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

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Abstract

During the Neolithic Revolution, seven populations independently adopted settled 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 become 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

During the Neolithic Revolution (ca. 10,000-5,000 Before Present), our ancestors abandoned nomadic hunting and gathering in favor of settled agriculture. This radically innovative lifestyle was untested, fraught with risk, and would change the face of the Earth forever.

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Agriculture was independently developed at least seven times, in as many separate locations across the globe, and each of the affected populations experienced similar broad trends (Barker, 2006). They learned how to cultivate certain locally available wild food species, eventually domesticating some of them. The farmers and their crops radiated outwards from their starting locations, forming the nucleus of the main ethnolinguistic groups still present today (Bellwood and Renfrew, 2002), and eventually developed complex urban societies with stratified classes, craft specialization, and organized religions. Surprisingly, archaeological evidence from skeletal remains suggests that in most of these locations, the last hunter-gatherers were eating an abundant and varied diet, while the arrival of domesticated crops is in general associated with a rapid decrease in consumption per capita (Cohen and Armelagos, 1984), which persisted at least until the onset of the industrial revolution. This widespread decrease in consumption per capita led Jared Diamond to title a famous 1986 article on the Neolithic “The worst mistake in the history of the human race”.

Despite sharing these striking similarities, the various agricultural inventions differ along a number of important dimensions: for example, they occurred in different latitude bands on different continents (see Figure 1), experienced different climatic shocks, and resulted in the domestication of different species. Plausible narratives exist for each Neolithic sequence individually, but invariably the factors proposed as central in one case of invention are seen to be entirely absent in others, and present in many locations which did not invent agriculture. This combination of broad similarities and differing details has presented the main obstacle in developing a convincing explanation for the Neolithic Revolution as a whole. For example: Diamond (1997) argues that the development of farming techniques in the Fertile Crescent can be explained by the presence of many local indigenous grasses with large seeds, but in the Andes there were no such plants, and yet the local populations created agricultural societies based on tubers and squash. Further, large seeded grasses occur in an enormous swath of Eurasia (Barker, 2006), while agriculture was invented in only a few of these. Comparative scholars of the Neolithic revolution agree that none of the explanations proposed thus far can satisfactorily account for all of the locations where agriculture was invented (Gremillion et al., 2014; Smith, 2014). It is hard to accept that widely differing causes in separate locations, produced very similar trends and at similar times.

This paper proposes a novel solution to this problem, translates the fundamental insights into an economic model, and empirically investigates the accuracy of the resulting predictions. I argue that increased climatic seasonality created predictable periods of scarcity, which could not be alleviated through nomadic migration. Many of the most affected populations decided to store food, so as to smooth their yearly consumption. Their food stocks were too heavy to carry, so that they necessarily had to spend most of the year in the same surroundings. Being nearly sedentary, they lost access to some food sources, leading to a decrease in consumption per capita. Still, they preferred to eat less on average, but to do so consistently throughout the year, rather than suffer an endless series of feast-to-famine cycles. Once these societies had become sedentary and started to store food, they would already have been practicing regularly two of the
main prerequisites for a successful agricultural society, and the development of farming techniques would have been much easier (Testart, 1982).

To formalize this theory, I construct a simple model with one agent, representing a single band of nomadic hunter-gatherers, deciding whether to remain mobile or become sedentary and store food. The band has access to two ecosystems, and must decide which one it wants to occupy in each of two seasons. Utility is increasing in average food consumption, and decreasing in consumption seasonality. The net fertility of the band follows a modified Malthusian process: as in the standard demographic model, net fertility is increasing in average consumption; but additionally I assume that high consumption seasonality depresses net fertility. If the band remains nomadic, it can always reside wherever food is temporarily most abundant. However, it cannot store, and must therefore endure whatever seasonality it is unable to run away from. If it becomes sedentary, it is limited to the average amount of food present in its most abundant environment, but is able to perfectly smooth consumption. I show that in such a setting, for any set of conditions in which it is rational for a band to remain nomadic, a sufficiently large increase in resource seasonality will make settled storage optimal. The model also shows that as long as the band remains nomadic, seasonality in food consumption will depress fertility and result in higher consumption per capita in equilibrium. When the bands starts storing, the population will converge to the carrying capacity of their environment, and consumption per capita will decline. However, the smoothness of their consumption profile will mean their utility is still higher than would be possible under nomadism. From this basic model, I derive the following testable implications:

• Agriculture should be invented in highly seasonal locations, at a highly seasonal time.

• Once invented, agriculture should spread faster where seasonality is high.

• Average consumption should decrease after populations become sedentary, and remain unaffected by subsequent discovery of agriculture (due to Malthusian effects).

• Early agricultural communities should arise in locations with high geographic correlation within plausible migratory range.

I take these predictions to the data, by employing a variety of archaeological, botanical, paleoclimatic and topographic data. These show that highly seasonal conditions were indeed rare before agriculture was invented, and became much more common shortly before the event. This was due to the fortuitous alignment in well-documented variations in Earth’s orbital parameters, producing exceptional temperature seasonality in the Northern hemisphere, and precipitation seasonality in the tropics. Further, all of the locations which invented agriculture were amongst those most affected by the change. Seasonality (of both temperature and precipitation) predicts a large fraction of the variation in

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1 During pregnancy and lactation, mothers and their infants are extremely vulnerable to even temporary disruptions to their food supply. Where food supply is inconsistent, these demands can only be met by accessing body fat reserves, which is metabolically costly: conversion by humans of carbohydrates to fat is only about 72% efficient (?), and the weight will increase the amount of energy necessary to gather more food. Thus, a regular season of food deprivation can only be survived if total average food supply is larger.
the date of agricultural appearance, with one standard deviation increase in seasonality associated with agriculture arriving between 500 and 1,500 years earlier than could otherwise be expected (0.2 to 0.6 standard deviations). This is shown to be the product of both higher likelihood of invention, and faster rate of diffusion: agriculture originated in highly seasonal locations, during a highly seasonal time; and once agriculture arrived in a given place, neighboring regions with high seasonality adopted agriculture approximately twice as fast as otherwise similar, but unseasonal, locations.

The results of this global investigation are then repeated on a more detailed sample of 765 archaeological sites in Western Eurasia for which $^{14}C$ dates for the earliest evidence of agriculture is available. This dataset, collected by Pinhasi et al. (2005), chronicles the spread of wheat, barley, goats and sheep from the hilly flanks of the Fertile Crescent, into the Mediterranean basin and North-Western Europe.

The relationship between seasonality and agriculture is statistically and economically significant, and robust to a variety of alternative specifications. However these results are potentially compatible with a variety of causative pathways. For example: many of the wild grasses which were later domesticated had already evolved large seeds, which allowed them to survive in highly seasonal environments, and which made their eventual cultivation more profitable. The early appearance of farming in highly seasonal locations could thus reflect differences in suitability for potential crop species (Diamond, 1997), rather than (as this paper argues) the increased attractiveness of food storage. To mitigate this risk, I conduct a further analysis using only the subset of the archaeological sites whose inhabitants were likely to have had access to wild forms of wheat and barley. I construct a proxy for the ability of nomads to access uncorrelated food sources, and I find that agriculture was more readily adopted where opportunities for geographic hedging were limited.

$^{14}C$ is a radioactive isotope of carbon, whose concentration declines steadily after an organism dies. It’s concentration is used in dating organic remains such as charcoal, seeds, or wood.
Figure 1: At least seven locations invented agriculture within a few thousand years. Despite different latitudes, climates, and available food species, each of these locations converged on ultimately similar social and technological arrangements.

The present approach draws from a number of existing studies on the origins of agriculture. [Diamond (1997)] has long championed geography as a primary determinant for the adoption of agriculture. [Testart (1982)] showed how populations of settled, storing, hunter-gatherers often developed cultural traits similar to those of subsistence farmers, despite relying on wild foods. [McCorriston and Hole (1991)] documented a marked increase in climate seasonality in the Middle East during the Early Holocene, and proposed that the resulting proliferation of annual plants favored their eventual domestication (they are careful to note that this theory had unknown applicability outside of the Middle Eastern context). Besides the broader geographic scope of my theory, I argue that the development of agriculture was not due to the migration of existing ecosystem types, or a change in their relative geographic preponderance, but rather the appearance of climatic conditions which did not previously exist anywhere on the planet (i.e. extreme climatic seasonality). This focus is shared with the paleoclimatic literature on no-analog communities [Williams and Jackson (2007)].

From a welfare standpoint, the theory I propose is based on a simple mean-variance

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A no-analog community refers to a novel combination of species that does not currently co-occur. In the case of this paper, I argue that the highly seasonal climates of the Early Holocene had no analogues previously.
tradeoff. Nomadism provided access to a greater variety of food-gathering locations, but prevented the band from smoothing consumption through storage. As long as climatic seasonality remained moderate, the cost of losing mobility was greater than the benefits of storing; populations remained nomadic, and the development of agricultural techniques remained unlikely. When climatic seasonality increased, the most affected populations saw sedentism as an attractive tradeoff, and farming could flourish. The emphasis on transient food shocks (rather than average conditions) as an explanation for choices of farmers in incomplete market settings is similar to the work on open fields by McCloskey (1991) and the literature on minimax preferences in economic development settings (Young, 1979).

The population limiting mechanism is conceptually similar to that of Voigtländer and Voth (2013), though in my case net fertility is restricted by regular seasonal oscillations, rather than epidemics of plague, or increased mortality in urban settings.

As in this paper, Ashraf and Michalopoulos (2013) argue that the Neolithic revolution was due to a change in a form of climatic variability. However they argue that intermediate levels of unpredictable variation caused faster accumulation of latent agricultural technology, and show empirically that locations which have recently experienced more inter-annual climatic volatility (measured using the variance of the average temperatures of the same trimester across several years) generally adopted agriculture earlier. Conversely, I propose that increased seasonality (i.e. variation) altered the incentives to store food, which nudged hunter-gatherers to become sedentary, and eventually start farming. I use a panel dataset of reconstructed climates to estimate the degree variation in temperature and precipitation within the average year. Their theory seeks only to explain the geographic pattern of adoption, while my explanation also successfully predicts the observed reduction in consumption per capita (i.e. consumption per capita decreased because smoother food consumption resulted in increased fertility, but risk aversion meant that sedentary storage was still more attractive than nomadism).

The association between seasonality and invention of agriculture is summarized in Figure 2. The locations which invented agriculture are clustered in two latitude bands: between 30° and 40° North, and around 10° to 20° on either side of the Equator. The higher of the two latitude bands is characterized by wide swings in temperature, while the lower of the two has very seasonal precipitations due to the oscillations in the tropical monsoon. As can be seen, the Ice Age did not materially expand the envelope of temperature conditions present on the planet, and had only a small effect on average precipitations. On the other hand, it greatly increased the amount of both forms of climatic seasonality, particularly in the Northern hemisphere.
Figure 2: Top row: average yearly temperature and precipitation for each latitude band, during the Ice Age (solid) and Neolithic (dashed), and present at each independent adoption (green circles, see Figure 1). Agriculture was clearly compatible with dry, wet, warm and cold. Average climates similar to those of the independent adopters were present even during the worst of the Ice Age. Bottom row: seasonality of temperature and precipitation during the Ice Age and Neolithic. During the Neolithic, temperature seasonality between 30N and 40N spiked severely, leading to adoption in the temperate locations. Simultaneously, the tropical monsoon strengthened, and the added precipitation seasonality led to the equatorial adoptions. The Equator saw a marked increase in average rainfall, but agriculture here was not invented independently. Temperature seasonality is defined as the difference between the temperature during the warmest and coldest trimester, censored at zero. Precipitations seasonality is the difference between wettest and driest trimester, divided by average precipitations.

This paper’s main contribution lies in proposing a new theory for the timing, geographic pattern, and health consequences of the Neolithic revolution, in formulating predictions from the theory, and in verifying these predictions against a variety of climatic, geographic, and anthropological data. The effects of the Neolithic Revolution are hard to overstate: many of the earliest crops are still providing the vast majority of calories consumed by man; the locations where they were domesticated have proven to be nucleation sites for the main ethno-linguistic groups observed today [Bellwood and Renfrew 2002]; the requirements of the crops shaped the laws [Wittfogel 1957; Mayshar et al. 2013], social customs [Alesina et al. 2013], and even the genes [Galor and Moav 2007] of the societies which relied on them; the presence of accumulated stores created both the motive and the opportunity for mass organized warfare [Ferrill 1985]; finally,
thousands of years of intensive cultivation have led to massive degradation of once-fertile soil (Diamond, 2005; Cowen, 2014).

Together, these factors effectively shaped the playing field on which all subsequent events have played out, and each has been the focus of independent analysis in the long run growth literature (Weisdorf, 2005) and Spolaore and Wacziarg (2012) provide literature reviews). Ashraf and Galor (2011) show that the timing of the Neolithic revolution is an independent predictor of population densities before the industrial revolution, and Hibbs and Olsson (2004) and Olsson and Paik (2013) draw a link between agricultural adoption and contemporary measures of development.

The rest of this paper is organized as follows. In Section 2 I summarize the historical background on the Neolithic. In Section 3 I describe some of the previously proposed theories; in Section 4 I explain my theory in detail; in Section 5 I describe the model; in Section 6 I present the empirical analysis; in Section 7 I relate the evidence on health indicators across the transition; in Section 8 I explore some robustness checks; while section 9 concludes.

2 Historical Background

It would be impossible, within the confines of this section, to cover all of the Neolithic sequences at a level of detail sufficient to allow the reader to form his own opinion as to the plausibility of my proposed explanation. As a compromise I will first describe the specific series of adaptations which occurred in the case of the Fertile Crescent, by far the best studies case of agricultural adoption. Then, I will briefly describe similarities and differences with other areas. This review is mainly based on Barker (2006).

South West-Asia lies at the junction of the European, Asian, and African continents, and can be roughly defined as all lands found south of the Black and Caspian Seas, east of the Mediterranean, north of the Red sea and the Persian Gulf, and west of the Iranian Plateau and the Caspian sea. The southern reaches of this region are located in the Horse Latitudes, which see nearly constant low precipitations, and where most of the temperate deserts are located. The potential for rainfall increases towards the north, but here the mountainous topography determines the relative distribution. Rainfall is abundant along the coastlines, and on the arch formed by the Zagros and Taurus mountains. The plains to the south of this arch are for the most part devoid of precipitation, and are only watered along the large rivers which traverse the region.

2.1 The Neolithic Revolution in the Fertile Crescent

During the Last Glacial Maximum (21,000 BP), temperatures in the region were around eight degrees lower than today. Winters were cold, summers were lukewarm, and both were equally dry. Most of the region, inhabited at the time by the Kebaran culture, was covered in desert or steppe-desert, while deciduous woodland (common today) was confined to a few refugia along the Mediterranean and Caspian seas. Seasonality in food availability was present, but could be effectively managed by regular and opportunistic
migration from the steppe to the woodland. The archaeological site of Ohalo II, on the shores of the Sea of Galilee, shows that the local Kebarans subsisted mainly on a diet of fish, gazelle, deer, small game, birds, and barley. The food was mainly prepared by roasting, though simple ovens were also present. They hunted with nets and arrows, and dressed their kills with a variety of knives and scrapers. Plant remains were also common, and cereals were important enough to justify the development of specialized sickles to harvest them, and mortars and pestles to grind them. Ohalo II shows signs of multiple occupations, suggesting that the same site could be visited at least semi-regularly. At 1500 sqm, Ohalo II is amongst the largest Kebaran sites unearthed, and should thus be considered as an example of what this culture could produce in an uncommonly productive lakeshore setting. Still, the site was composed of only half a dozen small kidney-shaped huts made of brush. Most Kebaran sites were smaller still, with 350sqm camps common, being used at most by 15 to 30 individuals. The presence of communal hearths and processing areas points to an important role of the extended family in all phases of food procurement. Since there are considerable economies of scale in hunting with nets, it is likely that different groups would come together occasionally to perform this activity. There is no evidence in favor of either farming or herding, suggesting that the Kebarans were pure hunter-gatherers.

The inhabitants of Ohalo II lived amongst stands of wild cereals, developed specialized tools to harvest and process their seeds, and were almost certainly aware that they could be consumed many months after harvest. When conditions dictated it, they were able to mobilize labor in groups larger than their immediate family. In short, by 19,000 BP the Kebarans already possessed virtually all of the technological and social prerequisites for developing agriculture. The lack of cultivation at any of their sites shows that populations can remain hunter-gatherers for thousands of years, despite being in constant mutual interaction with domesticable species.

Approximately 15,000 BP, during the Bolling-Allerod, the climate of South-West Asia improved considerably. Average temperatures and precipitation both increased, so that vast areas were rapidly covered by deciduous woodland, where cereals thrived. This type of environment provided large amounts of food in the aggregate, but in a highly seasonal pattern.

These new conditions saw the appearance of the Early Natufians, who when possible located themselves at the border of the upland woodlands and the lowland steppes. The former gave them access to deer, nuts and cereals, while the latter allowed them to hunt gazelle and collect grassland seeds. At Abu Hureya, mass killing of gazelle would occur between mid April and late May. Available plants would ripen steadily through the spring, reaching peak availability in early July, but remaining reasonably abundant until late October.

The inhabitants of Abu Hureya were regularly collecting at least twenty different plant species, and grinding tools of many different types are ubiquitous in Early Natufian sites. Hunting had also become more capital intensive: the Natufians erected long stone walls, used to funnel migrating gazelles into prepared kill zones. The resulting carcasses would be processed using a highly specialized toolkit.
Their cultural traits and subsistence strategy were so different from that of the late Kebarans, that archaeologists at first thought that they had migrated into the region from somewhere else. Today, it is generally agreed that they arose organically from previous hunter-gatherer groups.

Despite this abundant and apparently diversified food base, the dry and cold winter made the vast majority of these resources almost entirely unavailable for nearly six months (see Figure 3). The incentives to store food, in particularly cereal grains, were clearly strong, and in fact Early Natufian dwellings show plentiful evidence of baskets, bins, and other storage vessels. The Early Natufians can thus be described as delayed return hunter-gatherers: while they were not engaging in outright cultivation, their use of storage shows that they were planning their subsistence months in advance. This change in economic strategy was accompanied by an apparent rise in the importance of the nuclear family, whose dwellings now incorporate private hearths, as well as production and storage facilities.

**Figure 3:** Chart of the seasonal food availability for Early Natufian groups at Abu Hureyra. Most foods were completely unavailable for almost six months out of every year. Figure adapted from Barker (2006)
During the following 2,000 years, both temperatures and precipitations declining steadily, followed in 13,000 BP by a sudden drop back to Ice Age temperature averages, called the Younger Dryas. The result was a retreat of the woodland from much of the range it had gained during the Bolling-Allerod, leading to the abandonment of many Early Natufian settlements, such as Abu Hureyra. The Natufian response to this climate worsening varied with the location. In areas where the woodland was replaced by steppe or desert-steppe, the local population returned to nomadic hunting-and-gathering. In the sheltered locations where woodland persisted, the locals responded by becoming even more sedentary, as shown by their dwellings, which are now often made of sun-baked bricks, rather than branches and reeds. Storage was clearly extremely important to Late Natufian settlers, as evidenced by the great variety of storage vessels recovered.

Late Natufian settlers favored alluvial soils next to the receding shoreline of the many lakes present at the time. These sites were excellent potential habitats for cereals, but were often remote from the locations where wild stands were already present. It is possible that while they were not cultivating plants in the modern sense (e.g. working the soil every year), these populations would transport seed and sow it into favorable locations to help the formation of wild stands, which where then harvested yearly without significant subsequent cultivation.

Late Natufians buried their dead below the floor of their dwellings, extending their attachment to a specific locations beyond death.

The Younger Dryas came to an abrupt and definitive end around 10,500 years ago, giving way to the warmer Holocene interglacial, which continues today. Precipitations and temperatures rose once again, prompting the renewed expansion of the woodland area. The Late Natufians evolved into the Pre-Pottery Neolithic A culture, and took advantage of the renewed abundance of cereals by harvesting them extensively, and storing them in communal granaries. Grain processing technology advanced, with querns replacing pestle and mortar as the dominant grinding implement. Heavy equipment, such as picks and adzes also became more frequent, pointing to more intensive shaping of their natural environments. While pottery is still absent, but the presence of baked clay bricks and figurines establishes their familiarity with the thermal properties of clay. PPNA settlements were much larger than those observed previously, averaging around 2-3000sqm, with the largest settlements reaching two or three hectares. These sometimes featured impressive architectural achievements, such as the massive wall of Jericho, or the large ceremonial complex at Gobekli Tepe. All these factors create a strong presumption of an almost entirely sedentary population.

The PPNA marks the earliest period in which significant numbers of seeds with domesticated-type characteristics appear, but wild types still predominate. The inhabitants of Jericho harvested emmer wheat and barley, while those at Tell Aswad relied heavily on emmer wheat, peas and lentils. The evidence for direct cultivation is still not definitive: the emergence of domesticated phenotypes is also possible under certain types of intensive harvesting. Gazelle was still the main source of meat, but a decrease in the size of specimens, and a growing relative importance for various types of small game suggest the possibility of over-hunting.
The trends of greater sedentism, increased reliance on plants, and intervention in their reproduction all coalesced approximately 9,500 years ago, during the Pre-Pottery Neolithic B, which brought together for the first time the core of the Eurasian agricultural system. PPNB settlements are significantly larger than PPNA settlements, up to 12 hectares in size, and had populations of one or two thousand. The continued expansion of the woodland belt during the Holocene led to the resettlement of sites which had been abandoned during the Younger Dryas, such as Abu Hureyra. The inhabitants lived in very substantial square house of stone and mud brick, with plastered floors. Each dwelling contained separate storage pits, silos and hearths, suggesting that the family was the central unit of production.

Domesticated seed types now become very abundant, and their proportion rises through time. PPNB populations were now definitely cultivating emmer, einkorn, barley, and legumes. They were also herding goats and sheep, probably in part by allowing them to graze on the post-harvest stubble. They still hunted and collected wild fruits and nuts, but these activities were now secondary from a subsistence viewpoint.

Their stone technology had become highly elaborate, producing standardized blanks, which were then transformed into more specialized tools as needed. The groups would sometimes venture into the steppe for hunting, but these appear to have been limited excursions undertaken by a part of the population, rather than a movement of the entire group.

The next big development was the invention and diffusion of ceramic vessels for storage and cooking (i.e. the Pottery Neolithic). Domestication and pottery complemented each other perfectly: pots could safeguard stored grains from rodents and water, and could be used to boil water for broths and porridges. They made milking animals easier, and allowed our ancestors to discover brewing. The addition of pottery to the Neolithic toolkit would mark a new phase in the relationship of our ancestors with fire, which would soon become just as important for its ability to affect chemical changes in inorganic materials, as it had been for cooking for hundreds of thousands of years.

2.2 World distribution of neolithic societies.

The historical importance of the Middle East has led to extreme interest by archaeologists, and the areas has been subject to the most detailed surveys, and the most advanced site analysis. The orthodox theory argues that during the PPNA (11,500 BP), wild cereals were domesticated in the Western area of the Fertile Crescent, inland from the eastern Mediterranean shoreline; while goats and sheep were domesticated in the Eastern part, along the Zagros and Tauros mountains. These separate advances are thought to have then come together during the PPNB (10,500 BP). Domestication appears to have been triggered by the transition from the LGM to the early Holocene, along with its Bolling-Allerod "dress rehearsal". Archaeologists have long been aware that most of the progenitors of the important domesticates are still growing wild in this region and we know that the Natufians were settled, and were harvesting and storing wild cereals. However, it should be noted that many or all of the early domesticates are present in
a wide swath of land ranging from Gibraltar to Quetta in Pakistan, and from Cairo to Belgrade. Unsurprisingly, archaeologists have found early agriculture where they have searched for it. Further, it should always be remembered that agriculture was only one of the multiple responses of South-West Asian hunting and gathering communities to their changing environments.

If the Levant is the most studied example of independent adoption, then Europe is the best understood case of Neolithic diffusion. From its apparent origins in the Fertile Crescent, farming spread along the Mediterranean coastline, reaching Greece about 8,000 BP, only half a millennium after the Eurasian agricultural system had coalesce in PPNB cultures. From there, farming crept up the Adriatic, colonizing the western Balkans, and also crossed the sea into Apulia. The former branch broke into Central and Northern Europe, while the latter continued along the Mediterranean coastline into Sicily, Sardinia, France and Spain.

Until recently, the dominant model for the spread of agriculture saw a nearly continuous wave of advance by a colonizing Middle-Eastern population, but it is now understood that farming techniques leapfrogged each other significantly, leaving pockets of hunting and gathering behind them, so that pure hunter-gatherers continued to interact with farmer-forager neighbors for hundreds of years, before eventually a local tipping point would be reached, and the entire area would begin farming exclusively.

Interestingly, paleo-linguistic evidence suggests that the spread of the Eurasian agricultural system was essentially parallel to that of Proto-Indoeuropean, the reconstructed ancestor of most languages spoken between Iceland and Bangladesh. Genetic evidence from Europe however does not see significant arrival of Middle-Eastern genotypes during the Early Neolithic, suggesting that even when domesticated seeds became separated from their original populations, the terms that had been originally used to describe them remained attached to them.

The traditional viewpoint for the appearance of farming into Central and South Asia sees PPNB-inspired agriculture arriving from fertile crescent into Iran and the Indus Valley, while rice farming descending from China into the Gangetic plain. In fact this model was formulated mainly through assumed symmetry with the European sequence, since there was little archaeological evidence from the early farmers of South Asia, and virtually none for the previous hunter-gatherer population.

As more evidence has been unearthed, the derivative nature of the Indian Neolithic has recently been called into question. It is still generally accepted that the Harappan civilization received its crops from the Fertile Crescent, and that Indus valley farmers would eventually gain access to plants from Oman (1250 km), Mesopotamia (2500 km), and East Africa (3000km). But genetic studies on cattle and cereals support a distinct domestication event somewhere in the Indian subcontinent, possibly contemporaneous to the appearance of the PPNB complex in South-West Asia. Also, a growing body of archaeological evidence supports the independent domestication of rice in the Ganges valley and of various millets and small seeded grasses in South and Central India. As in the Middle East, the triggering event would have been the widespread climatic changes which accompanied the end of the last Ice Age.
In the Americas, agriculture was independently invented at least three times, in the 5,000 years period between the end of the Pleistocene and the early Holocene. In South America, the Andes saw the emergence of Neolithic systems centered around potatoes and other tubers. In Mexico, maize and various types of squash were domesticated. Eastern North America was settled by populations subsisting on cultivated sunflowers and weedy marsh plants.

Political, social and economic constraints have resulted in enormous gaps in the African archaeological record. It is however generally accepted that the dynamics Neolithic in Africa differed on either side of the Sahara. Egypt and the southern Mediterranean coast saw the introduction of wheat, barley and the rest of the Eurasian agricultural system, though recent evidence suggests that these intrusive crops in fact displaced a set of previously domesticated native plants. As in the Fertile crescent, the Nile valley was supporting semi-sedentary populations during the late Pleistocene. In the Sahel, local forms of millet were independently domesticated, supporting the appearance of the Bantu ethno-linguistic group, which would later come to dominate most of the arable land south of the Sahara desert.

2.3 The Legacy of the Neolithic Revolution

The replacement of nomadic hunting and gathering with settled agriculture set the stage for the stunning developments of subsequent history. The early Neolithic populations faced incentives and constraints that were far removed from those of their ancestors, and to these they responded by developing the first large scale urban civilizations, the cultural ancestors of our own modern societies.

Despite the centrality of the Neolithic Revolution to all subsequent human history, it has proven difficult to pinpoint a specific transition point in the continuum of intensification choices made by populations during the transition. Higgs and Jarman (1972) commented “domestication can be regarded as a long term process whose limit at one end is defined by the present day, and at the other only by the earliest date that anyone has yet had the temerity to propose”. Increased population density, greater reliance on plants for food, and settlement are considered indicative of possible agricultural intensification, but not definitive tests. The general demarcation point is usually taken as the evolution of crop varieties which are incapable of surviving without human assistance. Layton et al. (1991) notes that at some point a critical threshold was passed, but that it is unproductive to argue too much on what the threshold is, or when it happened. At least since they had left Africa, our ancestors had proved able to exploit new landscapes in new ways, in many cases significantly modifying their environment, so in some sense the Neolithic Revolution fits a general pattern in which Homo Sapiens were continuously prodding at the geographic and technological boundaries of their own societies.

The most astounding aspect of the Neolithic Revolution in the Fertile Crescent is perhaps not the domestications of wheat and barley, but rather that these two plants would enjoy extraordinary success in an enormous swath of first Eurasia first, and later the Americas as well. Still, the development of agriculture was the result of a process...
which was neither monolithic nor continuous. Each of the populations that domesticated plants did so in their own way, and there are important cases of populations that flirted with cultivation (e.g. the Natufians) or herding (e.g. of Barbary sheep) only to revert to hunting and gathering later, when conditions changed. But it is undeniable that very different societies somehow came up with very similar adaptations within a restricted timeframe.

A lot of research has gone into determining which plants would have been easiest to domesticate. Many of the early cereals are self-pollinating, develop large seeds and store well. They are also free from toxins, relying instead on their hard seed skins for defense from predators. Once humans had mastered the mechanical process for defeating these defenses, their processing into food was direct and efficient. However, humans also domesticated plants without these characteristics: tubers that are toxic before cooking, fruiting trees, and fibrous plants for textiles. On the animal front, it is true that Fertile Crescent was home to many herbivores over fifty pounds, but only about 15 out of 150 such animals were domesticated worldwide, so the predictive accuracy of this metric must necessarily be limited.

Diamond (1997) called attention to the differing orientation of the world’s continents. The unbroken east-west corridor running from Gibraltar to Beijing would have allowed for rapid spread of domesticable species in substantially similar environments, while the North-South orientation of the Americas and Africa would have prevented dispersion. This theory captures the importance of the arrival of wheat in East Asia, and rice in Western Eurasia, but cannot account for the multiple independent adoption of agriculture, which necessarily occurred well before the footprint of these plants had begun to spread.

As cultural contact on intercontinental scale is not considered plausible in the timeframe involved, the only explanation with the necessary global scope is a large change in global climate patterns. In the Early Holocene, our ancestors were exposed to environments that were more seasonal than any they had experienced up to that point. They answered these novel incentives with a novel response: a switch to sedentary occupation close to seasonal food sources, with food storage playing a dominant role in their consumption smoothing strategies. Thus, without cultivation having played a determining role up to this point, they were already storing food intensively, and living year-round in the same surroundings. These two developments made them essentially pre-adapted for the development of cultivation techniques and the domestication of plants and animals.

3 Previous Explanations

The history of domestication has been the focus of concentrated research from scholars in the fields of botany, anthropology, archaeology, agronomy, history, and geography. If farming had simply resulted in certain local populations increasing their productivity, the Neolithic would be no different from other specific technological advances, such as e.g. the elaborate salmon traps of native groups of the US North West. Instead, in the case of the Neolithic Revolution, these initially local adaptations spread to nearly
all corners of the globe, and were continuously specialized and improved upon, forever changing both the history and geography of our planet.

In this section we review some of the theories which have been advanced to explain the transition.

### 3.1 Logical next step

Before modern archaeological methods uncovered evidence to the contrary, it was widely assumed that hunter-gatherers spent most of their short, miserable lives within a hair’s breadth of starvation, and would have therefore gladly taken up farming as soon as their knowledge of plant biology, and their increasing social complexity, would have allowed them to do so. In the words of [Darwin (1868)]:

> The savage inhabitants of each land, having found out by many and hard trials what plants where useful, [. . .] would after a time take the first step in cultivation by planting them near their usual abodes. [. . .] The next step in cultivation, and this would require but little forethought, would be to sow the seeds of useful plants.

These sentiments were echoed by a succession of other researchers (e.g. [Roth (1887); Peake and Fleure (1927); Peake (1928); Childe (1935); Cole (1959); Braidwood (1960)]) who were mostly concerned with identifying the crops which would have been easiest to domesticate, and the environmental and social conditions most conducive to such a leap. These theories uniformly relied on the twin assumptions that a) the payoffs from agriculture dominated those from hunting and gathering and b) ignorance of the relevant plant biology and cultivation techniques was all that prevented hunter-gatherers from becoming farmers. Both of these assumptions were roundly disproven in the 1960s, when systematic studies from anthropologists living with the last few hunter-gatherer populations found that their diet was superior (both in quantity and variety) to that of otherwise similar farming neighbors, and that their understanding of plant reproduction was sufficiently advanced to make basic farming a trivial endeavor ([Boserup (1965); Campbell (1965); Leec (1965); Jones (1969); Gould (1969)])). These findings were reinforced by the work of Neolithic archaeologists, whose excavations found that early farmers in fact worked more than their foraging ancestors and neighbors, and received less food in exchange ([Cohen and Armelagos (1984)])). The data suggested that typical hunter-gatherers enjoyed a standard of living far in excess of that available to pre-industrial farmers.

### 3.2 Population pressure

If agriculture was not such an attractive proposition after all, then perhaps our ancestors could have been forced into it. [Binford (1968)] and [Flannery (1969)] proposed that rising populations eventually forced our ancestors to farm in order to avoid (or delay) starvation. These models were criticized by Rindos, who stated:

> Any theory that calls for the [purposeful] invention of agricultural behavior requires either intermediate or long-term rewards. Long-term rewards can be
excluded by excluding precognition. Short-term rewards require the invention of more than one agricultural behavior at a time. \cite{Rindos1984}

In the context of overpopulation, this criticism reminds us that large social groupings faced with severely inadequate food supplies have usually been unable to invent new subsistence strategies on the fly, but have traditionally responded by dying in large numbers, until the population size was again in line with the resource base (Malthus 1798).

Alternatively, our ancestors may have been lured by the greater food abundance which farming promised, but could have seen these advances reversed by unexpected runaway population growth, itself a byproduct of the reduced growth spacing that sedentary life allowed. Jared Diamond accepted this “entrapment” mechanism, and (as mentioned earlier) argued that adopting agriculture was “The Worst Mistake in the History of the Human Race” \cite{Diamond1987}.

### 3.3 Social Factors

Other researchers have focused on human social organization as the triggering mechanism behind the Neolithic revolution. \cite{Hayden1990} proposed that agriculture may initially have been adopted for religious or ceremonial reasons. \cite{Acemoglu2012} proposed that hunters didn’t begin to grow crops of their own accord, but rather were forced to do so by their elites, which could expropriate food stored in granaries more easily than that gathered daily from dispersed locations. \cite{Hodder2012} argues that agriculture was in fact developed in response to a basic human need for greater social aggregation.

### 3.4 Climate

Agriculture was invented independently on multiple continents, at roughly the same time. Barring an extraordinary coincidence, this would suggest a common cause. But what could have prompted simultaneous innovation in populations separated by thousands of kilometers, and which had diverged from each other tens of thousands of years before?

Climate change provides on obvious answer: all documented cases of invention occurred after the end of the last Ice Age, which raised global temperature by approximately five degrees, completely transforming the environment of most locations on Earth. The exact triggering mechanism has depended on the domestication episode in question, and the researcher conducting the analysis. \cite{Wright2004} 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. \cite{Wright2004} 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, we must be mindful that different groups domesticated different plants, and that all of the plants eventually domesticated were living somewhere
Richerson et al. (2001) proposed that incipient development of agricultural techniques during the Ice Age might have been negated by the wide climatic fluctuations, which are known to have taken place throughout this period. In contrast, the Holocene was characterized by stable conditions, which would have allowed any attempts at farming to blossom and spread. Ashraf and Michalopoulos (2013) present a similar framework, in which too much unpredictable climatic variation erodes the usefulness of past farming advances, but too little variation reduces the incentives to innovate.

4 My Theory

Orbital parameters influence the amount of solar radiation reaching each latitude throughout the year, and are responsible for the regular variations in Earth’s climate (see Figure 4). Approximately 12,000 years ago, the orbital parameters were very different from today, or from those prevalent during the previous 100,000 years: axial tilt was close to its maximum value of 24.5°, orbital eccentricity was at a local maximum of 0.02, and the closest approach to the sun occurred during the Northern summer. Thus in July, the northern hemisphere would be both angled towards the Sun and was closer to it, while in December it would be tilted away, and further from it.

![Figure 4](image-url)

**Figure 4:** The conditions during the Ice Age, and during the Early Holocene (when the neolithic took place)

The change in orbital parameters had a profound and generalized effect on Earth’s climate. The increased axial tilt increased temperature seasonality in both hemispheres, with the impact being more marked at higher latitudes. In the Northern Hemisphere,
this effect was compounded by the fact that the point of closest approach to the sun (perihelion) corresponded to the season in which the hemisphere was tilted towards the sun (June Solstice).

The warm summers accelerated ice melt, which resulted in the retreat of glaciers in the Northern Hemisphere, and a generalized increase in global temperatures. Greater seasonality of solar radiation also strengthened the tropical monsoon, which increased precipitation seasonality in many tropical regions (Kutzbach et al. 1998).

4.1 Effect on human subsistence

All human foods are ultimately derived from photosynthesis, a process which requires both sufficient precipitation and warm temperatures to be productive. If either drought or frost hold back plant growth, both gathering of wild plants and hunting of herbivores will become difficult. Since precipitation and temperatures became more seasonal starting 12,000 years ago, it is likely that more humans than ever would have found it difficult to find food during part of the year. To some extent, these problems could be offset by increasing the distances travelled during their seasonal migrations. But in many areas the geographic correlation of weather patterns would have necessarily outstripped human locomotion capabilities, and hunger must have been a periodic scourge.

4.2 Incentives to store food

Faced with an abundant but discontinuous supply of food, storage would have provided an attractive way to smooth their consumption and avoid hunger during the season of scarcity (Testart 1982). This method would only have been practicable where hunter-gatherers had access to a food source that was both sufficiently concentrated and highly storable. Since food is heavy, intensive food storage would have in most cases have required the band to spend most of the year in the same location (first stocking their granaries, then drawing on them for sustenance).

4.3 Incentives to cultivate

Once a given population had chosen to subsist as sedentary storers, their incentives to start cultivating plants would have changed dramatically. First, sedentism would have allowed them to observe the effect of their actions on the environment throughout the year, affording them more opportunities to discover ways of increasing its productivity. Second, their survival would have depended almost exclusively on the amount of food available within a fairly short radius from their settlement. Third, the access to storage technology meant that any resulting surplus could aid the future survival of the population, rather than rot on the ground. In short, once a band of hunter-gatherers had become settled and had started storing, it would have already acquired several of the pre-requisites for a successful farming community, and the adoption of cultivation and food production could be expected to ensue relatively promptly.
4.4 Domestication and spread

The increasingly tight relationship between humans and the wild plants which they cultivated led to drastic changes in the selective pressures faced by seeds. Humans deliberately placed seeds at the optimal depth for germination, aggressively weeded their fields to remove competing, less palatable plants, and cleared forested areas to open entire new areas to cultivation. The precise changes which occurred are specific to each domestication event, but in general the size of edible parts increased and became easier to harvest and process (Harlan 1992); new varieties appeared, which were more tolerant of sub-optimal soil conditions and climate types; and the biological machinery responsible for seed dispersal was suppressed.

Over a period of thousand of years, all these changes had the effect of steadily increasing yields, independently of any progress to cultivation techniques. Crucially, humans with domesticated plants were able to colonize areas with quite different starting environments, and to transform large portions of them into functional replicas of their starting ecosystems.

Figure 5: Summary of proposed cause and effect relationships.

5 Model

5.1 Model summary

The main purpose of the model is to show how the incentives to adopt agriculture vary with two environmental parameters: the degree of seasonality in food availability, and the correlation in food availability in the ecosystems within migratory range of a nomadic group.
First, I describe the choice faced by a rational ban on the verge of adopting agriculture: it has concave preferences defined over food consumption, and has access to two separate locations, each of which provides varying amount of food across two seasons. The maximum amount of average food is consumed if the band decides to be nomadic, which allows it to access the most productive environment in each season. However, their mobility prevents them from storing food, so they are forced to endure any food scarcity they are exposed to. If the band decides to become sedentary, average food consumption will decrease, but the band will be able to store and completely smooth their consumption.

Second, I compute how the utility of the band is affected by changes in two environmental parameters: the degree of climatic seasonality, and the potential for geographic hedging. I show that environments with more seasonal food supplies will naturally prefer food storage, but access to suitable “refuge” environments will increase the attractiveness of nomadism.

Third, I show how reduced consumption seasonality increases fertility, and results in a higher population size in equilibrium.

5.2 Assumptions

The band has control over two locations, which I will refer to as Home $H$ and Refuge $R$. Each year is composed of two seasons, July ($J$ subscripts) and December ($D$ subscripts) \[4\] and each ecosystem provides a given amount of resources in each season, provided that the band is actually residing there at the time.

The unit agent of the model is the band, a small kin group, no larger than an extended family or clan, controlling a specific territory. The band has Cobb-Douglass utility defined over consumption per capita in each season:

\[
U = \ln(c_J) + \ln(c_D)
\]  

(1)

(2)

I normalize the amount of resources present in the Home location during July to 1, and specify the other endowments in relation to it. During December, the Home location has a lower endowment, of $h < 1$. The other location, Refuge, has a higher December endowment of $r$, $h > r > 1$, but it is lower in July. These relationships are summarized by the following equations:

\[4\] The months are used instead of the seasons to avoid notation confusion between variables relating to Summer and to Settlement.
The $\sigma$ parameter defines the base degree of seasonality of the environment, while $\gamma$ is the advantage that being nomadic confers to the band in December. This parameter is high when the resource endowments of the two ecosystems are only weakly correlated.

**Figure 6:** July consumption in the home environment is set to one, December consumption at home is lower by a factor of $0 < \sigma < 1$, while December consumption in the refuge environment is somewhere in between, due to imperfect correlation between the two ecosystems. The nomadic band is able to always reside in the environment with the highest endowment in each season, achieving consumption profile N.

### 5.3 Residence strategies and their utility

The band has two alternative strategies at its disposal. It can either be Nomadic, in which case it can always reside in whichever location offers the highest endowment in
each season, thus achieving consumption profile $C_N$; or it can be sedentary, in which case it must select one location to reside in year-round, but will be able to costlessly store food from one season to the next. In practice, the optimizing settled band will reside in the environment with the highest average endowment (Home), and will store food so as to completely smooth its consumption, thus achieving consumption profile $C_S$.

\[
C_N = (\max(E_{JH}, E_{JR}), \max(E_{DH}, E_{DR})) = (1, r)
\]

\[
C_S = \left(\frac{E_{JH} + E_{DH}}{2}, \frac{E_{JH} + E_{DR}}{2}\right) = \left(\frac{1 + h}{2}, \frac{1 + h}{2}\right)
\]

The population dynamic of the band is determined by its consumption profile, and specifically net fertility $\phi$ is a weighted average of consumption per capita in both seasons (per capita variables are given in lower case), with the weighting favoring consumption per capita in the scarcest period:

\[
\phi = \alpha \max(c_J, c_D) + (1 - \alpha) \min(c_S, c_D) \quad (8)
\]

\[
0 < \alpha < 0.5 \quad (9)
\]

If $\alpha$ were equal to 0, then fertility would be equal to the minimum of consumption per capita in both seasons, while if $\alpha$ were equal to 0.5, than 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.

Thus, to find the equilibrium level of population for nomads, $P_N^*$:

$$1 = \frac{\alpha \times 1 + (1 - \alpha)r}{P}$$  \hspace{1cm} (10)

$$P_N^* = \alpha + r - \alpha r$$  \hspace{1cm} (11)

When nomads are able to smooth consumption perfectly ($r = 1 \iff \sigma = 0$), equilibrium population and average consumption will both be 1, while higher levels of consumption seasonality will result in lower populations size and higher average consumption per capita.

The equilibrium consumption profile of Nomads is thus:

$$c_{JN}^* = \frac{1}{\alpha + r - \alpha r}$$  \hspace{1cm} (12)

$$c_{DN}^* = \frac{r}{\alpha + r - \alpha r}$$  \hspace{1cm} (13)

Which in turn implies an equilibrium utility level for nomads of:

$$U_N^* = \ln \left( \frac{1}{\alpha + r - \alpha r} \right) + \ln \left( \frac{r}{\alpha + r - \alpha r} \right)$$  \hspace{1cm} (14)

If the band is settled, its consumption per capita will be perfectly smooth, resulting in an equilibrium population, consumption profile and utility of:
\[ P_S^* = 1 \]  
\[ c_{JS}^* = 1 \]  
\[ c_{DS}^* = 1 \]  
\[ U_S^* = 0 \]

For agriculture to be developed in a given region, a significant number of its inhabitants must have decided to have 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.

We will first determine under what conditions Settlement is better than Nomadism in the long run. That is, we will compare the utility that individuals enjoy pursuing the two settlement strategies, once their populations have achieved equilibrium, and characterize the parameter space in which Settlement is optimal. To do so, we set \( U_S^* = U_N^* \) and solve for \( r \), thus obtaining the the threshold level of Winter endowment in the Refuge location:

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

This threshold condition can be expressed in terms of the seasonality parameter \( \sigma = 1 - r + \gamma \):

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

If seasonality is higher than this threshold, settlement will provide the highest utility for the band in the long run. I.e., Settlement is optimal when \( \sigma \) is high and \( \gamma \) is low.

We now analyze incentives faced by a Nomadic population in the short-run, before the population size will have had time to adjust. The relative utility enjoyed by the population under the two strategies will depend entirely on whether the loss in average consumption resulting from abandoning the Refuge environment will be compensated by the decrease in consumption seasonality which storage allows.

The utility of settlers in the short run \( U_{S-} \) can be written as:

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

For the nomadic band to be indifferent to switching in the short run, it must be true
that:

\[ U_{S_1} = U_{N_1} \]

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

We can 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

\[ h = -1 + 2\sqrt{\gamma} \]

In terms of \( \sigma \) and \( \gamma \), this threshold can be written as:

\[ \sigma = 2\sqrt{\gamma} \]

The long run and short run thresholds (equations 20 and 25) allow us to divide 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 9](image.png)

**Figure 9:** The four possible situations. For agriculture to be developed, settlement must be optimal both in the short and long run.

### 5.4 Predictions

We thus arrive at the following results:

- There exists a boundary seasonality \( \sigma^B \) and a boundary geographic correlation \( \gamma^B \) such that:
  - For any level of \( \sigma > \sigma^B \), there will exist a level of \( \gamma = \gamma^T \) below which nomadism is preferred in the long run, and above which settlement is preferred.
Figure 10: (i) When $s$ is low and $g$ is high, Nomadism is better than Settlement both in the short run and in the long run. (ii) When $s$ is high and $g$ is low, Settlement is better than Nomadism both in the short run and in the long run. (iii) Even if a high $s$ makes settlement better than nomadism in the long run, a sufficiently high $g$ can make settlement too costly in the short run. (iv) Even if a low $s$ makes settlement worse than nomadism in the long run, a very low $g$ can make lure a population into settlement with short term gains.

- For any level of $\sigma > \sigma^B$, there will exist a level of $\gamma = \gamma^T$ below which in the long run nomadism is preferred, and above which settlement is preferred.
- For any level of $\gamma < \gamma^B$, there will exist a level of $\sigma = \sigma^T$ below which in the long run nomadism is preferred, and above which settlement is preferred.
- For any level of $\gamma = \gamma^B$, there will exist a level of $\sigma = \sigma^T$ below which in the short run nomadism is preferred in the short run, and above which settlement is preferred.
- The higher $\gamma$ is, the higher $\sigma$ must be for agriculture to be adopted.
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 the boost in July endowment in the Home location, the threshold condition to adopt agriculture in the short run will be given by

$$U_{S-} = U_{N*}$$

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

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

**Figure 11:** If significant numbers of hunter-gatherers decide to become sedentary, eventually it will learn how cultivate the land. This will lead to an increase in the summer harvest, and a temporary increase in consumption per capita.

Substituting $r = 1 - \sigma$

$$\sigma = f + 2 \sqrt{\gamma - f}$$

For any given level of $\gamma$, a higher level of agricultural technology $f$ will result in a lower threshold value of seasonality $\sigma$ before settlement becomes optimal. Conversely, the higher the seasonality, the lower the level of agriculturally technology required before settlement becomes optimal.

Summarizing the results of the model, we can make the following predictions:

- Agriculture should appear in location with high seasonality.
- Agriculture should appear in location with high geographic correlation.
Figure 12: If the cultivation techniques and domesticated varieties are available to neighboring populations, eventually even nomadic populations with access to uncorrelated food sources will want to adopt.

- The transition from hunting and gathering to settlement should be associated with a decrease in consumption seasonality.
- The transition from hunting and gathering to settlement should be associated with a decrease in average consumption.

6 Evidence

6.1 Empirical Strategy

The ultimate purpose of this empirical section is to show that seasonality was the main driver of the multiple invention of agriculture. To this end, I will first show that climatic seasonality explains a significant amount of the variation in date adoption across different location, using a straightforward linear regression of the dataset, collapsed into a cross section. While this methodology does little to establish causality or the precise channel (greater likelihood of invention, or faster diffusion), the analysis confirms that seasonal locations indeed started farming earlier than otherwise similar locations, that this association is economically and statistically significant, and that it is robust to a variety of specifications.

Then, I will concentrate only on the process of invention, to show that agriculture originated from situations of truly exceptional climatic seasonality. Not only was agriculture invented in highly seasonal locations, but the timing of the invention itself coincides with one the most seasonal period in the recent climatic history of our planet. Taken together, these findings suggest that our ancestors which invented farming did so in response to what were almost certainly the most seasonal conditions that our species had ever experienced.
My next step is to concentrate on the subsequent process of diffusion. I construct a dataset consisting entirely of observations (time x space) that are within 500km of a population which has already begun to farm, inhabit a pleasant climate, and have yet to adopt agriculture. I use both discrete- and continuous-time duration models to track the spread of farming, and I find that more seasonal locations waited far less to adopt agriculture from their neighbors.

Finally, I replicate the most important steps of this analysis on a cross-section of 765 archaeological sites in Western Eurasia, with a much higher geographic and chronological resolution.

6.2 Data

6.2.1 Data on domestication

Data on domestication 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 dataset was coded as latitude, longitude and time of invention, with different dummy variables recognizing whether each location is one of the seven universally considered as having domesticate crops wholly independently, or as one of the seventeen for which opinion is divided. Even if agriculture in some of these seventeen cases was in fact inspired by neighboring farmers, each of these locations domesticated their own crops, and can therefore be considered as more enthusiastic adopters than locations which simply received crops and the associated cultivation techniques from their neighbors.

6.2.2 Data on global spread of agriculture (Putterman)

The previous dataset only 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, 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.
6.2.3 Data on Western Eurasia spread of agriculture (Pinhasi)

While the Puttermann dataset enables us to track the spread of agriculture on a global scale, the use of countries as a unit of analysis limits the ability to examine the diffusion of Neolithic technologies at the regional level. To obtain finer-grained data, I employ the dataset 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.

6.2.4 Panel Climate Data

The TraCE Dataset Hé (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. From this raw data I first constructed seasonal averages of precipitation and temperature for each season, in each cell, for each of 500 year period.

6.2.5 Cross-sectional Climate Data

While the TraCE data has the advantage of providing insight into past climates, 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.

While the use of present data is problematic when comparing outcomes in very distant regions far into the past, 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).

6.3 Variable construction

Mean Temperature is the average temperature in degrees Celsius across the four seasons, within a given 500 year period. Similarly, Mean Precipitation is the the average amount of rainfall in the four seasons, measured in mm per day. For temperature seasonality I use the difference in temperature between the coldest and warmest trimester of the year, replacing any below-zero temperature with zero (this is because once water has frozen,
colder temperatures have little further effect on food availability). For Precipitation Seasonality, I use the difference in rainfall between the wettest and driest quarter of the year, divided by the amount of precipitation in the average quarter.

Temperature Seasonality = max(SummerTemperature, 0) – max(WinterTemperature, 0)

Precipitation Seasonality = \frac{Precip.Wettest - Precip.Driest}{MeanPrecip.}

These two variables are aggregated into a Seasonality Index defined as

Seasonality Index = \max(Quantile(TemperatureSeasonality), Quantile(PrecipitationSeasonality))

That is, I map both measures to quantiles of their respective distributions, and take the maximum. The intuition behind this measure comes from "Liebig’s law of the minimum", which says that the total growth of plants will be limited mainly by the least favorable factor (Sinclair (1997)). In economic terms, the biomass production of an ecosystem can be modeled as a Leontief production function using water and temperature as inputs. Thus, even if rainfall is perfectly evenly distributed throughout the year, highly seasonal temperatures are sufficient to ensure seasonality in food consumption, and the same is true for seasonal rainfall and constant temperatures.

I also employ a climatic Means Index which combines average temperature and precipitation, using the minimum (since e.g. low average rainfall is enough to severely limit food availability in a given area).

Means Index = \min(Quantile(MeanTemperature), Quantile(MeanPrecipitation))

6.4 Results

6.4.1 Basic Linear Model

I begin my analysis by investigating whether seasonality can in fact explain a significant part of the observed variation in date of farming adoption, regardless of whether farming was independently invented or adopted from neighbors. Each observation is one 3.75 degree cell. The dependent variable is the date of adoption (expressed as a negative number of years before present), and my main explanatory variables are the degree of climatic seasonality, embodied either by Temperature and Precipitation seasonality separately, or by the Seasonality Index described previously. Each dependent variable is the sample average for the last 22,000 years of available data. Table I shows the summary statistics for this dataset:
Table 1: Summary statistics for the adoption cross-section dataset.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
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Figure 13 shows binned scatterplots of date of adoption against climatic means and climatic seasonality. The early adopters were unremarkable in their average climates, but were clearly highly seasonal.

Figure 13: Binned scatterplots of climatic variables vs date of adoption. Climatic means (top row) are weak predictors of the date of adoption. Conversely, highly seasonal locations adopted agriculture ahead of more stable locations.

The basic specifications are:
\[ YearAdop_i = \alpha + \beta_1 \text{TempDiff}_i + \beta_2 \text{PrectSeas}_i + \gamma \left[ \text{Controls} \right]_i + \epsilon_i \quad (30) \]

\[ YearAdop_i = \alpha + \beta_1 \text{SeasIndex}_i + \gamma \left[ \text{Controls} \right]_i + \epsilon_i \quad (31) \]

where observation \( i \) is a single geographic cell, and all regressors are time averages of respective variable for each cell, for the entire period for which data is available.

The results of this analysis are presented in Table 2, which reports beta coefficients. Both Temperature Difference and Precipitation Seasonality are associated with earlier adoption of agriculture. The effect is larger for temperature, but is statistically and economically significant for both factors. Specifically we expect that one extra standard deviation of Temperature Difference will result in agriculture appearing approximately 1500 years earlier than would otherwise have been the case. The corresponding effect for precipitation is 400 year per extra standard deviation of seasonality, while the Seasonality Index gives an intermediate value of 1000 years. The "Extra Controls" specified in the table are the squares of temperature Mean, precipitation Mean, and absolute latitude and dummy variable for the Americas.

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</table>

Standardized beta coefficients

* \( p < 0.1 \), ** \( p < 0.05 \), *** \( p < 0.01 \)

Table 2: Cross-section dataset. Linear regression of date of adoption on time-averaged climatic variable of each cell. Models 1-4: robust standard errors. Models 5-8: clustered errors (123 geographic neighborhoods)

All of these estimate are significant at the 1% level when using robust standard errors (specifications 1 through 4) and by clustering the standard errors using a grid of 123 local neighborhoods. Note that while the measures of seasonality preserve their significance, the same cannot be said of the climatic means and absolute latitude, which are insignificant in some of the specifications. 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.
6.4.2 Independent invention - Cross Section

I continue my analysis by checking whether the location where agriculture originated are in fact highly seasonal. The dependent variable is now a dummy that takes the value of 1 if agriculture was independently invented in a given location, and 0 otherwise, and I keep the same explanatory variables used in the previous analysis. The basic specification is now:

\[
\text{IndepInv}_i = \alpha + \beta_1 \text{TempDiff}_i + \beta_2 \text{PrectSeas}_i + \gamma [\text{Controls}]_i + \epsilon_i \tag{32}
\]

\[
\text{IndepInv}_i = \alpha + \beta_1 \text{SeasIndex}_i + \gamma [\text{Controls}]_i + \epsilon_i \tag{33}
\]

where observation \( i \) is a single geographic cell, and all regressors are time averages of respective variable for each cell, for the entire period for which data is available. The models is estimated through ordinary least squares.

The results of this analysis are presented in Table 3, which reports beta coefficients. Both Temperature Difference and Precipitation Seasonality are associated with a higher probability of inventing agriculture. The effect is larger for temperature, which is also the only one of the two which achieves statistical significance. Considering that the dataset is composed of 1029 zeros, and only 7 ones, this is not a particularly damning performance. I repeat the analysis using the expanded set of 24 domestication locations (the 7 certain independent inventions plus the 17 possible), and find that all measures of seasonality achieve at least 10% significance level. In this table, "GeoControls" refers to Absolute Latitude squared and the Americas dummy, while "Climate\(^2\)" are the squares of the climatic means.

<table>
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Table 3: Cross-section dataset. Linear regression of independent adoption dummy on time-averaged climatic variable of each cell. Clustered errors (123 geographic neighborhoods)

6.4.3 Independent Invention - Timing

I have so far shown that seasonality is associated with earlier appearance of farming (autonomously developed or not), and with a higher likelihood of inventions, but have
restricted myself to the cross-section. Before I tackle the full panel dataset, I will make some brief notes on the time-series element of this dataset.

As discussed in section 4, changes in the orbital parameters resulted in a marked increase in the seasonality of Earth’s climate, which peaked approximately 11,000 years ago. Figure [14] shows that this resulted in an increase in the number of seasonal locations present in the world.

Figure [14] shows the conditions prevalent during the last glacial maximum, during the Neolithic, and today. Seasonal locations were much more common at the height of the Neolithic, and the maps show that most of the independent invention locations were located precisely in these areas. The line plot shows how pleasant climates did not become particularly more common, while seasonal climates did.

In Figure [15] I disaggregate this information for the various measures of seasonality, and compare them to the independent inventions of agriculture, their timing, and their climates.

---

**Figure 14:** The three maps show the climatic conditions prevalent during the Last glacial maximum, in the middle of the period of invention, and today. Black: arctic and/or desert climates. Grey: hospitable climates. Blue: seasonal climates. Green symbols: locations of independent invention. The line plot shows the number of cells with pleasant, seasonal, and pleasant AND seasonal climates, together with the timing of the independent inventions.
Figure 15: The evolution through time of important climate variables, and the conditions and dates of the independent inventions. In each graph, the lines represent (from top to bottom) the 98th, 75th, 50th, and 25th percentile of all observations of a given time period. Green circles represent temperate adoptions (ca. 30 to 40N). Mean Temperature: the end of the Ice Age warmed the bottom end of the distribution, while leaving the top unaffected; agricultural inventions span the full range of average temperature above freezing. Mean Precipitation: very weak effect of the end of the Ice Age on the distribution of rainfall, agricultural inventions range from extremely dry to extremely wet. Mean Index: again, places with horrible climates became slightly more tolerable, but there was very little improvement in the sort of locations where agriculture was actually invented. Temperature Seasonality: the end of the Ice Age introduces climates of unprecedented temperature variability, three out of four temperate locations are above the 98th percentile of the Last Glacial Maximum. Precipitation Seasonality: the Ice Age brought a marked and persistent increase in the top percentiles of the distribution, with two out of three equatorial inventions occurring above the 75th percentile. The Seasonality Index shows that four of the seven independent adoptions are above the 75th percentile, and all but one are above the median.
Figure 16: While the detailed paleoclimatic reconstruction goes back only 22,000 years, in practice we can safely assume that seasonality had been low at least since 50,000 BP. The chart plots the number of seasonal cells against an aggregate measure of northern hemisphere insolation seasonality, as reconstructed from simulations of the past orbit of Earth. Despite the limited overlap, it is clear that the frequency of seasonal conditions tracks insolation seasonality.

6.4.4 Independent invention - Panel

I will now show that the same results observed in the cross-section also hold in the panel. The basic specification is:

\[
\text{Year Adopt}_{it} = \alpha + \beta_1 \text{TempDiff}_{it} + \beta_2 \text{PrectSeas}_{it} + \gamma \text{[Controls]}_{it} + \epsilon_{it} \quad (34)
\]

\[
\text{Year Adopt}_{it} = \alpha + \beta_1 \text{SeasIndex}_{it} + \gamma \text{[Controls]}_{it} + \epsilon_{it} \quad (35)
\]

Where observation \( it \) denotes location \( i \) during period \( t \). In Table 4, I use logistic regression to estimate the model, and I find that both temperature and precipitation seasonality are associated with an increased probability of adoption, though the relationship is significant only for temperature. The coefficient on the seasonality index is positive and significant, and the results are not materially altered by using robust standard errors or clustering using each location as its own cluster.

The same results can be observed by repeating the regression using only locations
which still haven’t adopted agriculture (Table 5).

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

Table 4: Panel dataset. Logit of independent adoption dummy on period- and cell-specific climatic variables. All observations Models 1, 3, 5: Robust standard errors. Models 2, 4, 6, 7, 8: clustered errors with all observations relating to same location as their own cluster.

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

Table 5: Duration model of independent adoption dummy on period- and cell-specific climatic variables. Locations dropped from sample after they adopt agriculture. Models 1, 3, 5: Robust standard errors. Models 2, 4, 6, 7, 8: clustered errors with all observations relating to same location as their own cluster.

6.4.5 Spread of agriculture - Discrete Panel Data

Having analyzed the factors influencing invention in some detail, I now turn my attention to the process of diffusion, which lead agriculture from a handful of isolated outposts to becoming lifestyle on Earth.

For this part of the analysis, I use a dataset constructed from the basic panel by dropping all observations that have either already adopted agriculture, that have inhospitable
climates at a specific point in time, or that are more than 500km away from a location which has already adopted agriculture. This sample represents the population which is "at risk" of adopting agriculture from their neighbors. Each observation enters the dataset when a neighbor develops farming, and has a series of zeros until the period in which it finally adopts (symbolized by a one), after which it is dropped from the sample. The basic specification is:

\[ Adoption_{it} = \alpha + \beta_1 \text{TempDiff}_{it} + \beta_2 \text{PrecipSeas}_{it} + \gamma \text{[Controls]}_{it} + \epsilon_{it} \]  

Where \( it \) is once again the observation describing geographic log action \( i \) at time \( t \). This model is first estimated using the logistic estimator (first two columns of Table 6, and then with the linear probability model (last two columns). In both cases I find that seasonality is associated with a higher probability of adopting agriculture from neighbors.

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<td>0.0226***</td>
<td>0.0390***</td>
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<tr>
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<td>(3.74)</td>
<td>(2.95)</td>
<td>(3.69)</td>
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<tr>
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<td>0.00464**</td>
<td></td>
</tr>
<tr>
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<td>(2.24)</td>
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<td>0.246***</td>
<td>0.0198</td>
</tr>
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<td>(-4.01)</td>
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<td>(0.17)</td>
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<td>1735</td>
<td>1735</td>
<td>1735</td>
</tr>
</tbody>
</table>

\* statistics in parentheses
\*\*\* p < 0.01, \*\* p < 0.05, \* p < 0.01

Table 6: Spread of agriculture. Neolithic frontier locations only. Regression of adoption dummy on climatic variables. Models 1 and 2: Logit with robust s.e. Models 3 and 4: linear regression with robust s.e.

### 6.4.6 Spread of agriculture - Cross-section

Finally, I check my results by using a continuous-time duration model, by collapsing the dataset to a cross-section, in which the dependent variable is the number of years that a given location remained exposed to farming neighbors, before adopting agriculture (i.e. the number of period multiplied by 500). All of the explanatory variable are, as before,
the time-average of their values for each cell. The general specification is:

$$AdopLag_i = \alpha + \beta_1 \text{TempDiff}_i + \beta_2 \text{PrecSeas}_i + \gamma [\text{Controls}]_i + \delta \text{Fixed Effect}_i + \epsilon_i$$ (37)

I use the least squares estimator with robust s.e. to estimate the parameters, and I find that high seasonality is associated with quicker adoption, regardless of the measure employed (Table 7).

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<tr>
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<td>-0.138**</td>
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<td>(0.208)</td>
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</table>

Standardized beta coefficients; Standard errors in parentheses

$^* p < 0.1, \; ^{**} p < 0.05, \; ^{***} p < 0.01$

Table 7: Spread of agriculture. Linear regression of time in frontier on climatic variables. All models: robust standard errors.

I also estimate a continuous time duration model with Weibul distribution, and plot the resulting survival curves for various specifications (Figure 17). An increase in temperature difference from 0°C to 25°C results in only half the probability of a population still relying on hunting and gathering 2000 years after first being exposed to farming techniques, with a similar reduction for a population going from a precipitation seasonality of 0 to 3.
6.5 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 presents 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 18 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 as the lower panel of Figure 18 shows, 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, that the most seasonal locations are the ones that invent agriculture.
Figure 18: 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. The locations with the earliest agriculture are not unique in their fertility, but are within the narrow intersection of areas that are both pleasant and seasonal.

This relationship is also apparent from the analysis of the raw data on the spread of farming techniques through the archaeological sites in the sample, and their date of adoption. As the scatterplots in Figure 21 show, the locations which adopted early were neither the warmest, nor the wettest. They instead possessed intermediate mean temperature, and low precipitation. The equivalent plots for climatic seasonality show the expected relationship: the earliest farmers were subject to wide annual swings both in seasonality and precipitation, while locations with stable climates adopted agriculture much later.
Figure 19: The relationship between timing of adoption and climate in the Pinhasi Dataset. Seasonality is at least as important as average climate in determining adoption.

The basic specification is the same that I used in the basic linear model of Section 6.4.1,

$$YearAdop_i = \alpha + \beta_1 \text{TempDiff}_i + \beta_2 \text{PrectSeas}_i + \gamma [Controls]_i + \delta \text{Fixed Effect}_i + \epsilon_i$$

The results are shown in Table 8 which shows that once again 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.
6.6 Geographic Heterogeneity

The analysis conducted so far have established that seasonality is strongly associated with the adoption of agriculture, and that the effect can be tracked separately by looking at the invention of agriculture, and its subsequent spread. 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 were known to grow wild, i.e. areas that were on a substantially equal footing in terms of domesticate availability. 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 temperatures, have different precipitation regimes, are likely to have slopes with different exposures to the sun, and will generally possess a variety of microclimates. In short they are highly unlikely to experience a single season in which food is unavailable in all locations.

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 be easily accessible to the nomad, but beyond the grasp of the settler. Locations with such a topography will create an incentive to remain nomadic. Finally at very large ranges the uncorrelated food sources will be beyond the migratory ability of even the most mobile nomads, and therefore irrelevant.

**Figure 20:** Locations at different elevations are more likely to have uncorrelated food sources (high g). If this variation occurs within a comfortable daily commuting radius (5km), both Summer and Winter food sources can be accessed from a single settlement. If the variation occurs at large radii, nomadism will be necessary. The two hills have similar amounts of variation within a 5km radius, but the one in the center has a lot more variation within 50km. The model predicts that the central hill will be settled later than the hill on the left.
Figure 21: Early adopters have a disproportionate amount of altitude range within settled foraging radius, while lower than average altitude range within nomadic foraging radius. At the extremes of nomadic migratory distance, the altitude range is similar to the average.
<table>
<thead>
<tr>
<th></th>
<th>(1) Years Ago</th>
<th>(2) Years Ago</th>
<th>(3) Years Ago</th>
<th>(4) Years Ago</th>
<th>(5) Years Ago</th>
<th>(6) Years Ago</th>
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<td>-0.829</td>
<td>-0.984*</td>
<td>-0.970*</td>
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<td></td>
<td>(0.442)</td>
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<td>0.518*</td>
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</table>

Table 9: Regression result for altitude range. Columns: (1) 250km from known cereals. (2) 100km from known cereals. (3) Only know cereals. (4) 100km with controls. Note lack of significance of climatic controls in this highly homogeneous environment. (5) 100km with controls and 200km radius altitude variation. Outside of comfortable migratory range, variation in altitude loose significance. (6) 100km with controls, alternate measures: average of r(3), r(5) and r(8), and average of r(50), r(75) and r(100).

7 Consumption Seasonality and Human Health

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
suggests that the adoption of agriculture was associated with lower average consumption, but higher seasonality in fat reserves.

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.

When faced with persistent malnourishment, fat reserves can only last for so long. Eventually, the body will either be able to reduce its energy requirements to fit the available resources, or death by starvation will ensue.

As discussed in the introduction, most of the locations for which data exist saw average consumption decrease when farming replaced nomadism. Achieved adult height is one of the most commonly used proxies for health, and as Figure 22 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, teeth wear, joint diseases due to overwork, and evidence of disease and infection. These are the findings that prompted Diamond to title his famous 1987 article “the worst mistake in the history of the human race”.

![Figure 22: 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.](image)

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 most 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 many 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 staple food.

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, the same catch-up growth process that erases the impact of starvation on final height 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 23).
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.

8 Robustness

Table 10 shows the results of running the same associative regression as in Section 6.4.1 but including fixed effects for geographic neighborhoods (the same grid previously used to cluster the standard errors). The inclusion of local fixed effect weakens the point estimates for the seasonality measures (now one standard deviation more seasonality results in approx. 400 years earlier adoption regardless of the measure being considered), but preserves significance. Again, clustering by geographic neighborhoods maintains the significance level of seasonality above accepted thresholds.
Table 10: Cross-section dataset. Linear regression of date of adoption on time-averaged climatic variable of each cell. Geographic neighborhood fixed effects. Models 1-4: robust standard errors. Models 5-8: clustered errors (123 geographic neighborhoods)

<table>
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<td>-0.185***</td>
<td>-0.121***</td>
<td>-0.185***</td>
<td>-0.121***</td>
<td></td>
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</tr>
<tr>
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<td>-0.180***</td>
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<td>-0.211***</td>
<td>-0.190***</td>
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<tr>
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<td>0.223**</td>
<td>0.223**</td>
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Table 11: Duration model with Rare Events correction of independent adoption dummy on period- and cell-specific climatic variables. Models 1,3,5: King-Zeng Rare Events standard errors. Models 2,4,6,7,8: clustered errors with all observations relating to same location as their own cluster.

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Table 9: Conclusion

During the Neolithic Revolution, apparently very different populations independently converged on settled agricultural life. These remarkably similar technological and social arrangement spread rapidly to neighboring populations, eventually supporting the life of the vast majority of humans. Plausible theories exist for the sequence of events observed for each independent adoption, but invariably these models conflict with the evidence from other locations.

53
I show that many of the most important unresolved questions on the Neolithic Revolution can be answered by taking into account how changes in climatic seasonality affected our ancestors’ incentives to become sedentary. I develop a model in which nomadic hunter-gatherers respond to increased resource seasonality by becoming sedentary and storing wild foods. In the process, their consumption per capita and consumption seasonality decreases, while their population size and utility increasing. Settlement greatly facilitates the development of cultivation techniques, setting off the development of ever more complex societies. Crucially, the transition is due only to an exogenous change in the incentives provided by the local climate; the utility, production and fertility functions of the agents are held constant.

Consistent with this theory, I find that agriculture was invented in some of the most seasonal locations in the world, during the most seasonal period of the last 100,000 years. The spread of farming techniques shows a similar pattern. Hunter-gatherers in more seasonal locations adopted agriculture more readily, once exposed to farming techniques developed elsewhere.

The combined result of these two effects was such that one standard deviation increase in consumption seasonality as associated with adopting agriculture 1,000 to 1,500 years sooner than would otherwise have been the case. This result is potentially compatible with a number of explanations, e.g. seasonal climates favor evolution of domesticable species. However, the storage-incentives pathway proposed in this paper also formulates predictions on the type of site topography which the first farmers would select, and the expected change in paleopathological markers. As predicted, I find that farming first appeared where the rewards to mobility were low, and that consumption seasonality decreased after agriculture was adopted.

The findings of this paper are relevant to a wide variety of economic literatures. In the field of long run growth, several recent contributions have demonstrated strong correlations between the timing of the Neolithic Revolution, and measures of development today and in the past (see Spolaore and Wacziarg (2012) for a review). My theory suggests that some of this effect might be due early adopters being more seasonal even today.

By modeling the effect of consumption seasonality on fertility, this paper contributes to the literature on Malthusian dynamics. Resource seasonality never ceased to be an important aspect of many human habitats, and storage technologies are necessarily imperfect. The same fertility-reducing fasting which Nomads suffered would also be present, anywhere high resource seasonality coexists with ineffective storage. The model predicts that such a population would have a smaller population, but higher consumption per capita.

Due to the greater speed of cultural transmission, most important innovations spread rapidly across the globe, precluding the possibility of multiple adoption. E.g.: from its British origins, knowledge of steam technology spread too rapidly to allow anybody else to invent it independently. Thus we cannot know which countries would have been the next to invent it, had they been afforded the time to do so. The uniqueness of the Neolithic Revolution lies in the fact that very similar technologies arose in very different
locations, allowing us to identify which factors are common to all.

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58


