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

JOB MARKET PAPER

Andrea Matranga *
Universitat Pompeu Fabra

October 28, 2014

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.

1 Introduction

Why was agriculture invented? The long run advantages are evident: farmers produced food surpluses that allowed population densities to rise, labor to specialize, and cities to

*email: andrea.matranga@upf.edu. I am grateful to my advisor Joachim Voth, for his continuous guidance and support. I also thank for useful comments Ran Abramitzky, Francesco Amoedo, Leonardo Bursztyn, Paula Bustos, Davide Cantoni, Bruno Caprettini, John Cherry, Paul David, Christian Dippel, Oded Galor, Nicola Gennaioli, Fabrizio Germano, Albrecht Glitz, Libertad Gonzalez, Avner Greif, Jonathan Hersh, Peter Koudijs, Thomas Leppard, Lorenzo Magnolfi, Alberto Martin, Stelios Michalopoulos, Mrdjan Mladjan, Omer Moav, Michele Monti, Luigi Pascali, Gonçalo Pina, Andrei Potlogea, Marta Reynal, Paul Seabright, Yannay Spitzer, Jaume Ventura, Nico Voigtlander, Noam Yuchtman, Romain Wacziarg, and David Weil. This project benefited greatly from audience comments received at the World Economic History Congress in Utrecht, the EHS Annual Conference in Oxford, The TSE Brow Bag seminar, the Yellow Pad Seminar at Santa Clara University, the SSH seminar at Stanford, the Macro Lunch at Brown, the History Tea at Harvard, the Cliometric Conference in Tucson, the World Cliometric Conference in Honolulu, the BGSE Jamboree, and the International Lunch and Applied Seminar at Pompeu.
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 independently invented at least seven times within a 7,000 year period (the Neolithic Revolution). Moreover, the first farmers were shorter and had more joint diseases, suggesting that they ate less than hunter gatherers, and worked more (Cohen and Armelagos, 1984). Why would seven different human populations decide to adopt remarkably similar technologies, around the same time, and in spite of 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 and exogenous 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 of hunter-gatherers faced with 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 past 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 1,000 years earlier. 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. Qualitatively similar results are obtained in a higher resolution regional dataset, covering the invention and spread of cereal agriculture in Western Eurasia.

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 resource shocks. Other sites were surrounded by areas of similar alti-
Figure 1: Right panel: Seasonal locations became more common shortly before agriculture was invented. Left panel: binned scatterplot of temperature seasonality and adoption; early adopters tend to be highly seasonal, and vice versa.

tude 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 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). 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 technological transformations 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. Climate has often been proposed as a trigger for agricultural invention. 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 suggest that greater food consumption is unlikely to be the motive. Other contributions have focused on explaining the loss in consumption per capita. This loss
has been variously attributed to unforeseen population growth \cite{Diamond1987}, the
need for defense \cite{Rowthorn2010}, or expropriation by elites \cite{Acemoglu2012}. While these may all have been contributing factors, they do not
explain why agriculture was invented in particular places at a particular time.

The key contribution of this paper lies in proposing a unified theory for the ori-
gins 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.

2 Literature review

A large multidisciplinary literature has tried to explain why humans started to farm.
Early contributions \cite{Darwin1868} 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 simul-
taneous invention on different continents \cite{Richerson2001}, and indeed agriculture
was invented after the end of the last Ice Age. This suggested that warmer climates
may have made farming more productive \cite{Diamond1997, Bowles2013}, or else drier conditions made hunting and gathering worse \cite{Braidwood1960}. For Dow
et al. \cite{Dow2009}, 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 con-
tions, 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.

\cite{Ashraf2013} 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 \cite{Olsson2001, Smith1975}. \cite{Locay1989} 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 seen as a 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 correlation 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, 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].
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 fill 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? Global climate patterns had become steadily more seasonal between 22,000 and 12,000 BP, under the influence of long-run changes in the shape of Earth’s orbit (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.

Figure 3: Three orbital parameter (black) combine to determine insolation seasonality in the northern hemisphere (red). During the Early Neolithic, these three cycles peaked simultaneously for the first time in over 100,000 years (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).

In contrast, it is unlikely that the invention of agriculture was caused by changes in average climate. 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. These narrow confines would have provided the right incentives for agricultural adoption. Jr. 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, 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. I base the model around three main assumptions. First, I assume that the underlying resource base varies across space and time. Second, I force the band to choose between nomadism, or storage. Third, I modify the standard Malthusian populations dynamics, by assuming higher consumption seasonality depresses fertility. 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.

4.1 Setup

The unit agent of the model is a band, which has exclusive control over a specific territory. I assume that there are two months in the year, July ($J$) and December ($D$); and two locations in the band’s territory, Home ($H$) and Refuge ($R$). The band has an initial population size of $P$. It can move costlessly from one location to the other, but must reside on only one during each month. The territory supplies a food endowment of $E_{ij}$, where $i$ is the location currently occupied by the band, and $j$ is the month. Initially, I assume that agriculture is impossible.

To avoid symmetric cases and simplify notation, I make the following assumptions:

\[
E_{HJ} = 1 \\
E_{HD} = h = 1 - \sigma \\
E_{RJ} = 0 \\
E_{RD} = r = 1 - \sigma + \gamma \\
0 < \gamma \leq \sigma < 1
\]

That is, I normalize to one the endowment provided by Home in July and define a seasonality parameter $\sigma$, which represents how much worse Home is in December. I also assume that in December, the Refuge provides $\gamma$ more food than Home does, but in July it doesn’t have any food. The parameter $h$ is the December endowment of Home, while $r$ is the December endowment of the Refuge. Figure 5 clarifies the relationship between these quantities.
The seasonality parameter $\sigma$ determines how much worse the Home’s December endowment ($h$) is relative to Home’s July endowment, which is always 1. The geographic heterogeneity parameter $\gamma$ determines how much better the Refuge ($r$) is in December. In the lower left corner, $\gamma = \sigma = 0$. Home has as much food in December as in July, and the Refuge also has the same amount. In the upper left corner, seasonality is now 1, while $\gamma$ is still 0. This implies that both Home and Refuge have no food in December. Finally in the upper right corner, $\gamma = \sigma = 1$. In December, Home has no food but Refuge has an endowment of 1. This is the condition in which nomadism is most useful.

The band acts as an expected utility maximizer, with a utility function defined over the levels of consumption per capita in both months. Specifically, the utility function is a Cobb-Douglas with equal weighting.

$$U(c) = \ln(c_J) + \ln(c_D)$$

(6)

Where $c = \{c_J, c_D\}$ is a consumption per capita profile composed of consumption per capita of $c_J$ in July and $c_D$ in winter. I will denote the aggregate consumption in each season with the capital letters $C_J$ and $C_D$.

The band knows exactly how much food will be available in each locations and month, and decides whether to be nomadic or sedentary. If it chooses nomadism, then it can always forage in whichever location is temporarily most abundant. However, it will not be able to store food from one month to the other. If instead it chooses to settle, it will have access only to the resources of the chosen ecosystem, but will be able to costlessly store food.

The population dynamic of the band is determined by its consumption profile. Specifically, net individual fertility $\phi$ is a weighted average of consumption per capita in both months, with the weighting favoring consumption per capita in the scarcest period:
\[ \phi = \alpha \max(c_J, c_D) + (1 - \alpha) \min(c_S, c_D) \quad (7) \]
\[ 0 < \alpha < 0.5 \quad (8) \]

If \( \alpha \) 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 been a Leontief function), while if \( \alpha \) 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].

4.2 Optimal nomadism and optimal storage

First I will characterize the equilibrium outcomes for a band that has exogenously decided for either Nomadism or Settlement. To this end I first establish a fundamental demographic result of the model:

**Proposition 1.** Greater consumption seasonality will result in higher consumption per capita once population equilibrium is achieved.

**Proof.** From equations 7 and 8 and the definition of a population equilibrium, we know that
\[ 1 = \alpha \frac{\max(C_J, C_D)}{P} + (1 - \alpha) \frac{\min(C_S, C_D)}{P} \]
where \( P \) is population size. By solving for \( P \), it is evident that when seasonality is absent \((C_J = C_D)\), population size will be equal to average aggregate consumption, and consumption per capita must necessarily be 1. If consumption is redistributed from December to July (an increase in consumption seasonality), the equilibrium population size will decrease. Since the average amount of resources did not change, we know that consumption per capita increased.

To maximize their utility, nomads will spend July at Home, and retreat to the Refuge in December. Their aggregate consumption will be

\[ C_N = (\max(E_{HJ}, E_{RJ}), \max(E_{HD}, E_{RD})) \quad (9) \]
\[ = (E_{HJ}, E_{RD}) \quad (10) \]
\[ C_N = (1, r) \quad (11) \]

Thus, to find the equilibrium level of population for nomads, \( P^*_N \), we must plug the
nomadic aggregate consumption figure into the fertility function:

\[ 1 = \frac{\alpha \times 1 + (1 - \alpha)r}{P} \]  

(12)

\[ P^*_N = \alpha + r - \alpha r \]  

(13)

**Proposition 2.** When nomads are able to smooth consumption perfectly \((r = 1 \Leftrightarrow \sigma = \gamma)\), equilibrium population and average consumption will both be 1. Higher levels of consumption seasonality will result in lower populations size and higher average consumption per capita.

**Proof.** Trivial from proposition [1] and equation [11].

Specifically, the consumption profile of Nomads is:

\[ c^*_JN = \frac{1}{\alpha + r - \alpha r} \]  

(14)

\[ c^*_DN = \frac{r}{\alpha + r - \alpha r} \]  

(15)

**Proposition 3.** When \(\sigma = \gamma\), nomads will consume one unit of food in each season, and their utility be zero when in equilibrium. Holding \(\gamma\) constant, more seasonality will initially increase their equilibrium utility. For higher levels of seasonality, utility will decrease and eventually fall below zero.

**Proof.** From proposition [2] we know that increasing seasonality will always result in a lower population, and higher consumption per capita. Since utility is Cobb-Douglas, when seasonality is low the band is nearly indifferent between consumption in December and July, and effectively only cares about consumption. Thus, utility is increasing in seasonality. However, we also know that as seasonality increases, the marginal rate of substitution between consumption in the two months goes to infinity. Therefore eventually increasing seasonality must decrease and fall below zero.

Specifically, the equilibrium utility level for nomads will be:

\[ U^*_N = \ln \left( \frac{1}{\alpha + r - \alpha r} \right) + \ln \left( \frac{r}{\alpha + r - \alpha r} \right) \]  

(16)

Note that the endowment seasonality experience by nomads has an ambiguous effect on utility. A lower \(r\) (higher \(\sigma\) and lower \(\gamma\)) reduces the amount of food available in December (numerator of second term), therefore decreasing utility. However, it also reduces population size (the denominators of both terms), boosting consumption per capita in both months, and therefore raising utility. When \(r\) is high (low seasonality), the first effect dominates and increasing seasonality raises utility, while the reverse is true for low values of \(r\). The higher the seasonality a nomadic band is exposed to, the higher its consumption per capita will be.
I will know derive the outcomes for a nomadic band that decides to settle. The optimal settlers will instead spend both months at Home (which has the highest average endowment), and will save exactly enough in Summer to ensure that consumption is constant throughout the year.

\[
C_S = \left( \frac{E_{JH} + E_{DH}}{2}, \frac{E_{JH} + E_{DH}}{2} \right)
\]

(17)

\[
= \left( \frac{1 + h}{2}, \frac{1 + h}{2} \right)
\]

(18)

**Proposition 4.** In equilibrium, settlers will always have a consumption per capita of one.

**Proof.** Settlers will always smooth their consumption perfectly, which implies that population will stabilize when it is equal to the average level of resources. \(\square\)

The equilibrium outcomes for a settled population are:

\[
P^*_S = 1 - \frac{\sigma}{2}
\]

(19)

\[
c^{*}_{JS} = 1
\]

(20)

\[
c^{*}_{DS} = 1
\]

(21)

\[U^*_S = 0
\]

(22)

Note that a settled band in equilibrium always has consumption per capita, and utility equal to one, regardless of the level of environmental seasonality. However, if a band transitions from nomadism to settlement, its population will initially remain fixed at whatever level the nomads had. As a result, consumption per capita immediately after the transition will in general be different from zero, and specifically will equal:

\[
C^{*}_{JS} = C^{*}_{DS} = \frac{1 + h}{2(\alpha - \alpha r + r)}
\]

(23)

### 4.3 The choice to settle

For agriculture to be developed in a given region, a significant number of its inhabitants must have decided to become settled, and to sustain this residency pattern for multiple generations. In practice, this means that the invention of agriculture is extremely unlikely unless settlement provides a higher utility than nomadism both in the short run and in the long run (i.e. after population size adjusts).

Let’s examine the case of a nomadic band which is at its long run population equilibrium, and is considering whether to switch to settlement. Settlement will be optimal in the short run if:
Figure 5: By being mobile, a nomadic band can spend July at Home ($H^*$), and December in the Refuge ($R^*$), thus achieving the consumption profile $N^*$. Since $N^*$ is on the population replacement line, equilibrium is achieved. If the band decided to settle, it would have to rely entirely on the resources of $H$, but it would be able to store food costlessly, and could thus reach consumption profile $S^-$. Since the consumption profile is too low to ensure replacement, population size will decrease until the long run equilibrium $S^*$ is reached. Whether this is optimal or not depends on the relative values of $r$ and $h$.

\[ U_{S^-} > U_{N^*} \]  \hspace{1cm} (24)  

\[ 2 \ln \left( \frac{1 + h}{2(\alpha - \alpha r + r)} \right) = \ln \left( \frac{1}{\alpha + r - \alpha r} \right) + \ln \left( \frac{r}{\alpha + r - \alpha r} \right) \]  \hspace{1cm} (25)  

Where $U_{N^*}$ is the equilibrium utility of nomads, while $U_{S^-}$ is the utility of settlers before population adjusts. This condition will be true whenever seasonality $\sigma$ is sufficiently high. In terms of $\sigma$ and $\gamma$, this threshold can be written as:

**Proposition 5.** Settlement will be optimal in the short run if seasonality $\sigma$ is high and geographic heterogeneity $\gamma$ is low. The transition will increase short run utility if

\[ \sigma > 2\sqrt{\gamma} \]  \hspace{1cm} (26)  

*Proof.* Starting from equation (25), solve for $h$, thus finding the threshold level of Home-territory Winter food availability above which the band will have a short term incentive to become sedentary:

\[ h = -1 + 2\sqrt{r} \]  \hspace{1cm} (27)  

By substituting $h$ and $r$ with their definitions in term of $\sigma$ and $\gamma$, and rearranging, I obtain equation (26). 

14
As time goes by, the population size of the band will reflect its new consumption profile, and consumption per capita will settle at unity. Will the band still be better off than it was during nomadism?

**Proposition 6.** Settlement will be optimal in the short run if seasonality \( \sigma \) is high and geographic heterogeneity \( \gamma \) is low. The band will be better off in the long run if:

\[
\sigma > \gamma + \frac{1 - 2\alpha}{(\alpha - 1)^2}
\]

(28)

**Proof.** The condition for long run optimality can be written as

\[
U^*_S > U^*_N
\]

(29)

\[
0 > \ln \left( \frac{1}{\alpha + r - \alpha r} \right) + \ln \left( \frac{r}{\alpha + r - \alpha r} \right)
\]

(30)

solving for the threshold level of seasonality yields:

\[
r^* = \frac{\alpha^2}{(\alpha - 1)^2}
\]

(31)

Substituting \( r = 1 - \sigma \) and rearranging produces the result.

The short run and long run thresholds (equations 26 and 28) partition the \((\sigma; \gamma)\) parameter space into four regions, according to whether settlement is optimal in the short run only, long run only, neither, or both. Figure 6 shows how the two constraints partition the parameter space.

Once large numbers of settlers have appeared, cultivation techniques and incipient domestication will increase the amount of food available during July to Settlers. To the extent that these advances are also available to neighboring populations, they will change their incentives by making settlement more attractive in the short run. Defining \( f \) as the boost in July endowment in the Home location, the threshold condition to adopt agriculture in the short run will be given by

\[
U^*_{S_0} = U^*_N
\]

(32)

\[
2 \ln \left( \frac{1 + h + f}{2(\alpha - \alpha r + r)} \right) = \ln \left( \frac{1}{\alpha + r - \alpha r} \right) + \ln \left( \frac{r}{\alpha + r - \alpha r} \right)
\]

(33)

\[
r = \frac{(1 + f + h)^2}{4}
\]

(34)

Substituting \( r = 1 - \sigma \), and solving for the threshold level of farming technology:

\[
f^* = \sigma + 2 \sqrt{1 - \sigma + \gamma - 2}
\]

(35)

Substituting \( r = 1 - \sigma \)

\[
\sigma = f + 2 \sqrt{\gamma - f}
\]

(36)
Figure 6: Sedentarism is optimal in the short run (long run) when seasonality is higher than indicated by the SR (LR) line. Settlement is optimal both in the short run and long run in region marked “Settlement”; in “Barriers”, settlement is optimal in the long run, but not in the short run; in “False Start”, the opposite is true; and in “Nomadism” settlement is not optimal in either timescale. During the Ice Age, no population was seasonal enough to want to settle (points A, B, and C). When seasonality increased, some areas gained the right incentives to store food (point A’), while others did not (points B’ and C’).

Intuitively, the threshold level of farming technology necessary for settlement to become optimal is lower when seasonality $\sigma$ is large relative to the nomadic advantage $\gamma$. Thus we expect large climate variations to lead to faster adoption from neighbors, while access to uncorrelated food sources for nomads will delay the spread of farming.

4.4 Predictions

We thus arrive at the following results:

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 $\gamma$, a sufficiently large increase in seasonality can make settlement optimal both in the short run and in the long run.

4. The higher $\gamma$ is, the higher $\sigma$ 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.
Figure 7: Sedentarism is optimal in the short run (long run) when seasonality is higher than indicated by the SR (LR) line. Settlement is optimal both in the short run and long run in region marked “Settlement”; in “Barriers”, settlement is optimal in the long run, but not in the short run; in “False Start”, the opposite is true; and in “Nomadism” settlement is not optimal in either timescale. During the Ice Age, no population was seasonal enough to want to settle (points A, B, and C). When seasonality increased, some areas gained the right incentives to store food (point A'), while others did not (points B' and C').

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

The TraCE Dataset He (2011) 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 3.75 x 3.75 degree cells, at a yearly frequency. I aggregate the time dimension of the dataset into 44 periods of 500 years each.

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, 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:

\[
Temp\text{Seas} = \max(Temp/Warmest, 0) - \max(Temp/Coldest, 0)
\]

For precipitation, I use the amount of precipitation during the wettest month minus the level during the driest, divided by mean precipitation.

\[
Precip\text{Seas} = \frac{Precip/Wettest - Precip/Driest}{MeanPrecip}.
\]

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, I define the following Seasonality Index:

\[
Seas\text{Index} = \max(Quantile(Temp\text{Seas}), Quantile(Precip\text{Seas}))
\]

That is, for each cell and period, I transform the two seasonality measures into quantiles (1000 categories). The seasonality index is equal to whichever 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 harsh winters, or a parched 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 × Longitude × 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 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 (e.g. Greenland). The average location on Earth started farming 4500 years ago, had an average temperature of 2 °C, received 1.8mm/day of rainfall (approximately 650mm/year), had a temperature
seasonality of 9 °C, a temperature seasonality of 1.3, and a seasonality index of 625 (out of 1000).

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

**Table 1:** Summary statistics for the adoption cross-section dataset.

How well does my story fit the basic features of the data? Figure 8 shows how many cells were seasonal during the last 22,000 years. A location is considered seasonal if it either has one trimester with average temperatures below 0 °C, and one above 20 °C, or if it has one trimester that receives less than 2 mm of rain in total, and one that receives more than 360 mm (4 mm/day). Seasonal locations were rare during the Ice Age, but became increasingly common in the lead up to the adoption of agriculture, in fact more than tripling in frequency. Figure 9 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.

**Figure 8:** 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.
Figure 9: 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. Locations that were not hospitable in 8,000 BP are omitted. Most of the areas where agriculture was invented had recently become extremely seasonal.

### 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). I also use the Putterman dataset to exclude from the sample locations which could no longer independently invent agriculture, because they had already adopted it.

Each observation is one 3.75x3.75 degree cell, during a specific 500 year period. The basic specification is:

\[
I_{it} = \alpha + \beta_1 T_{it} + \beta_2 P_{it} + \gamma C_{it} + \epsilon_{it}
\]  

(37)

(38)

Where \( I_{it} \) is a dummy for whether agriculture was invented in cell \( i \) at time \( t \), \( \alpha \) 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 ones 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 2. 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 provided by Zheng, by clustering standard errors at the location level, or if different measures of seasonality are used. These results are line with what the model predicts: the places that invented agriculture were all extremely seasonal.

<table>
<thead>
<tr>
<th>Dependant variable: independent invention dummy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Basic Controls</td>
</tr>
<tr>
<td>Temp. Seas.</td>
</tr>
<tr>
<td>Precip. Seas.</td>
</tr>
<tr>
<td>Seas. Index</td>
</tr>
<tr>
<td>Temp. Mean</td>
</tr>
<tr>
<td>Precip. Mean</td>
</tr>
<tr>
<td>Abs Lat</td>
</tr>
<tr>
<td>Temp. Seas. Today</td>
</tr>
<tr>
<td>Precip. Seas. Today</td>
</tr>
<tr>
<td>Seas. Index Today</td>
</tr>
<tr>
<td>Extra Controls</td>
</tr>
<tr>
<td>p</td>
</tr>
<tr>
<td>N</td>
</tr>
</tbody>
</table>

Standard errors in parentheses

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

**Table 2:** Duration model of independent adoption dummy on period- and cell-specific climatic variables. Dependent variable is a dummy which is one if agriculture was invented in that cell, in that period, and zero otherwise. Locations dropped from sample after they adopt agriculture. See text for explanation.

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\textsuperscript{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:

$$A_{it} = \alpha + \beta_1 T_{it} + \beta_2 P_{it} + \gamma C_{it} + \epsilon_{it}$$ (39)

Where $A_{it}$ is a dummy for whether agriculture has already been adopted. Each observation enters the dataset when a neighbor adopts farming, and has a series of zeros until the period in which it finally adopts, in which it receives a one. Thereafter it is dropped from the sample. This model is estimated using the logistic estimator (first tree columns of Table 3 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.

<table>
<thead>
<tr>
<th>Dependent variable: adoption dummy</th>
<th>Logit model</th>
<th>Linear Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear</td>
<td>Linear+Lat</td>
</tr>
<tr>
<td>Temp. Seas.</td>
<td>0.005**</td>
<td>0.004*</td>
</tr>
<tr>
<td></td>
<td>(0.002)</td>
<td>(0.002)</td>
</tr>
<tr>
<td>Precip. Seas.</td>
<td>0.035*</td>
<td>0.043**</td>
</tr>
<tr>
<td></td>
<td>(0.019)</td>
<td>(0.019)</td>
</tr>
<tr>
<td>Seas. Index</td>
<td></td>
<td>0.156**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.064)</td>
</tr>
<tr>
<td>Temp. Mean</td>
<td>-0.007***</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>(0.002)</td>
<td>(0.004)</td>
</tr>
<tr>
<td>Precip. Mean</td>
<td>0.023***</td>
<td>0.031***</td>
</tr>
<tr>
<td></td>
<td>(0.008)</td>
<td>(0.008)</td>
</tr>
<tr>
<td>Abs Lat</td>
<td>0.005**</td>
<td>0.005**</td>
</tr>
<tr>
<td></td>
<td>(0.002)</td>
<td>(0.002)</td>
</tr>
<tr>
<td>Observations</td>
<td>1735</td>
<td>1735</td>
</tr>
</tbody>
</table>

Table 3: Spread of agriculture. Neolithic frontier locations only. Regression of adoption dummy on climatic variables. Models 1, 2 and 3: Logit with robust s.e. Model 4, 5 and 6. Linear probability model with robust s.e.

I also estimate a continuous time duration model with Weibul distribution, and plot the resulting survival curves for various climate types (Figure 10). The more seasonal a location was, the sooner the locals would adopt agriculture from farming neighbors. For

\textsuperscript{1}A location is considered hospitable if it has average temperatures above 0 $^\circ$ C, and more than 100mm of rain a year.
example, 2,000 years after being exposed to agriculture, a location with zero temperature seasonality still has a 40% chance 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.

![Figure 10](image1.png)

**Figure 10:** The solid lines plot the expected fraction of high seasonality locations that are already farming after a given number of years of being exposed to farming. The dotted lines do the same for 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 11 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 11](image2.png)

**Figure 11:** Binned scatterplots of climatic seasonality vs date of adoption. Early adopters were exposed to more seasonal conditions, according to a variety of measures.
For this part of the analysis, I collapse the data into a panel, 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:

\[ Y_i = \alpha + \beta_1 T_i + \beta_2 S_i + \gamma C_i + \epsilon_i \]  

(40)

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

The results of this analysis are presented in Table 4. Both Temperature and Precipitation Seasonality are associated with earlier adoption of agriculture across a wide range of specifications. The effect is larger for temperature, but is statistically and economically significant for both factors. 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 years 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 as a dummy for the New World. 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.
<table>
<thead>
<tr>
<th>Dependant variable: date of adoption</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
</tr>
<tr>
<td>(2)</td>
</tr>
<tr>
<td>(3)</td>
</tr>
<tr>
<td>(4)</td>
</tr>
<tr>
<td>(5)</td>
</tr>
<tr>
<td>(6)</td>
</tr>
<tr>
<td>Basic Controls</td>
</tr>
<tr>
<td>Temp. Seas</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Precip. Seas</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Seas. Index</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Temp. Mean</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Precip. Mean</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Abs Lat</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Extra Controls</td>
</tr>
<tr>
<td>Geographic FE</td>
</tr>
<tr>
<td>r2</td>
</tr>
<tr>
<td>p</td>
</tr>
<tr>
<td>N</td>
</tr>
</tbody>
</table>

Table 4: Linear regression of date of adoption on time-averaged climatic variable of each cell. All 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 of average temperature. 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 are somewhat weaker but still significant when using Conley’s geographically adjusted standard errors.

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. Secondly, the dependent variable (agricultural adoption) was coded with a single value for each country, 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 open that agriculture was adopted in e.g. the Amazon or Sub-Saharan Africa at a much earlier date than is currently known.
To verify the main findings in a setting free from these particular shortcomings, I know look at the spread of agriculture from the Middle East into Europe. These regions have been at the center of concentrated research 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 12 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.
The Pinhasi et al. dataset provides $^{14}$C dates for the onset of agriculture in 765 locations, chronicling the spread of agriculture from the Middle East into Europe.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>sd</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Adop.</td>
<td>-7218</td>
<td>1424</td>
<td>-12811</td>
<td>-5140</td>
</tr>
<tr>
<td>Temp. Seas.</td>
<td>15.2</td>
<td>3.2</td>
<td>6.9</td>
<td>25.1</td>
</tr>
<tr>
<td>Precip. Seas.</td>
<td>.23</td>
<td>.18</td>
<td>.038</td>
<td>.72</td>
</tr>
<tr>
<td>Temp. Mean</td>
<td>12.0</td>
<td>4.7</td>
<td>4.4</td>
<td>30.2</td>
</tr>
<tr>
<td>Precip. Mean</td>
<td>1.84</td>
<td>.73</td>
<td>.04</td>
<td>4.77</td>
</tr>
<tr>
<td>Observations</td>
<td>765</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: 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 13 show, the locations which adopted early had high seasonality of temperature and precipitation, while locations with stable climates adopted agriculture much later.
The basic specification is the same that I used in the basic linear model of Section 6.1.3:

\[ Y_i = \alpha + \beta_1 T_i + \beta_2 P_i + \gamma C_i + \epsilon_i \]  

(41)

Where \( Y_i \) is again the year 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 [1] 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 speeds 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.
Table 6: European dataset, linear model, robust standard errors.

The analysis conducted so far has established that seasonality is strongly associated with the adoption of agriculture. These findings are in complete agreement with the results from the model previously developed, and thus support the hypothesis that farming was invented by groups which had previously become settlers in order to store food.

However, the association between storage and agriculture could also be due to the availability of easily domesticable plants, in the spirit of Diamond (1997). Plants adapted to highly seasonal environments react by conducting their own 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 easy 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 grow 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 showed that if seasonality is held
equal, we would expect locations with higher geographic correlation within likely human migratory range to adopt agriculture ahead of of less homogeneous areas.

To this end I construct a series of proxies, each measuring the range in altitudes present within a specified distance from the location under observation. The idea is that areas with different altitudes will experience different temperature and precipitation regimes, are likely to have slopes with different exposures to the sun, and will generally possess a wide variety of microclimates. In short, it is highly unlikely that areas at widely differing altitudes will suffer the type of perfectly correlated seasonal food shocks that 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 (≈ 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 7 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.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>sd</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years Ago</td>
<td>-9520</td>
<td>1336.849</td>
<td>-12811</td>
<td>-7276</td>
</tr>
<tr>
<td>r(5)</td>
<td>366</td>
<td>297.817</td>
<td>16</td>
<td>1330</td>
</tr>
<tr>
<td>r(50)</td>
<td>1485</td>
<td>666.4563</td>
<td>99</td>
<td>3108</td>
</tr>
<tr>
<td>Temp. Seas.</td>
<td>18.1</td>
<td>4.122969</td>
<td>11.4</td>
<td>24.7</td>
</tr>
<tr>
<td>Precip. Seas.</td>
<td>.54</td>
<td>.1053444</td>
<td>.2113971</td>
<td>.6708408</td>
</tr>
<tr>
<td>Temp. Mean</td>
<td>17.9</td>
<td>3.314162</td>
<td>8.1</td>
<td>24.1</td>
</tr>
<tr>
<td>Precip. Mean</td>
<td>1.03</td>
<td>.6018897</td>
<td>.1068493</td>
<td>3.260274</td>
</tr>
<tr>
<td>Latitude</td>
<td>34.2</td>
<td>3.015114</td>
<td>29.55</td>
<td>41.4669</td>
</tr>
<tr>
<td>Longitude</td>
<td>37.9</td>
<td>4.252285</td>
<td>26.1167</td>
<td>49.6333</td>
</tr>
<tr>
<td>Altitude</td>
<td>487</td>
<td>523.5334</td>
<td>-405</td>
<td>2376</td>
</tr>
<tr>
<td>Dist. Coast.</td>
<td>1.80</td>
<td>1.58</td>
<td>0</td>
<td>5.86</td>
</tr>
<tr>
<td>Observations</td>
<td>101</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Summary statistics for the subsample of the Western Eurasian dataset which had access to wild cereals.
Figure 14: The graph shows the altitude range that settlers could access (0-5km from site), how much extra range they could access if they were nomadic (5-50km), and how much was out of reach even for nomads (50-100km, and 100-200km). When the late adopters eventually became settled, they had to abandon on average 1,250m of altitude range. The early adopters faced a lower opportunity cost: on average they lost only 1,000m.

The basic specification is:

\[ Y_i = \alpha + \beta_1 r(5) + \beta_2 r(50) + \gamma C_i + \epsilon_i \]  

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 model, and the results are presented in Table

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 \( r(50 : 100) \) is statistically significant.

<table>
<thead>
<tr>
<th>Dependant variable: date of adoption</th>
<th>(1) (&lt;200\text{km})</th>
<th>(2) (&lt;100\text{km})</th>
<th>(3) Clim. Means Smooth Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r(5) )</td>
<td>-0.772**</td>
<td>-0.990**</td>
<td>-0.986*</td>
</tr>
<tr>
<td></td>
<td>(0.414)</td>
<td>(0.496)</td>
<td>(0.580)</td>
</tr>
<tr>
<td>( r(50) )</td>
<td>0.414**</td>
<td>0.517**</td>
<td>0.587**</td>
</tr>
<tr>
<td></td>
<td>(0.179)</td>
<td>(0.221)</td>
<td>(0.267)</td>
</tr>
<tr>
<td>( r(3:8) )</td>
<td></td>
<td>-0.858</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.597)</td>
<td></td>
</tr>
<tr>
<td>( r(50:100) )</td>
<td></td>
<td>0.500*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.254)</td>
<td></td>
</tr>
<tr>
<td>( r(200) )</td>
<td></td>
<td>0.111</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.266)</td>
<td></td>
</tr>
<tr>
<td>Temp. Seas.</td>
<td>-161.6</td>
<td>-158.0</td>
<td>-144.5</td>
</tr>
<tr>
<td></td>
<td>(114.1)</td>
<td>(116.4)</td>
<td>(116.1)</td>
</tr>
<tr>
<td>Precip. Seas.</td>
<td>737.9</td>
<td>471.2</td>
<td>-442.4</td>
</tr>
<tr>
<td></td>
<td>(4268.1)</td>
<td>(4417.6)</td>
<td>(4040.5)</td>
</tr>
<tr>
<td>Controls</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>129</td>
<td>101</td>
<td>101</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.037</td>
<td>0.051</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Table 8: Linear regression of year of adoption of agriculture on the range of altitude within various radii.

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 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 15 shows, this parameter declined drastically as agriculture became the dominant lifestyle (Cohen and Armelagos 1984). Similar declines in health are evident from a host of other indicators, such as measures of skeletal robustness, tooth wear, joint diseases due to overwork, and evidence of disease and infection. These are the findings that prompted Diamond to title his famous article “the worst mistake in the history of the human race” (Diamond 1987).

Figure 15: Achieved adult height across the Neolithic sequences reported in Cohen and Armelagos (1984). Each line represents the progression in observed heights in one location, expressed as a difference from its value during the Paleolithic (nomadic hunting and gathering). The sedentary farmers (Neolithic) were clearly shorter than their nomadic ancestors. In the cases for which independent data was independently recorded for the Mesolithic (transitional) phase, the decrease in standard of living can be seen to have predated domestication.

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

35
result in the child rejoining its original growth curve, and achieving virtually the same adult height as if the starvation episode had not occurred (Williams, 1981). Similar considerations hold for other skeletal disease markers, which also tend to show accumulation of stress factors over time (e.g. tooth wear and joint disease inform us of the average grittiness of food and the amount of labor expended in procuring it, rather than the time pattern of these factors). Thus the most commonly used health markers are woefully inappropriate for assessing the degree of seasonality in consumption.

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

![Figure 16: Example of Harris lines in 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)](image)

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.

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.

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 which nomads suffered through. The model predicts that such a society would have a lower population density, but higher consumption per capita.

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 was invented. 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.

References


Harris, H. (1933): “Bone Growth in Health and Disease: The Biological Principles Underlying the Clinical, Radiological, and Histological Diagnosis of Perversions of.”


Kuijt, I. (2011): “Home is where we keep our food: The origins of agriculture and late Pre-Pottery Neolithic food storage,” *Paleorient*.


