9.358)	(44.619)
Precip. Mean		-151.651***	-159.218	-124.245**	-119.856
		(56.568)	(137.292)	(53.962)	(113.156)
Abs Lat			-56.459*		-65.099**
			(32.189)		(29.837)
GeoControls	No	No	Yes	No	Yes
Climate^2	No	No	Yes	No	Yes
Observations	530	530	530	530	530

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

Table 11: The effect of climate on the spread of agriculture. Dependent variable counts how long each location waited before adopting agriculture, after first being exposed to it. Each location is dropped from sample after they adopt agriculture. All columns: robust standard errors. The more seasonal the climate, the less the locals waited before becoming farmers.

Finally, I check whether the regressions of year of adoption on seasonality are robust to taking into account spatial correlation. Table 12 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: year of adoption					
	(1)	(2)	(3)	(4)	(5)	(6)
	Basic	Controls	Basic Spat.Lag	Controls Spat. Lag	Basic Conley	Controls Conley
main						
Temp. Seas	-222.5***	-143.8***	-42.4***	-45.5***	-222.5***	-143.8***
	(13.4)	(38.4)	(11.1)	(14.1)	(24.7)	(29.0)
Precip. Seas	-529.4***	-936.5***	-347.1***	-469.2***	-529.4**	-936.5***
	(131.1)	(249.2)	(94.2)	(104.6)	(245.5)	(243.4)
Temp. Mean	107.3***	71.5**	-21.7**	-22.7**	107.3***	71.5***
	(15.9)	(29.6)	(10.6)	(10.5)	(33.0)	(26.3)
Precip. Mean	-464.3***	90.0	-414.1***	-103.6	-464.3***	90.0
	(71.2)	(235.8)	(50.5)	(112.2)	(122.3)	(231.9)
Abs Lat	46.3***	207.6***	-40.3***	29.8	46.3*	207.6***
	(13.6)	(64.9)	(9.3)	(19.2)	(27.8)	(44.4)
Extra Controls	No	Yes	No	Yes	No	Yes
r2	0.24	0.40			0.82	0.86
p	0.00	0.00	0.00	0.00	0.82	0.86

Standard errors in parentheses

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

Table 12: 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.

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