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The Climatic Origins of the Neolithic Revolution: Theory and Evidence*

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Abstract

This research examines theoretically and empirically the origins of agriculture. The theory highlights the role of climatic sequences as a fundamental determinant of both technological sophistication and population density in a hunter-gatherer regime. It argues that foragers facing volatile environments were forced to take advantage of their productive endowments at a faster pace. Consequently, as long as climatic shocks preserved the possibility for agriculture, differences in the rate at which foragers were climatically propelled to exploit their habitat determined the comparative evolution of hunter-gatherer societies towards farming. The theory is tested using both cross-country and cross-archaeological site data on the emergence of farming. Consistent with the theory, the empirical analysis demonstrates that, conditional on biogeographic endowments, climatic volatility has a non-monotonic effect on the timing of the transition to agriculture. Farming was undertaken earlier in regions characterized by intermediate levels of climatic volatility, with regions subjected to either too high or too low intertemporal variability transiting later.

Keywords: Hunting and Gathering, Agriculture, Neolithic Revolution, Climatic Volatility, Technological Progress, Population Density.

JEL Classification Numbers: J10, O11, O13, O33, O40, Q54, Q55.

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1 Introduction

The impact of the transition from hunting and gathering to agriculture on the long-run economic transformation of mankind is perhaps only comparable to that of the Industrial Revolution. Hunting and gathering, a mode of subsistence that entails the collection of wild plants and the hunting of wild animals, prevailed through most of human history. The prehistoric transition from foraging to farming has been referred to as the Neolithic Revolution, a term that captures both the general period in history when the transition took place and the profound socioeconomic changes associated with it.

This research examines theoretically and empirically the origins of agriculture. The theory highlights the role of climatic sequences as a fundamental determinant of both technological sophistication and population density in a hunter-gatherer regime. It argues that foragers facing climatically volatile environments were forced to take advantage of their productive endowments at a faster pace. Consequently, as long as climatic shocks preserved the possibility for agriculture, differences in the rate at which foragers were climatically propelled to exploit their habitat determined the comparative evolution of hunting and gathering societies towards farming.[1]

The theory links the need for a more efficient exploitation of resources, instigated by climatic variability, to the observed increased investments of foragers in intermediate activities like tool assemblages, settlements, plant-interventionist practices, etc. It illustrates why earlier episodes of environmental stress in human history did not lead to farming, highlighting the importance of those climatic downturns in augmenting productive knowledge, relevant for agriculture, in hunter-gatherer societies. Focusing on both the short- and long-run impact of climatic stress on hunter-gatherer diets and subsistence patterns, via the gradual inclusion and, ultimately, the efficient exploitation of marginal and potentially domesticable species, the theory predicts that there need not be a tight coincidence of the transition to agriculture with a certain climatic event. In fact, the study identifies the heterogeneity of regional climatic sequences after the Last Glacial Maximum (LGM), dated around 19,000 Before Present (BP) as the fundamental source of the differential timing of agricultural transitions in various parts of the world. Under static climatic conditions, groups are not forced to take advantage of the productive potential of their respective habitats, and remain indefinitely in a hunter-gatherer regime. On the other hand, occurrences of extreme environmental stress (e.g., a return to semi-glacial or arid conditions), by eliminating the potential for farming, erode any accumulated human capital useful for agriculture, further delaying its adoption. This prediction is readily asserted by the distribution of contemporary hunter-gatherer societies, found either in areas hostile to agriculture, like the poles and deserts, or in rich coastal regions with little climatic variation (see, e.g., Keeley, 1995).

The proposed theory suggests that intermediate levels of intertemporal climatic volatility fostered the transition from foraging to sedentary agriculture, with regions characterized by either too high or too low volatility experiencing a late onset of farming. The framework can be easily modified to explain instances of adoption of agricultural practices via technological diffusion. To the extent that adopting a new technology, in this case becoming an agriculturalist, depends on preexisting levels of society-specific knowledge complementary to such practices, then populations residing along places characterized by intermediate levels of climatic volatility would be more likely to have accumulated knowledge that would facilitate the adoption

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[1] Indeed, the historical and archaeological record on the instances of pristine agricultural transitions, surveyed in detail in the appendix sections, emphasize the role of climatic changes in transforming hunter-gatherer activities.

of farming techniques once they become available. In this regard the theory may be falsified using data on the timing of the advent of agriculture across regions.

This is pursued in the empirical analysis that provides evidence demonstrating a robust hump-shaped relationship between the intertemporal variance of temperature and the timing of the Neolithic Revolution. Specifically, the analysis exploits cross-country variation in temperature volatility to explain the cross-country variation in the timing of agricultural transitions. Due to the unavailability of a worldwide prehistoric temperature data series, the analysis employs highly spatially disaggregated monthly data between 1900 and 2000 to construct country-level measures of the mean and standard deviation of temperature over the last century. The interpretation of the empirical results is, thus, based on the identifying assumption that the cross-country distribution of temperature volatility in the 20th century was not significantly different from that prior to the Neolithic Revolution. While this may appear to be a rather strong assumption, it is important to note that the spatial distribution of climatic factors is determined in large part by spatial differences in microgeographic characteristics, which remain fairly stationary within a given geological epoch, rather than by global temporal events (e.g., an ice age) that predominantly affect the worldwide temporal distribution of climate. Nevertheless, to partially relax the identifying assumption, the analysis also employs a new data series on historical temperatures between the years 1500 and 1900 (albeit for a smaller set of countries), and uncovers findings that are qualitatively similar to those revealed using temperature volatility of the last century.

Arguably, the ideal unit of analysis for examining the relationship between climatic endowments and the advent of farming would reside at the human settlement level rather than the country level. It is precisely along this dimension that the empirical analysis is augmented. Specifically, the analysis employs data on the timing of Neolithic settlements in Europe and the Middle East to explore the role of local, site-specific climatic sequences in shaping the transition to farming across reliably excavated and dated archaeological sites. Consistent with the predictions of the theory, and in line with the pattern uncovered in the cross-country sample, Neolithic sites endowed with intermediated levels of climatic volatility transited earlier into agriculture, conditional on local microgeographic characteristics. The recurrent finding that climatic volatility has had a non-monotonic impact on the emergence on farming, across countries and archaeological sites alike, sheds new light on the climatic origins of the Neolithic Revolution.

In revealing the climatic origins of the transition to agriculture, this research contributes to the literature on the long-run determinants of comparative economic development. The differential timing of the emergence of agriculture led to the early rise of civilizations and conferred a developmental head-start of thousands of years to early agriculturalists. Diamond (1997) argues that the surplus generated by the superior agricultural mode of production made possible the establishment of a non-producing class whose members were crucial for the rapid development of written language and science, and for the formation of cities, technology-based military powers and nation states. Interestingly, Olsson and Hibbs (2005) show that geography and biogeography may, in part, predict contemporary levels of economic development through the differential timing of the transition to agriculture, whereas Ashraf and Galor (2010) establish the Malthusian link from technological advancement to population growth, demonstrating the explanatory power of the timing of the Neolithic Revolution for population density in pre-industrial societies.

The archaeological evidence provided draws primarily from the Natufian culture of the Levant, the most extensively dated entity in the Near East (Bar-Yosef and Belfer-Cohen, 2000). The Natufians have been identified with the transformation from mobile foragers to a predominantly sedentary culture involved in cultivation, the domestication of plants and animals, and herding. The earliest recorded evidence of domestication comes from Abu Hureyra, a Late Natufian site on the Euphrates in Northwest Syria, where morphologically domesticated rye seeds first appear in the archaeological record at 12,700 BP. Detailed evidence on the Natufians and archaic foraging cultures in New Guinea and North Central China as well as contemporary hunter-gatherer societies is provided in Appendix A. Appendix B relates the predictions of the theory with other known instances of pristine agricultural transition as well as cases of foraging cultures associated with non-transitions.

The rest of the paper is organized as follows. Section 2 briefly reviews the related literature. The main elements of the proposed theory are summarized in Section 3. Section 4 covers the basic structure of the model. Sections 5 and 6 discuss the time-path of macroeconomic variables and the dynamical system respectively, whereas Section 7 analyzes various scenarios of climatic sequences and their effect on the transition from foraging to farming. Section 8 presents the empirical findings at the cross-country and cross-archaeological site levels, and, finally, Section 9 concludes.

2 Related Literature

The Neolithic Revolution has been a long-standing subject of active research for archaeologists, historians and anthropologists, recently receiving an increasing attention from economists. The present study falls in the general rubric of the long-run growth literature that investigates the interaction between economic and demographic variables in the transition from stagnation to growth (e.g., Galor and Weil, 1999; Galor and Weil, 2000; Galor and Moav, 2002; Hansen and Prescott, 2002; Lucas, 2002; Lagerlöf, 2003; Galor and Michalopoulos, 2006; Ashraf and Galor, 2007; Strulik and Weisdorf, 2008). Despite their long-run perspective, however, these papers focus primarily on the transition from agriculture to industry as opposed to the rise of agriculture itself. Nonetheless, a growing body of literature within economics has emerged to explain the Neolithic transition from foraging to farming. The following review is not meant to be exhaustive and is only indicative of hypotheses advanced by economists.[2]

Early work by Smith (1975) examined the overkill hypothesis whereby the Pleistocene extinction of large mammals, as a consequence of excessive hunting, led to the rise of agriculture. According to his analysis, increased hunting efficiency eventually resulted in lowering the growth rate of hunted biomass and, therefore, reduced the returns to labor in hunting and promoted the adoption of farming. North and Thomas (1977), in pioneering the institutional view, argue that population pressure coupled with the shift from common to exclusive communal property rights altered rational incentive structures sufficiently to foster technological progress with regard to domestication and cultivation techniques. Locay (1989), however, suggests that population growth, due to excessive hunting, resulted in smaller land-holdings per household inducing a more sedentary lifestyle, favoring farming over foraging.

More recently, Marceau and Myers (2006) provide a model of coalition formation where at low levels of technology a grand coalition of foragers prevents the over-exploitation of resources. Once technology reaches a critical level, however, the cooperative structure breaks down and ultimately leads to a food crisis that, along with technological growth, paves the way to agriculture. In other recent work, Weisdorf (2003) proposes that the emergence of non-food specialists played a critical role in the transition to agriculture by releasing labor from food-generating activities. Olsson (2001), on the other hand, theoretically revives Dia-

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[2] See Pryor (1983) and Weisdorf (2005) for a comprehensive survey.

mond's (1997) argument that regional geographic and biogeographic endowments, regarding the availability of domesticable species, made agriculture feasible only in certain parts of the world. Finally, Baker (2008) develops and estimates a model of the transition to agriculture using cross-cultural data on the incidence of farming and finds that cultures located further from pristine centers of agricultural transition experienced a later onset of farming. A similar result is uncovered by the empirical analysis in this study where distance from the Neolithic frontier is found to have a negative impact on the timing of the transition to agriculture both across countries and across Neolithic sites.

Despite the varied contributions of the economics literature in explaining the Neolithic Revolution, population pressure, in most cases, is the ultimate driving force behind the transition to agriculture. Building on the ideas of Boserup (1965), who proposed that a growing population provided the impetus for the development of intensive agriculture, archaeologists (e.g., Binford, 1968; Flannery, 1973; Cohen, 1977) have long argued that hunter-gatherer economies continually evolved to accommodate exogenously growing populations, with the ever-expanding need for increased food supplies eventually leading to the adoption of farming. Others, however, maintain that population pressure alone could not have played a critical role since there is no archaeological evidence of food crises prior to the development of agriculture (see, e.g., Harlan, 1995; Mithen, 1999). This has led to the formation of theories that attribute the Neolithic Revolution to environmental factors as well. In this view, hunter-gatherer communities maintain a constant population size over time unless disturbed by environmental shocks, implying that the adoption of agriculture must have taken place as a result of unusual climatic changes in the early Holocene (Byrne, 1987; Bar-Yosef and Belfer-Cohen, 1992).

In taking the position that environmentally triggered population pressure was crucial for the transition to agriculture, this study is related to recent work by Dow et al. (2009). According to their analysis, an abrupt climatic reversal (the Younger Dryas) forced migration into a few ecologically favorable locations. The resultant increase in local populations reduced the returns to labor in foraging at these sites, making agriculture more attractive in the short-run. In principle, their approach is complementary to that pursued in this research. However, the proposed unified theory, by explicitly identifying the *short- and long-run* impacts of climatic volatility on hunter-gatherer subsistence strategies, is more consistent with the current consensus among historians and archaeologists that the transition to agriculture, rather than being an abrupt event as suggested by Dow et al., was in fact a process that unfolded over several millennia (see, e.g., Tanno and Willcox, 2006; Balter, 2007).

3 Elements of the Proposed Theory

Before presenting the model formally, it is useful to briefly review the main elements of the proposed theory and their interactions in transforming the hunter-gatherer regime towards the transition to agriculture. As illustrated in Figure 1, mild increases in environmental stress is associated with a higher risk of acquiring resources. This instigates hunter-gatherers to change their food acquisition patterns, necessitating the development of novel food extraction and processing techniques.[3] These are accommodated by an increased investment in intermediate activities such as tool making, plant management practices, or the building of a more sedentary infrastructure.

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[3] Changes in food acquisition patterns encompass both the inclusion of new species in the diet (the so-called Broad Spectrum Revolution), as well as increases in the efficiency with which currently exploited species are obtained.

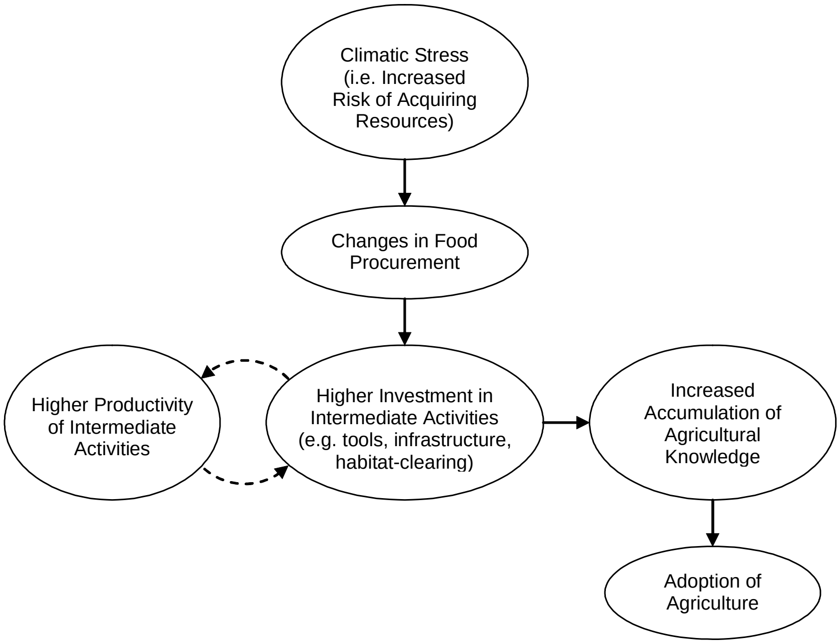

Figure 1: Elements of the Proposed Theory

The aforementioned increase in intermediate investment increases knowledge regarding the collection and processing of resources. As such, a climatically-induced temporary expansion in intermediate investments results in a permanently higher productivity of such practices for subsequent generations. This provides a novel mechanism for mild climatic stress to confer a "rachet" effect on intermediate investments. To the extent that such investments lead to the intensive foraging of domesticable flora, intrinsic agricultural knowledge accumulates and brings hunter-gatherer societies closer to an agricultural transition.

Appendix A examines evidence provided by archaeologists, paleoclimatologists and ethnographers that lends direct support to the building blocks of the proposed theory. The paper now proceeds to a formal exposition of how the short- and long-run interplay among environmental conditions, investments in intermediate technologies, and population densities transformed the foraging regime and led to the emergence of agriculture.

4 The Basic Structure of the Model

Consider an overlapping-generations economy in which economic activity extends over infinite discrete time. In every period t, the economy produces a single homogeneous final good (i.e., food) using land and labor as inputs in two possible production technologies: hunter-gatherer (denoted as sector h) and agriculture (denoted as sector g). Labor is allocated between intermediate activities (e.g., tool-making, investments in building infrastructure, habitat-clearing, etc.) and physical activities that are associated directly with production of the final good. The supply of land is exogenous and fixed over time. It is assumed to be a scarce factor for foraging purposes, leading to diminishing returns to labor in the hunter-gatherer sector.[4]

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[4] To simplify the analysis, land is considered to be in abundance for farming purposes, leading to constant returns to labor in the agricultural sector.

Labor in each period is supplied inelastically by households, and grows at the endogenously determined rate of population growth.

4.1 Intermediate Goods and Physical Labor

Intermediate goods (e.g., tools, dwellings, cleared habitats, etc.) are produced by combining natural resources (such as bones, wood, and lithic material) with pure labor. They are employed in the extraction and processing of food in both sectors, and are assumed to depreciate fully every period. The aggregate production of intermediate goods at time t in sector $i \in \{h, g\}$, B_t^i, is given by

$$B_t^i = \lambda s_t^i L_t^i, \tag{1}$$

where $\lambda > 0$ is a productivity parameter gauging the quality and quantity of available raw materials, and is fixed over time; $s_t^i \in [0, 1]$ is the fraction of total labor in sector i allocated to intermediate activities; and L_t^i is total labor employed in sector i at time t. The level of intermediate goods per worker is, therefore,

$$b_t^i \equiv \frac{B_t^i}{L_t^i} = \lambda s_t^i. \tag{2}$$

Physical labor in sector i at time t is total labor employed in sector i net of that allocated to intermediate activities. Thus, the amount of physical labor in sector i at time t is $(1 - s_t^i)L_t^i$. In the hunter-gatherer sector, physical labor may be regarded as time spent on foraging and mobility (i.e., moving from one temporary habitat to another as part of the subsistence strategy). Physical labor in the agricultural sector should analogously be regarded as time expended on farming. The aggregate labor force in the economy at time t, L_t, is the sum of total labor employed in all sectors at time t, i.e., $L_t \equiv L_t^h + L_t^g$.

4.2 The Production of Final Output

Production of final output in both hunter-gatherer and agricultural sectors occurs according to constant-returns-to-scale technologies subject to erosion by the prevailing degree of climatic stress. In early stages of development, the agricultural sector remains latent and production is conducted using only the hunter-gatherer production technology. However, in the process of development, adverse environmental fluctuations induce the growth of agricultural productivity (or embodied knowledge of agriculture), which eventually makes agriculture economically viable.

Let $e_t \in [0, 1]$ denote the degree of environmental harshness relative to the LGM with $e_t = 1$ at glacial conditions.[5] The output produced at time t in the hunter-gatherer sector, Y_t^h, is subject to a Constant Elasticity of Substitution (CES) production function given by[6]

$$Y_t^h = \max\left\{0,\ \left(1 - \frac{e_t}{B_t^h / \left(1 - s_t^h\right) L_t^h}\right)\left(\left[\left(\zeta_t B_t^h\right)^{\rho} + \left(\left(1 - s_t^h\right) L_t^h\right)^{\rho}\right]^{\frac{1}{\rho}}\right)^{\alpha} X^{1-\alpha}\right\}, \tag{3}$$

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[5] Note that $e_t = 1$ may equivalently represent the degree of environmental harshness under extreme aridity.

[6] The use of a CES production function is necessary to elucidate how an improvement in the productivity of intermediate goods affects the allocation of labor between intermediate activities and physical activities associated directly with the production of final output.

where X is land employed in foraging, which for simplicity is normalized to 1; ζ_t is the productivity of intermediate goods at time t; $\alpha \in (0,1)$; and $\rho \in (0,1)$ is the degree of substitutability between physical labor and intermediate goods.[7] The productivity of intermediate goods represents knowledge or specific human capital (or "taste" for food) passed through from previous generations regarding the application of intermediate goods in the extraction of resources and, analytically, captures the relative productivity of intermediate goods (versus physical labor) in the production process.

The hunter-gatherer production technology specified above explicitly allows environmental stress to be mitigated by increasing the amount of intermediate goods per forager. Specifically, the quantity $B_t^h/(1 - s_t^h)L_t^h$ in (3) measures intermediate goods per unit of foraging time. This mitigation mechanism is based on the notion that a given set of intermediate goods confers access to a certain dietary spectrum, whose expansion or more efficient use alleviates a deterioration of the environment.[8]

There are no property rights over land (i.e., the return to land is zero). Hence, the return per hunter-gatherer is equal to the average product of labor employed in that sector. Output per hunter-gatherer at time t, y_t^h, is

$$y_t^h \equiv \frac{Y_t^h}{L_t^h} = \max\left\{0, \quad \left(1 - \frac{e_t}{\lambda s_t^h / \left(1 - s_t^h\right)}\right) \left[\left(\zeta_t \lambda s_t^h\right)^\rho + \left(1 - s_t^h\right)^\rho\right]^{\frac{\alpha}{\rho}} \left(L_t^h\right)^{\alpha - 1}\right\}. \tag{4}$$

In the agricultural production technology, the adverse impact of the environment may not be alleviated and land is not a scarce factor in the production function.[9] Let $\bar{e}$ denote the level of environmental harshness beyond which environmental conditions render farming impossible. The output produced at time t in the agricultural sector, Y_t^g, is

$$Y_t^g = \begin{cases} A_t \left(1 - e_t\right) \left(B_t^g\right)^\beta \left(\left(1 - s_t^g\right) L_t^g\right)^{1-\beta} & \text{if} \quad e_t \in [0, \bar{e}) \\ 0 & \text{if} \quad e_t \in [\bar{e}, 1], \end{cases} \tag{5}$$

where A_t represents the TFP-augmenting agricultural technology at time t; and $\beta \in (0,1)$. Since land is not a binding factor in agricultural production, this implies constant returns to labor.[10] Hence, given the environment, e_t, and the size of the aggregate labor force, L_t, the agricultural sector will remain latent for a sufficiently low value of A_t. When agriculture is exercised, however, the return per farmer at time t is equal to the average product of labor employed in that sector at time t. Output per farmer at time t, y_t^g, is

$$y_t^g \equiv \frac{Y_t^g}{L_t^g} = \begin{cases} A_t \left(1 - e_t\right) \left(\lambda s_t^g\right)^\beta \left(1 - s_t^g\right)^{1-\beta} & \text{if} \quad e_t \in [0, \bar{e}) \\ 0 & \text{if} \quad e_t \in [\bar{e}, 1]. \end{cases} \tag{6}$$

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[7] Intermediate goods and physical labor are therefore imperfect substitutes in the hunter-gatherer production technology with a constant elasticity of substitution, $1/(1 - \rho)$, that is greater than unity.

[8] It is assumed that the development of new methods required to gain access to unexploited resources is independent of the stock of knowledge pertaining to the extraction of those already being exploited. Thus, intermediate goods productivity plays no role in alleviating the environmental erosion of output in the hunter-gatherer sector. This assumption is ultimately imposed to maintain expositional simplicity. In fact, when the productivity of intermediate goods is allowed to mitigate environmental erosion, the main results are qualitatively unaffected, given a sufficiently high elasticity of substitution between intermediate goods and physical labor.

[9] The absence of a mitigation mechanism in agriculture implies that climatic stress is biased in favor of hunting and gathering. This assumption is consistent with Richerson et al.'s (2001) main observation.

[10] This assumption has been widely used in the relevant literature to characterize an emergent agricultural sector where, at least in the beginning, land was abundant for farming purposes.

The agricultural production function is subject to endogenous technological progress both while agriculture is latent and when it is operative.

4.3 Labor Allocation in the Production Process

In every period t, individuals in each sector i choose the allocation of their labor between intermediate and final production activities, s_t^i, so as to maximize final output in that sector, taking into account the prevailing degree of environmental stress, e_t. The labor allocation problem for a hunter-gatherer at time t therefore reads as follows:[11]

$$s_t^{h*} = \underset{s_t^h}{argmax} \left\{ \left(1 - \frac{e_t}{\lambda s_t^h / \left(1 - s_t^h \right)} \right) \left[\left(\zeta_t \lambda s_t^h \right)^{\rho} + \left(1 - s_t^h \right)^{\rho} \right]^{\frac{\alpha}{\rho}} \left(L_t^h \right)^{\alpha - 1} \right\}, \tag{7}$$

subject to

$$0 \leq s_t^h \leq 1.$$

It follows directly from (4) that a small enough allocation of labor to intermediate activities would, in fact, make hunter-gatherer output negative.

The following set of assumptions is sufficient to guarantee positive output in the hunter-gatherer sector for all levels of climatic erosion. Moreover, when output is positive, environmental stress is also partially mitigated by the quantity of intermediate goods per forager at any level of e_t.[12]

$$\begin{array}{l} s_t^h \geq \frac{1}{1+\lambda}; \\ \zeta_t < \lambda^{-\frac{1}{\rho}}. \end{array} \tag{A1}$$

Lemma 1 (The Properties of s_t^{h*}) *Under (A1), the optimal allocation of labor to intermediate activities in the hunter-gatherer sector at time t is a unique single-valued function of the degree of environmental harshness and the productivity of intermediate goods at time t, i.e.,*[13]

$$s_t^{h*} = s^h(e_t, \zeta_t), \tag{8}$$

and is

1. *a monotonically increasing function of the degree of environmental harshness at time t, i.e.,*

$$\frac{\partial s^h \left(e_t, \zeta_t \right)}{\partial e_t} > 0;$$

2. *a monotonically increasing function of the productivity of intermediate goods at time t, i.e.,*

$$\frac{\partial s^h \left(e_t, \zeta_t \right)}{\partial \zeta_t} > 0.$$

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[11] The productivity of intermediate goods is not a choice variable for hunter-gatherers. However, as will become evident, it is endogenous to the climatic stress experienced by previous generations of hunter-gatherers.

[12] These conditions also suffice to ensure that the objective function in (7) is strictly concave. See Appendix C for details.

[13] For simplicity, we abstract from the comparative static effects of natural resources, λ, throughout the analysis.

Proof. Follows from the optimality conditions of (7) and the *Implicit Function Theorem*. See Appendix C for details. ■

According to Lemma 1, an increase in the degree of environmental stress induces hunter-gatherers to optimally allocate a larger fraction of their labor to intermediate activities. This consequently leads to a larger aggregate set of intermediate goods used in foraging, which occurs precisely because an increase in the amount of intermediate goods per forager helps dissipate the adverse effects of a deteriorating climate. Such an increase in the stock of intermediate goods implicitly corresponds to a proportionate increase in the breadth of the dietary spectrum exploited by the hunter-gatherers facing a harsher environment relative to that of their ancestors.[14] Lemma 1 shows that the optimal allocation of labor to intermediate activities in the hunter-gatherer sector also increases with the productivity of intermediate goods, ζ_t. This arises from the gross substitutability between intermediate goods and physical labor (or hunter-gatherer mobility) in the production technology, which implies that an increase in the productivity of intermediate goods will induce foragers to optimally reallocate their labor away from direct foraging towards augmenting the stock of intermediate goods.[15]

Let y_t^{i*} denote the maximal level of output per adult in sector i. Lemma 1 implies that maximal output in the hunter-gatherer sector is implicitly defined by a unique single-valued function of the degree of environmental harshness, e_t, the productivity of intermediate goods, ζ_t, and the size of the total labor force employed in this sector, L_t^h, so that

$$y_t^{h*} = y^h(e_t, \zeta_t, L_t^h). \tag{9}$$

Lemma 2 (The Properties of y_t^{h*}) *Under (A1), the maximal output per hunter-gatherer at time t is*

1. *a monotonically decreasing, strictly convex function of the degree of environmental harshness at time t, i.e.,*
$$\frac{\partial y^h\left(e_t, \zeta_t, L_t^h\right)}{\partial e_t} < 0 \text{ and } \frac{\partial^2 y^h\left(e_t, \zeta_t, L_t^h\right)}{\left(\partial e_t\right)^2} > 0;$$
2. *a monotonically increasing function of the productivity of intermediate goods at time t, i.e.,*
$$\frac{\partial y^h\left(e_t, \zeta_t, L_t^h\right)}{\partial \zeta_t} > 0;$$
3. *a monotonically decreasing, strictly convex function of the size of the labor force in that sector at time t, i.e.,*
$$\frac{\partial y^h\left(e_t, \zeta_t, L_t^h\right)}{\partial L_t^h} < 0 \text{ and } \frac{\partial^2 y^h\left(e_t, \zeta_t, L_t^h\right)}{\left(\partial L_t^h\right)^2} > 0.$$

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[14] The increased allocation of labor towards intermediate activities may also occur in the absence of dietary expansion. This is consistent with a climatically driven need for the more efficient procurement of the existing resource base, which shrinks under climatic stress.

[15] Alternatively, if the productivity of intermediate goods, ζ_t, were allowed to alleviate the environmental erosion of hunter-gatherer output, it would generate an additional marginal effect on the optimal allocation of labor to intermediate activities. In this case, given the prevailing harshness of the environment, a higher intermediate goods productivity would imply that the degree of mitigation could be maintained by a *lower* allocation of labor to intermediate activities. The "mitigation effect" and the "gross substitutability effect" would therefore work in opposite directions, with the former dominating the latter at low values (and vice versa at high values) of ζ_t. Nonetheless, the results of the model remain intact given a sufficiently large value of $\rho \in (0, 1)$, which makes the gross substitutability effect unambiguously dominant at all values of ζ_t.

Although unexplored by the model, a similar intuition applies for the comparative statics with respect to λ.

Proof. Follows from the production function, Lemma 1 and applications of the *Envelope Theorem* and the *Implicit Function Theorem*. See Appendix C for details. ■

The corresponding analysis for the optimal allocation of labor to intermediate activities in the agricultural sector is straightforward due to the Cobb-Douglas nature of the production technology, and the fact that the adverse effect of the environment on agricultural output cannot be mitigated. The labor allocation problem for a worker in the agricultural sector at time t, given $e_t \in [0, \bar{e})$, reads

$$s_t^{g*} = \underset{s_t^g}{argmax} \left\{ A_t \left(1 - e_t\right) \left(\lambda s_t^g\right)^{\beta} \left(1 - s_t^g\right)^{1-\beta} \right\}, \tag{10}$$

subject to

$$0 \leq s_t^{g*} \leq 1.$$

It is easy to show that the output-maximizing allocation of agricultural labor to intermediate activities at time t is β, whereas $1 - \beta$ is devoted to physical activities. Note that, unlike the hunter-gatherer sector, the optimal allocation of labor to intermediate activities in agriculture is independent of the degree of environmental harshness. Therefore,

$$s_t^{g*} = \beta, \tag{11}$$

which implies that the maximal output per worker in the agricultural sector is

$$y_t^{g*} \equiv y^g\left(e_t, A_t\right) = \begin{cases} A_t \left(1 - e_t\right) \left(\lambda \beta\right)^{\beta} \left(1 - \beta\right)^{1-\beta} & \text{if} \quad e_t \in [0, \bar{e}) \\ 0 & \text{if} \quad e_t \in [\bar{e}, 1]. \end{cases} \tag{12}$$

Given $e_t \in [0, \bar{e})$, it follows trivially from (12) that the maximal agricultural output per worker is monotonically decreasing in the degree of environmental harshness, and monotonically increasing in the level of agricultural productivity, A_t.

It remains to be shown how sectoral employment is determined in the model. Noting (8) and (11), the optimal allocation between intermediate and physical activities *within* each sector is independent of the fraction of the total labor force employed in that sector. Thus, the problem of allocating the total labor force at time t, L_t, *across* the two sectors is determined entirely by the average products of labor (returns to labor) in the two sectors at time t. Denote by L_t^{h*} and L_t^{g*} the equilibrium levels of employment in the hunter-gather and agricultural sectors in period t.

Proposition 1 *Given e_t, ζ_t, A_t and L_t such that $y^h(e_t, \zeta_t, L_t) < y^g(e_t, A_t)$, equilibrium employment in each sector at time t is determined by $y^h(e_t, \zeta_t, L_t^{h*}) = y^g(e_t, A_t)$ with L_t^{h*} workers in the hunter-gatherer sector and $L_t^{g*} = L_t - L_t^{h*}$ workers in the agricultural sector. Otherwise, i.e., if $y^h(e_t, \zeta_t, L_t) > y^g(e_t, A_t)$, the total labor force is employed in the hunter-gatherer sector, i.e., $L_t^{h*} = L_t$.*

Proof. Follows from the perfectly competitive nature of the economy, i.e., the absence of barriers to labor mobility, which guarantees the equalization of the returns to labor across sectors. ■

4.4 Preferences and Constraints

A generation consisting of L_t identical individuals joins the labor force in each period t. Each individual has a single parent and lives for two periods. In the first period of life (childhood), $t \square 1$, individuals are economically inactive, requiring parental care. In the second period (adulthood), t, individuals are endowed with one unit of time, which they supply inelastically as labor to the relevant sector. Child-rearing is costly, involving a fraction p of parental income per child. Members of generation t (i.e., the adult individuals in period t) choose the optimal quantity of children and allocate their earnings between child-rearing and consumption.

The preferences of members of generation t are defined over consumption above a subsistence level $\tilde{c}$, as well as over the number of their children. They are represented by the utility function

$$u_t = (1 \square \quad) \ln (c_t) + \quad \ln (n_t) , \tag{13}$$

where c_t is the consumption of an individual of generation t; n_t is the number of offspring; and $\quad \in (0, 1)$.

Income for a member of generation t, y_t, is the amount earned from supplying labor to the sector offering the higher wage rate, i.e., $y_t = \max\{y^h(e_t, \zeta_t, L_t), y^g(e_t, A_t)\}$. Earnings are divided between expenditures on child-rearing and consumption, c_t. Hence, the budget constraint faced by an individual in the second period of life reads as follows:

$$y_t p n_t + c_t \leq y_t. \tag{14}$$

4.5 Optimization

Members of generation t choose the number of children, and therefore their own consumption, so as to maximize the utility function subject to the budget and the subsistence consumption constraints. Substituting (14) into (13), the optimization problem for a member of generation t reads

$$n_t^* = \underset{n_t}{argmax} \{(1 \square \quad) \ln (y_t(1 \square p n_t)) + \quad \ln (n_t)\} , \tag{15}$$

subject to

$$\begin{aligned} & y_t(1 \square p n_t^*) \geq \tilde{c}; \\ & n_t^* \geq 0. \end{aligned}$$

The optimization implies that, as long as income is sufficiently high so as to ensure that $c_t > \tilde{c}$, a constant fraction $\quad$ of individual t's income is spent on child-rearing, whereas $1 \square \quad$ is the fraction of income devoted to consumption. However, at low levels of income, the subsistence consumption constraint binds. The individual consumes at the subsistence level $\tilde{c}$, and uses the remainder of his income for rearing children. Let $\tilde{y}$ be the threshold level of income at which the subsistence consumption constraint is just binding; i.e., $\tilde{y} \equiv \tilde{c}/(1 \square \quad)$. It follows that for $y_t \geq \tilde{c}$,

$$n_t^* \equiv n_t (y_t) = \begin{cases} \quad /p & \text{if} \quad y_t \geq \tilde{y} \\ (1 \square [\tilde{c}/y_t]) /p & \text{if} \quad y_t \leq \tilde{y}. \end{cases} \tag{16}$$

As long as the wage income for a member of generation t, y_t, is below $\tilde{y}$, subsistence consumption will only be ensured by devoting a fraction of income larger than $1 -$ to consumption. Moreover, as y_t increases (but remains below $\tilde{y}$), the individual will be able to maintain subsistence with a smaller fraction of income allocated to consumption, which, in turn, increases the income available for rearing children. Thus, in a regime where potential income is always below $\tilde{y}$ but above $\tilde{c}$, consumption remains at subsistence and fertility behaves like a normal good.

Since the period being analyzed is characterized by both subsistence consumption and a positive income elasticity of demand for children, the following assumption ensures that the economy captures these Malthusian attributes both in the hunter-gatherer and agricultural sectors:

$$\tilde{c} \leq y_t \leq \tilde{y}. \tag{A2}$$

5 The Time-Path of Macroeconomic Variables

5.1 The Dynamics of the Productivity of Intermediate Goods

This section proposes a mechanism illustrating how adverse climatic shocks may confer permanent effects on hunter-gatherer investment in intermediate goods (i.e., tools, infrastructure, etc.) as observed in the archeological record. In doing so, the analysis outlines the law of motion for the productivity of intermediate goods in the hunter-gatherer technology.

The model so far predicts that climatic reversals alter the optimal allocation of labor towards increased investment in intermediate goods. This change, however, should be aggregated across the hunter-gather population in order to produce a measure of the total change in subsistence strategies instigated by the increased climatic stress. The impact of a negative climatic shock on either the dietary spectrum or the efficiency with which the current spectrum is exploited would be more pronounced the larger is the underlying population. Intuitively, this occurs because each individual responds to the adverse shock by marginally increasing the intermediate goods he employs in order to include resources previously not consumed and/or increase the efficiency with which existing resources are exploited. Consequently, the larger the group of foragers affected by the shock, the larger will be the increase in aggregate intermediate investments and, thus, the larger the proportion of marginal species incorporated and/or the higher the effectiveness with which existing species are acquired.

Such climatically-induced increases in intermediate investments improves the productivity of intermediate goods for subsequent generations, either because of direct human capital transmission (in this context, representing knowledge on how to extract and process new or existing species) or because of the development of "taste" for foods previously not consumed.

Following the discussion above, the proposed law of motion for the productivity of intermediate goods in hunter-gatherer production reads

$$\zeta_{t+1} = \begin{cases} \zeta_t + F\left(B_t - B_{t-1}\right) & \text{iff} \quad \bar{e} > e_t > e_{t-1} \\ \zeta_t & \text{if} \quad e_t \leq e_{t-1} \leq \bar{e} \\ \tilde{\zeta} & \text{if} \quad e_t \in [\bar{e}, 1], \end{cases} \tag{17}$$

where $\zeta_0 > 0$ is given; and the function F captures the magnitude by which the intermediate goods productivity in period $t+1$, ζ_{t+1}, increases in response to a negative climatic shock in period t.[16] Moreover, F is strictly positive, increasing, and concave in the difference in the aggregate stock of intermediate goods between the generation experiencing the shock and the generation immediately preceding it.[17] Thus, while the productivity of intermediate goods in any given period is not a choice variable for the generation of that period, climatically-induced changes in the group's aggregate investment in intermediate activities shape the human capital that successive generations inherit.

The specified dynamics of the productivity of intermediate goods are designed to capture the permanent "rachet" effect of a negative climatic shock on hunter-gatherer investments in intermediate activities as observed in the archaeological record.

5.2 The Dynamics of Agricultural Knowledge

The evolution of agricultural productivity, A_t, is characterized by two distinct knowledge accumulation regimes – one when agriculture is latent, and another when it is practised. For notational convenience, the agricultural technology parameter will be denoted by A_t^h when the agricultural sector is latent, and by A_t^g once it becomes operative. It is assumed that agricultural productivity in either regime evolves so long as environmental conditions are amenable to farming, i.e., $e_t < \bar{e}$. Otherwise, the productivity parameter simply reverts to an initial, positive, irreducible level of agricultural knowledge $A_0 = A_{\min} > 0$. This restriction delivers that climatic reversals have to be mild enough to allow for any accumulation of agricultural knowledge.

5.2.1 Knowledge Accumulation when Agriculture is Latent

The archaeological evidence (reviewed in Appendix A) suggests that increased intermediate investments (e.g., larger toolsets, more sedentary infrastructure, etc.) had been a precursor to agriculture in several instances of pristine transitions. Hence, when agriculture is latent, the growth rate of agricultural knowledge between periods t and $t+1$ is a function of the allocation of hunter-gatherer labor to intermediate activities in period t, $s^h(e_t, \zeta_t)$.[18]

It is compelling to assume that the latent agricultural productivity is subject to erosion while transferred across generations. This depreciation arguably captures imperfections in the intergenerational transmission of economically unproductive knowledge in a pure hunter-gatherer society. One element of erosion may have been the lack of written languages in the Late Paleolithic. In the absence of a means to store and preserve knowledge through writing, discoveries made by any generation would be bound to not get fully assimilated into the next generation's stock of knowledge. Moreover, an important implication of the

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[16] In the case of hunter-gatherers in extreme climates the productivity of intermediate goods may evolve due to further specialization in the limited set of available species. Such knowledge, however, is bound to be of limited applicability beyond this extreme climatic regime. Thus, in the proposed law of motion, we abstract from the evolution of the productivity of intermediate goods under such climatic conditions, i.e., for $e_t > \bar{e}$, assigning it a constant value $\tilde{\zeta}$.

[17] This formulation captures both the individual and the aggregate effect of a climatic reversal on the evolution of ζ_t. The magnitude of the population is crucial in capturing how a certain climatic shock has a differential impact depending on the size of the hunter-gatherer group being affected (i.e. the larger the group size, the larger is the expansion of the stock of intermediate goods and, consequently, the more pronounced the effect on their productivity). This allows for recurrent climatic shocks of similar magnitude to continuously increase the productivity of intermediate goods over time.

[18] Although we do not explicitly model biogeographic endowments, this could be incorporated in the law of motion of latent agricultural knowledge by introducing it as an additional component, augmenting knowledge accumulation at any level of investment in intermediate goods.

nomadic lifestyle of hunter-gatherers is that it prevents them from sufficiently disturbing a given habitat so as to induce a process of artificial selection that could lead to plant domestication. Thus, while a generation may bequeath a relatively "disturbed" habitat to the next, the latter may nonetheless move to a different settlement as a consequence of the nomadic lifestyle, thereby "eroding" the disturbance generated by the previous generation whose habitat, now in the absence of human intervention, reverts to its original "wild" state.

Given the latency of the agricultural sector, the accumulation of embodied agricultural knowledge between periods t and $t+1$ may, therefore, be summarized as

$$A^h_{t+1} = \begin{cases} \max\left\{A_{\min}, A^h_t\left[(1-\xi) + H\left(s^h(e_t,\zeta_t)\right)\right]\right\} & \text{if} \quad e_t \in [0,\bar{e}) \\ A_{\min} & \text{if} \quad e_t \in [\bar{e},1], \end{cases} \tag{18}$$

where $\xi \in (0,1)$ is an exogenous, time-invariant erosion rate in the transmission of latent agricultural knowledge, and the function H is strictly positive, increasing, and concave in the amount of tool investment. Given $e_t < \bar{e}$, the growth rate of latent agricultural knowledge between periods t and $t+1$, g^h_{t+1}, is thus

$$g^h_{t+1} \equiv \left(A^h_{t+1} - A^h_t\right)/A^h_t = H\left(s^h(e_t,\zeta_t)\right) - \xi \equiv \tilde{H}(e_t,\zeta_t) - \xi, \tag{19}$$

where, as follows from Lemma 1 and the properties of H, $\tilde{H}_e(e_t,\zeta_t) > 0$ and $\tilde{H}_\zeta(e_t,\zeta_t) > 0$.

5.2.2 Climatic Reversals and the Evolution of Latent Agricultural Knowledge

The proposed dynamics of ζ_t and A^h_t imply that a permanent climatic reversal occurring in period t (i.e., $e_t > e_{t-1}$ and $e_{t+k} = e_t, \forall\, k > 0$) affects the growth rate of latent agricultural knowledge both between periods t and $t+1$, g^h_{t+1}, and between periods $t+1$ and $t+2$, g^h_{t+2}. Specifically, generation $t+1$ experiences an increase in its knowledge growth rate due to the higher intermediate investments of generation t (relative to generation $t-1$) in response to the climatic reversal. Generation $t+2$ in turn receives an additional boost in the growth rate of knowledge due to the following reason: While generation $t+1$ does not experience any change in environmental conditions, i.e., $e_{t+1} = e_t$, it further intensifies its labor allocation to intermediate activities (beyond that of generation t) due to the inherited higher magnitude of the productivity of intermediate goods, i.e., $\zeta_{t+1} > \zeta_t$. This increased intermediate investment of generation $t+1$ confers an even higher growth rate of latent agricultural knowledge for generation $t+2$.

In the absence of a climatic reversal the growth rate of knowledge would be identical and constant across generations. A marginal increase in climatic stress of magnitude Δe in period t would increase g^h_{t+1} beyond the pre-reversal knowledge accumulation rate by

$$\Delta\tilde{H}_1 = \frac{\partial \tilde{H}(e_t,\zeta_t)}{\partial e_t}\Delta e. \tag{20}$$

The same shock would also increase the growth rate of knowledge accumulation for the generation in period $t+2$, beyond the growth rate attained in period $t+1$, g^h_{t+1}, by[19]

$$\Delta \tilde{H}_2 = \left(\frac{\partial \tilde{H}\left(e_{t+1}, \zeta_{t+1}\right)}{\partial \zeta_{t+1}} \frac{\partial \zeta_{t+1}}{\partial e_t} \right) \Delta e. \tag{21}$$

Proposition 2 establishes the effects that a climatic reversal in period t may have on the level of the agricultural productivity in subsequent periods.

Proposition 2 *Suppose that a permanent climatic reversal occurs in period* t *(i.e.,* $e_t > e_{t-1}$ *and* $e_{t+k} = e_t, \forall\ k > 0$*) and let* $\Delta \tilde{H}_1$ *and* $\Delta \tilde{H}_2$ *be defined by (20) and (21) respectively. Then, given initial conditions* $A^h_t = A_{\min}$*, and an initial rate of knowledge accumulation* $\tilde{H}\left(e_{t-1}, \zeta_t\right) < \xi$*, the following four cases govern the evolution of latent agricultural knowledge:*

A. $A^h_{t+1} > A^h_t$ *iff* $\tilde{H}\left(e_{t-1}, \zeta_t\right) + \Delta \tilde{H}_1 > \xi$;
B. $A^h_{t+1} = A^h_t$ *iff* $\tilde{H}\left(e_{t-1}, \zeta_t\right) + \Delta \tilde{H}_1 \leq \xi$;
C. $A^h_{t+2} > A^h_t$ *if* $\tilde{H}\left(e_{t-1}, \zeta_t\right) + \Delta \tilde{H}_1 + \Delta \tilde{H}_2 > \xi$ *or* $\tilde{H}\left(e_{t-1}, \zeta_t\right) + \Delta \tilde{H}_1 > \xi$;
D. $A^h_{t+2} = A^h_t$ *iff* $\tilde{H}\left(e_{t-1}, \zeta_t\right) + \Delta \tilde{H}_1 + \Delta \tilde{H}_2 \leq \xi$.

Proof. From (18), (19) and noting that the total growth rate of knowledge in period $t+1$ and $t+2$ is the sum of the initial growth rate before the reversal $\tilde{H}\left(e_{t-1}, \zeta_t\right) - \xi$ and the cumulative increase induced by the climatic shock for each period respectively. ■

Hence, the level of latent agricultural knowledge of generation $t+1$, A^h_{t+1}, may increase as a result of a climatic reversal in period t if and only if the direct, first-generation effect of the reversal on the knowledge accumulation rate, $\Delta \tilde{H}_1$, coupled with the pre-reversal accumulation rate, $\tilde{H}(e_{t-1}, \zeta_t)$, is sufficiently large to overcome erosion between periods t and $t+1$. Otherwise, A^h_{t+1} will necessarily remain at the irreducible level of agricultural knowledge $A_{\min}$. Note that an increase in A^h_{t+1} necessarily implies an increase in the level of latent agricultural knowledge of generation $t+2$, A^h_{t+2}. However, even if A^h_{t+1} remains at the irreducible level it is possible that the second-generation effect of the reversal on the accumulation rate could induce an increase in A^h_{t+2} beyond $A_{\min}$.

Proposition 2 establishes the fundamental role of climatic histories coupled with current environmental conditions in governing the evolution of latent agricultural knowledge. Accordingly, differences in the intensity of intermediate investments result from differences in climatic histories. Such differences prior to a common environmental shock, like the Younger Dryas (see Appendix A for more details), are key in understanding the observed heterogeneity in the timing of the transition to agriculture.

5.2.3 Knowledge Accumulation when Agriculture is Active

Once agriculture becomes operative, learning-by-doing dynamics govern the evolution of agricultural technology. Endogenous technological progress of this sort is typical for a regime in its early stages of development. Specifically, the level of agricultural technology at time $t+1$, A^g_{t+1}, is assumed to be a positive, increasing

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[19] Note that since generations t and $t+1$ face the same (harsher) climate any difference in the knowledge accumulation rates between periods $t+2$ and $t+1$, i.e. $g^h_{t+2} - g^h_{t+1}$, arises from the indirect effect of the climatic shock on the productivity of intermediate goods, ζ_{t+1}.

and concave function of the level of technology at time t, A_t^g. Therefore,

$$A_{t+1}^g = \begin{cases} G\left(A_t^g\right) & \text{if} \quad e_t \in [0, \bar{e}) \\ A_{\min} & \text{if} \quad e_t \in [\bar{e}, 1], \end{cases} \tag{22}$$

where G is strictly positive, increasing, and concave in its domain.

5.3 The Dynamics of Population

The evolution of the working population over time is given by

$$L_{t+1} = n_t\left(y_t\right) L_t, \tag{23}$$

where $L_t = L_t^{h*} + L_t^{g*}$ is the population size in period t; $L_0^{h*} > 0$, $L_0^{g*} = 0$ and, therefore, $L_0 = L_0^{h*}$ are given; $n(y_t)$ is fertility under (A2) and (16); and y_t is the prevailing output per worker in period t, i.e., $y_t = \max\{y^h(e_t, \zeta_t, L_t), y^g\left(e_t, A_t\right)\}$. Note that (23) implicitly makes use of the equilibrium results of Proposition 1, i.e., if both sectors in the economy are active in period t, output per capita and, thus, fertility choices are identical across sectors.

5.4 The Post-Transition Long-run Equilibrium

Once the transition to agriculture occurs, the global concavity of the function G, as specified in (22), assures the existence of a unique, positive, and globally-stable steady state. As long as A_t^g increases, an increasing fraction of the total population joins the agricultural sector. This reallocation of labor keeps incomes equal across the two sectors. This section examines the equilibrium behavior of the economy once the post-transition steady-state level of agricultural technology is achieved. For simplicity, it is assumed that environmental conditions are stable.[20]

Let $\hat{A}^g$ and $\hat{e}$ denote the post-transition steady-state levels of agricultural technology and environmental harshness, respectively. Note that the stable climate implies that the productivity of intermediate goods in the hunter-gatherer sector is also at a steady-state level, $\hat{\zeta}$. Then, it follows from Proposition 1, that the steady-state level of income per capita is $y^g(\hat{e}, \hat{A}^g)$ and the steady-state labor market equilibrium is determined by $y^h(\hat{e}, \hat{\zeta}, \hat{L}^h) = y^g(\hat{e}, \hat{A}^g)$, with the number of individuals employed in the hunter-gatherer sector constant at $\hat{L}^h$. However, due to constant returns to labor in the agricultural sector and the perfectly competitive nature of the economy, it follows from (23) that total population in the post-transition steady state grows at the constant rate $n(y^g(\hat{e}, \hat{A}^g))$ □ 1. Since the hunter-gatherer population remains constant at $\hat{L}^h$, this implies that the population engaged in agriculture continues to increase in every period at the steady state.

6 The Dynamical System

The process of economic development is governed by the exogenous trajectory of climatic conditions, the endogenous evolution of the size of the population, the hunter-gatherer productivity of intermediate goods,

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[20] The theory may, nonetheless, generate instances of regression to hunting and gathering from agriculture as a result of increased climatic stress.

and embodied knowledge of agriculture. Thus the dynamic path of the economy is fully determined by the sequence $\{e_t, L_t, \zeta_t, A_t\}_{t=0}^{\infty}$ that satisfies equations (17), (23) and either (18) or (22) in every period t.

6.1 The Replacement Frontier − LL

The *Replacement Frontier* is the geometric locus of all pairs (L_t, e_t) such that, given ζ_t and the latency of the agricultural sector, i.e., $y^h(e_t, \zeta_t, L_t) > y^g(e_t, A_t)$, the fertility rate of members of generation t is at the replacement level, i.e., $n_t(y_t) = 1$. Recall that, when the agricultural sector is dormant, generation t is employed exclusively in the hunter-gatherer sector, i.e., $L_t = L_t^h$, and potential income for a member of generation t, y_t, is therefore given by $y^h(e_t, \zeta_t, L_t)$. Thus, noting (A2) and solving for y_t when fertility is at replacement, it follows that the Replacement Frontier LL is

$$LL \equiv \left\{(L_t, e_t; \zeta_t) : y^h(e_t, \zeta_t, L_t) = \tilde{c}/\left(1 - p\right)\right\}. \tag{24}$$

Lemma 3 (The Properties of LL) *Under (A1)-(A2), if $(L_t, e_t; \zeta_t) \in LL$ then, given ζ_t, the population at the replacement frontier, L_t^L, is a unique single-valued function of e_t,*

$$L_t^L = L^{LL}\left(e_t; \zeta_t\right) > 0,$$

where L_t^L is

1. *monotonically decreasing and strictly convex in e_t, i.e.,*
$$\frac{\partial L^{LL}\left(e_t; \zeta_t\right)}{\partial e_t} < 0 \text{ and } \frac{\partial^2 L^{LL}\left(e_t; \zeta_t\right)}{\left(\partial e_t\right)^2} > 0;$$
2. *monotonically increasing in ζ_t, i.e.,*
$$\frac{\partial L^{LL}\left(e_t; \zeta_t\right)}{\partial \zeta_t} > 0.$$

Proof. Follows from Lemma 2 and the *Implicit Function Theorem.* See Appendix C for details. ■

Corollary 1 *Given e_t, L_t, ζ_t and A_t such that $y^h(e_t, \zeta_t, L_t) > y^g(e_t, A_t)$,*

$$L_{t+1} - L_t \gtreqqless 0 \quad \text{if and only if} \quad L_t \lesseqqgtr L^{LL}\left(e_t; \zeta_t\right).$$

Hence, the Replacement Frontier, as depicted in Figure 2, is a strictly convex, downward sloping curve in (e_t, L_t) space where, conditional on the values of ζ_t and A_t, $y^h(e_t, \zeta_t, L_t) > y^g(e_t, A_t)$ is satisfied. The frontier shifts upward as ζ_t increases during the process of development. Note that this shift occurs only for the segment of the replacement locus that is below extreme climatic conditions, i.e., for $e_t < \bar{e}$. Furthermore, having fertility behave as a normal good ensures the existence of standard Malthusian population dynamics above and below the frontier.

6.2 The Hunter-Gatherer Frontier − yy

The *Hunter-Gatherer Frontier*, yy, is the geometric locus of all pairs (L_t, e_t) such that, conditional on ζ_t and A_t and given exclusive employment of the labor force in the hunter-gatherer sector, i.e., $L_t = L_t^h$, a member

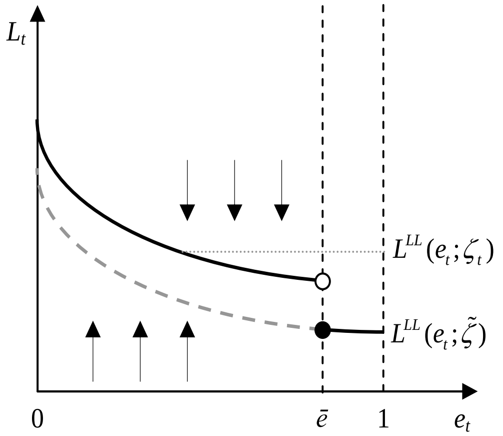

Figure 2: The LL Frontier – Conditional on $y^h > y^g, \forall e_t \in [0,1]$

of generation t is just indifferent between supplying his labor to the hunter-gatherer and agricultural sectors. Thus,[21]

$$yy \equiv \{(L_t, e_t; \zeta_t, A_t) : y^h\left(e_t, \zeta_t, L_t\right) - y^g\left(e_t, A_t\right) = 0\}. \tag{25}$$

Lemma 4 (The Properties of yy) *Under (A1), if $(L_t, e_t; \zeta_t, A_t) \in yy$ then, given ζ_t and A_t, the population containing the marginal worker who is just indifferent between agriculture and hunting and gathering, L_t^y, is a unique single-valued function of $e_t \in [0, \bar{e}]$,*

$$L_t^y = L^{yy}\left(e_t; \zeta_t, A_t\right) > 0,$$

where L_t^y is

1. *monotonically increasing and strictly convex in e_t, i.e.,*

$$\frac{\partial L^{yy}\left(e_t; \zeta_t, A_t\right)}{\partial e_t} > 0 \text{ and } \frac{\partial^2 L^{yy}\left(e_t; \zeta_t, A_t\right)}{\left(\partial e_t\right)^2} > 0;$$

2. *monotonically increasing in ζ_t, i.e.,*

$$\frac{\partial L^{yy}\left(e_t; \zeta_t, A_t\right)}{\partial \zeta_t} > 0;$$

3. *monotonically decreasing in A_t, i.e.,*

$$\frac{\partial L^{yy}\left(e_t; \zeta_t, A_t\right)}{\partial A_t} < 0.$$

Proof. Follows from the sectoral production functions, Lemma 2 and the *Implicit Function Theorem*. See Appendix C for details. ■

Corollary 2 *Given $e_t \in [0, \bar{e}]$, L_t^h, ζ_t and A_t,*

$$y^h\left(e_t, \zeta_t, L_t^h\right) - y^g\left(e_t, A_t\right) \gtreqless 0 \quad \text{if and only if} \quad L_t^h \lesseqgtr L^{yy}\left(e_t; \zeta_t, A_t\right).$$

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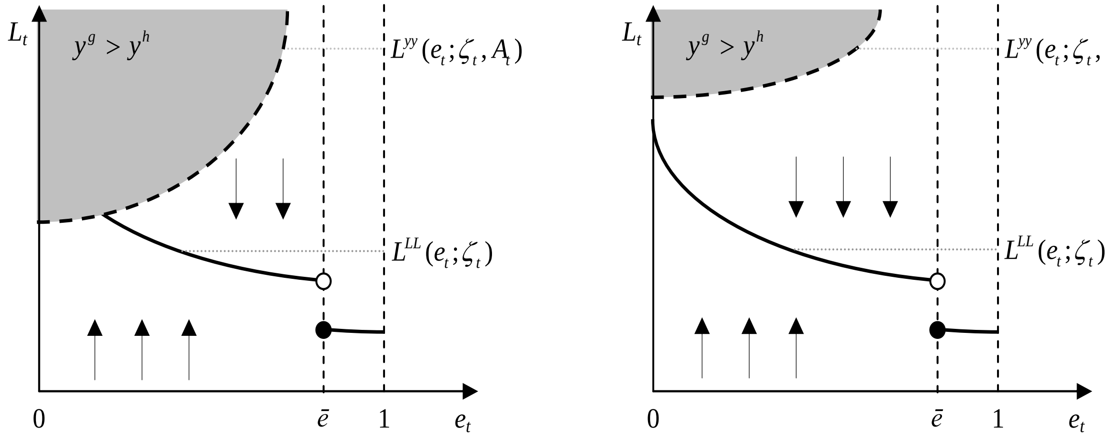
[21] To the extent that an agricultural transition might be associated with some fixed cost c, this may be incorporated in the hunter-gatherer frontier by setting the difference here equal to c rather than 0.



(a) For Relatively Low A_t

(b) For Relatively High A_t

Figure 3: The yy and LL Frontiers

Corollary 3 *Given* $e_t \in [0, \bar{e}]$*,* L_t*,* ζ_t *and* A_t *such that* $L_t > L^{yy}(e_t; \zeta_t, A_t)$*, equilibrium employment is given by* $L_t^{h*} = L^{yy}(e_t; \zeta_t, A_t)$ *and* $L_t^{g*} = L_t - L^{yy}(e_t; \zeta_t, A_t)$*.*

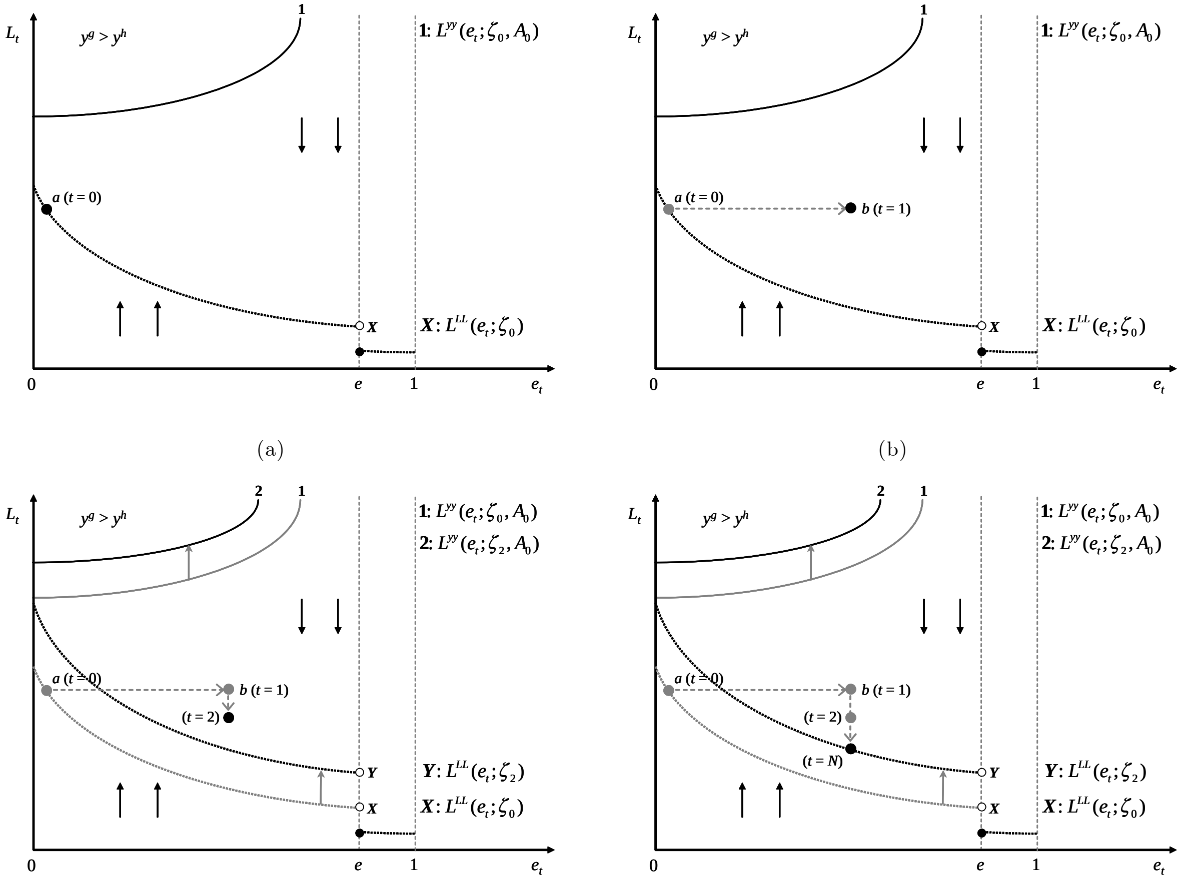
The Hunter-Gatherer Frontier, as depicted in Figures 3(a)–3(b), is therefore a strictly convex, upward sloping curve in (e_t, L_t) space where, given e_t and an arbitrary L_t, the fraction of the total labor force residing above (below) the frontier will be employed in the agricultural (hunter-gatherer) sector. Moreover, increases in ζ_t and A_t during the process of development have the opposing effects of shifting the frontier upward and downward, respectively.

7 Cases of Transition and Non-Transition

This section employs the framework established by the Hunter-Gatherer and Replacement Frontiers to examine various possible trajectories of the economy triggered by a single climatic reversal event. These are determined both by the magnitude of the reversal as well as the climatic history experienced by the afflicted foraging group. Consequently, the exposition shows how the model may account for different cases of the transition (or non-transition) to agriculture, as observed in the archaeological record, with respect to a certain adverse climatic shock.

7.1 Non-Transition During a Climatic Reversal

A common criticism to theories that focus on climatic shocks to explain the transition to agriculture is that earlier instances of increased climatic stress in prehistory did not have such an impact. The following example illustrates how moderate increases in climatic stress may fail to give rise to agriculture, highlighting the importance of the permanent increase in the productivity of intermediate goods for the affected hunter-gatherers. Also, it is easy to show that climatic extremes reset the accumulation of both the productivity of intermediate goods and latent agricultural knowledge to irreducible levels, essentially nullifying any "beneficial" effect of the climatic past.



(a) (b)

(c) (d)

Figure 4: Non-Transition During a Climatic Reversal

Figures 4(a)–4(d) depict the case of non-transition given a permanent mild climatic reversal. Note that such a scenario occurs under Case D of Proposition 2.[22]

The interpretation of Figures 4(a)–4(d) is as follows. Corresponding to Figure 4(a), suppose that in period 0 the economy is at a Malthusian steady state denoted by point a with non-increasing levels of latent agricultural knowledge, A_0, and intermediate goods productivity, ζ_0. In period 1, the economy experiences an adverse climatic shock, $e_0 < e_1 < \bar{e}$, and moves to point b, as depicted in Figure 4(b). Generation 1, responds to the harsher environment by simultaneously increasing it's intermediate activities and reducing fertility (relative to generation 0). By (17), the increased intermediate investments of generation 1 improve the intermediate goods productivity that generation 2 inherits. Following Lemma 3, the increase in ζ_2 over ζ_0 permanently shifts up the segment of the LL locus under $e_t < \bar{e}$ for all generations $t \geq 2$, as shown in Figure 4(c). Meanwhile, the initial reversal has failed to set in motion the accumulation of latent agricultural knowledge, because the expansion of society's intermediate goods by the generation experiencing the climatic reversal is not large enough to instigate an increase in latent agricultural productivity.

Thus, as depicted in Figure 4(c), the yy locus simply shifts up (when the intermediate goods productivity increases from ζ_0 to ζ_2) and remains there indefinitely. Subsequently, as Figure 4(d) illustrates, the economy gradually moves under Malthusian dynamics to eventually settle on its new steady state in period N.

This example offers a novel insight regarding instances of non-transition. In particular, a reversal may fail to set in motion the growth of latent agricultural knowledge either because the shock is not sufficiently large, or because the rate at which the habitat is disturbed (i.e., as proxied by the level of intermediate investments) prior to the shock is not substantial enough. Note that an extreme shock, i.e., $e_1 > \bar{e}$, would make both the levels of latent agricultural knowledge and the productivity of intermediate goods revert to their initial primitive values.

This framework explains the failure of reversals before the Younger Dryas in generating the transition to agriculture in the Near East. Nonetheless, following Proposition 2, such "unsuccessful" reversals had a long run payoff in that they were instrumental in "ratcheting" up the Replacement Frontier, inducing reduced mobility patterns and larger investments in intermediate activities leading to greater efficiency in obtaining domesticable species. These past episodes of moderate climatic stress, thus, fundamentally transformed the food acquisition patterns of hunter-gatherers, paving the way for subsequent reversals to lead to the emergence of agriculture.

It is interesting to note that the case illustrated here provides a framework for understanding the observed evolution of mankind during the foraging regime towards more technologically advanced modes of food acquisition, independently of the Neolithic Revolution.

7.2 Transition During a Climatic Reversal

The scenario of a transition to agriculture *during* a period of increased climatic stress illustrates the experience at Abu Hureyra. For the theory to give rise to such a case, it suffices to assume that there is either no climatic recovery following the reversal or that the recovery occurs after the transition has

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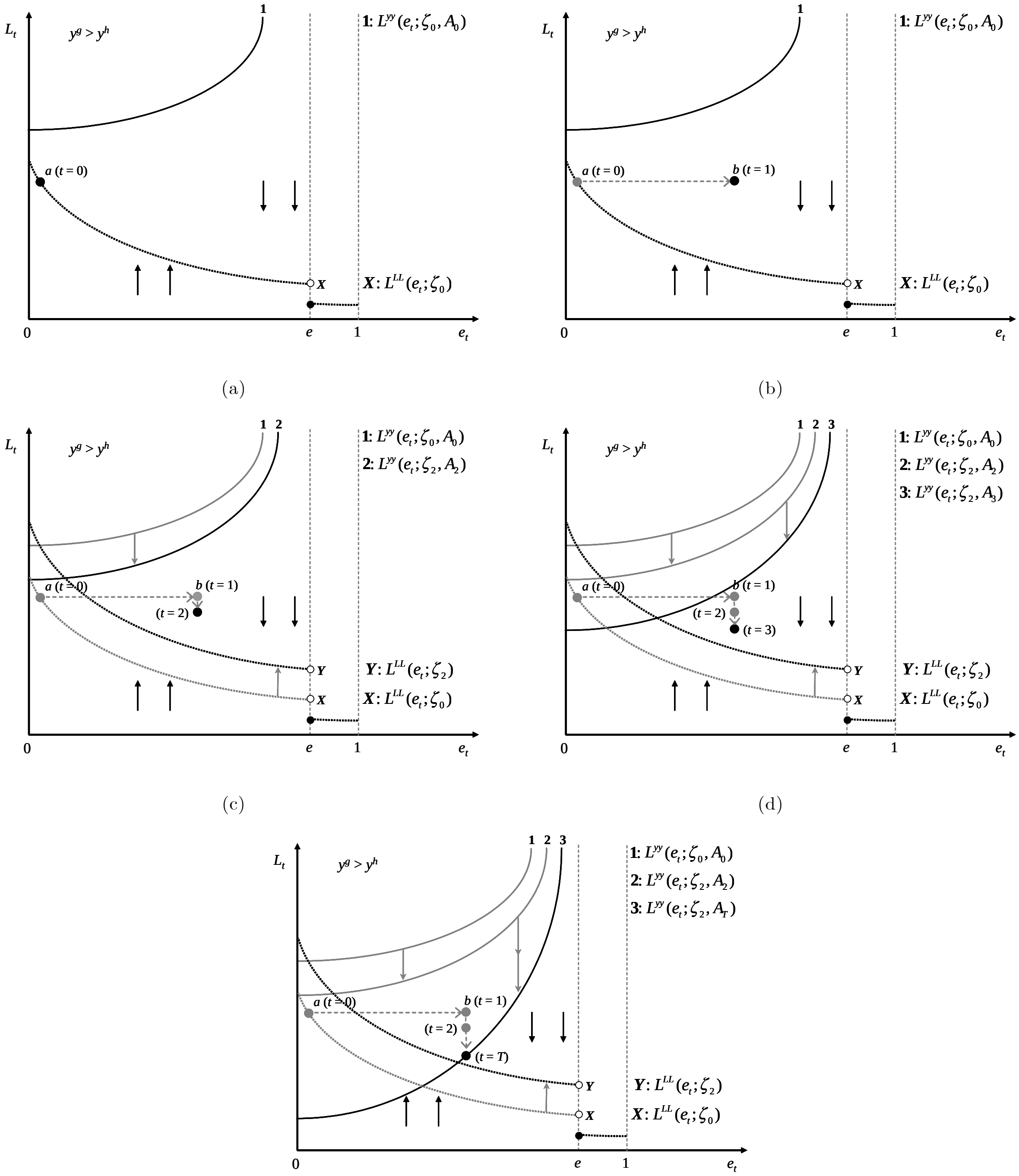
[22] For simplicity, the figures in this section are illustrated under assumption (D.A1) discussed in Appendix D. Assumptions (D.A1) and (D.A2) are made to facilitate the graphical exposition of the dynamics, and do not have any qualitative impact on the results unless noted otherwise.



(a)

(b)

(c)

(d)

(e)

Figure 5: Transition During a Climatic Reversal

already taken place. Figures 5(a)–5(e) illustrate the transitional dynamics of the economy for this particular case and, for simplicity, are depicted under the graphical assumptions discussed in Appendix D.

Figures 5(a)–5(e) may be interpreted as follows. Suppose, as shown in Figure 5(a), that in period 0 the economy resides at point a with levels of latent agricultural knowledge and intermediate goods productivity denoted by A_0 and ζ_0, respectively. Then, due to a climatic reversal in period 1, $e_0 < e_1 < \bar{e}$, the economy moves to point b, as depicted in Figure 5(b). The discussion from the previous case regarding the expansion of society's intermediate activities by generation 1 and the resultant increase of the productivity of intermediate goods (from ζ_0 to ζ_2) for subsequent generations applies here as well. This is illustrated in Figure 5(c). In this case, however, the growth of latent agricultural knowledge, instigated by the larger intermediate investments in period 1, occurs at a sufficiently high rate so as to ensure that the yy locus starts shifting down for subsequent generations. Figure 5(d) shows that this is the case for all generations beyond $t = 1$. Finally, as shown in Figure 5(e), the downward shifting yy locus eventually subsumes the economy at time T, where the transition to agriculture occurs.

This example applies to cultures that, prior to the climatic downturn, were already intensively investing in intermediate activities due to the experience of earlier mild climatic shocks. Small reversals would therefore be sufficient to induce high-population density groups to make the transition, whereas, for smaller groups, larger shocks would be necessary. This case illustrates why a common climatic deterioration could have a differential impact on the evolution of the foraging regime towards agriculture across different hunter-gatherer societies.

7.3 Transition Following a Climatic Recovery

This section shows how the theory may account for the emergence of agriculture under conditions of reduced climatic stress, as exemplified by cultures in North Central China.

To illustrate the case of a transition to agriculture after a full climatic recovery (following an initial reversal), it is necessary to impose two case-specific assumptions. Let R denote the period in which the climatic recovery occurs. Then, the generation immediately preceding the recovery, $R - 1$, strictly prefers hunting and gathering over agriculture, i.e.,

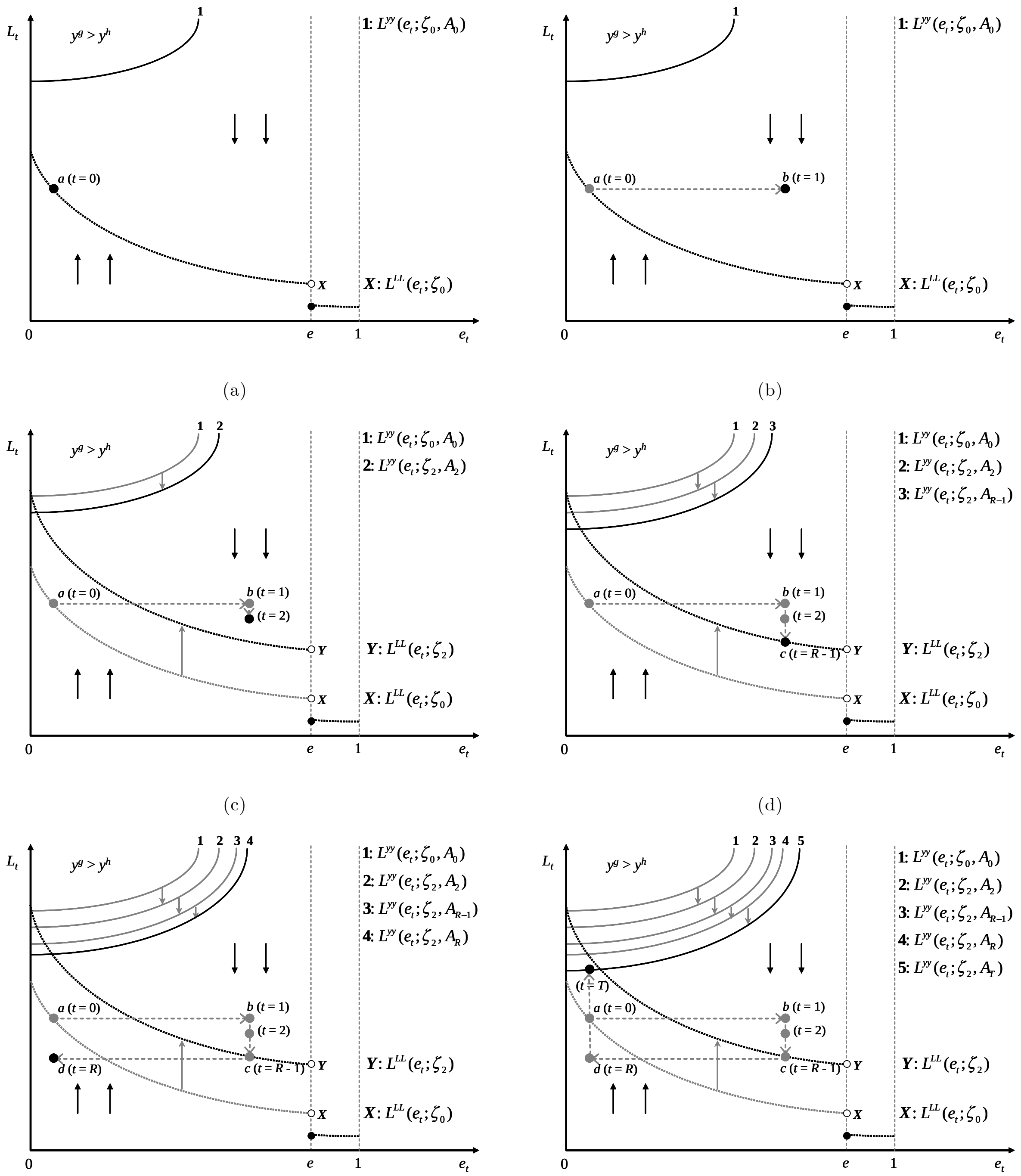
$$L_{R-1} < L^{yy}\left(e_{R-1}; \zeta_{R-1}, A^h_{R-1}\right), \tag{A3}$$

and the growth rate of latent agricultural knowledge between periods R and $R + 1$ is strictly positive, i.e.,

$$g^h_{R+1} \equiv \left(A^h_{R+1} - A^h_R\right) / A^h_R = \tilde{H}\left(e_R, \zeta_R\right) - \xi > 0. \tag{A4}$$

Figures 6(a)–6(f) illustrate this scenario and, for simplicity, are depicted under the graphical assumptions in Appendix D in addition to the case specific assumptions (A3) and (A4).

The interpretation of Figures 6(a)–6(f) is as follows. Corresponding to Figure 6(a), suppose that in period 0 the economy is at a Malthusian steady state denoted by point a with non-increasing levels of latent agricultural knowledge, A_0, and intermediate goods productivity, ζ_0. In period 1, the economy experiences an adverse climatic shock, $e_0 < e_1 < \bar{e}$, and moves to point b, as depicted in Figure 6(b). The discussion from the previous case regarding the expansion of society's intermediate activities by generation 1 and the



(a) (b)

(c) (d)

(e) (f)

Figure 6: Transition Following a Climatic Recovery

resultant increase of the productivity of intermediate goods (from ζ_0 to ζ_2) for subsequent generations applies here as well. This corresponds to Figure 6(c).

Meanwhile, the initial reversal has set in motion the accumulation of latent agricultural knowledge, which, as illustrated in Figure 6(c), shifts the yy locus downward. Over time, given no changes in environmental conditions, the economy settles in the new steady state denoted by point c, as shown in Figure 6(d). Suppose now that a positive climatic shock, which exactly offsets the initial reversal, occurs in period R with latent agricultural knowledge having accumulated to A_R. The economy immediately moves from point c to point d, as depicted in Figure 6(e). As follows from Lemma 1, the climatic recovery induces generation R to reduce society's intermediate activities, which has the effect of reducing the growth rate of agricultural knowledge between periods R and $R+1$, g^h_{R+1}. However, (A4) assures that this growth rate continues to remain positive. Graphically, this corresponds to a smaller downward shift of the yy locus, depicted by the move from curve 3 to 4 in Figure 6(e). From point d, Malthusian dynamics propel the economy up towards the new LL locus. At the same time, the yy locus keeps shifting down, as agricultural knowledge keeps accumulating beyond A_{R+1}, until, as shown in Figure 6(f), the economy's upward trajectory meets the downward shifting yy frontier in period T. At this point, the economy experiences the transition to agriculture.[23]

This example illustrates the significance of the permanent effect of climatic reversals on human capital specific to intermediate activities in hunter-gatherer societies. Notably, in the absence of cumulative learning, the level of intermediate investments following the recovery would revert to its pre-reversal level, thereby causing the depletion of latent agricultural knowledge. As such, the case of a transition to agriculture following a climatic recovery would have never been observed. Interestingly, the case of a transition during a climatic recovery is observationally equivalent to pure population pressure leading to agriculture. However, the analysis firmly identifies the past experience of climatic stress as the driving force here, and exemplifies Bellwood's (2005) assertion that "if climatic reversal was the trigger, it took a while to go off."

8 Empirical Evidence

The theory suggests that moderate levels of intertemporal climatic volatility, by increasing society-specific human capital and technological endowments more complementary to farming, fostered pristine cases of transition from hunting and gathering to sedentary agriculture. Nevertheless, the proposed framework can be easily modified to explain instances of adoption of agricultural practices via technological diffusion. The intuition is straightforward. To the extent that the adoption of farming was determined by the pre-existing level of society-specific human capital complementary to agricultural practices, then populations residing along territories characterized by intermediate levels of climatic volatility would have been more likely to have accumulated knowledge that would facilitate the adoption of farming techniques once they had become available. Accordingly, regions characterized by either too high or too low climatic volatility would have experienced a delayed onset of the Neolithic Revolution. Thus, while the model explicitly considers only pristine transitions, the fact that the theoretical framework can be used to conceptualize instances of adoption as well, implies that the theory may be falsified using cross-sectional data on the timing of the Neolithic

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[23] Without loss of generality, Figure 6(f) is drawn under the assumption that the economy resides below its LL locus when the transition occurs.

Revolution, despite the fact that the vast majority of regions adopted sedentary agriculture via technological diffusion from societies at the frontier.

8.1 Cross-Country Analysis

This section provides empirical evidence in support of the proposed theory, demonstrating a highly statistically significant and robust hump-shaped relationship between the intertemporal standard deviation of temperature and the timing of the Neolithic Revolution across countries. Specifically, the analysis exploits cross-country variation in temperature volatility as well as in other geographical determinants, such as mean temperature, absolute latitude, land area, distance from the closest "Neolithic frontier" (one of 7 localities around the world that experienced a pristine agricultural transition), and biogeographic endowments, to explain the cross-country variation in the timing of the Neolithic. Due to the unavailability of worldwide prehistoric temperature data, however, the analysis employs highly spatially disaggregated monthly data between 1900 and 2000 to construct country-level measures of the mean and standard deviation of temperature over the last century.

Data for the monthly time series of temperature, 1900–2000 is obtained from the Climate Research Unit's CRU TS 2.0 dataset, constructed by Mitchell et al. (2004). This dataset employs reports from climate stations across the globe to provide 1,200 monthly temperature observations over the last century, spanning the global land surface at a 0.5 degree resolution. To construct country-level measures of the mean and standard deviation of temperature using this dataset, the analysis at hand first computes the intertemporal moments of temperature at the grid level and then performs a spatial aggregation by simply averaging this information across grids that correspond to a given country.[24] As such, the volatility of temperature between 1900 and 2000 for a given country should be interpreted as the volatility prevalent in a representative grid within that country during this time frame.

The qualitative interpretation of the empirical results is thus based on the identifying assumption that the cross-country distribution of temperature volatility in the 20th century was not significantly different from that which existed prior to the Neolithic Revolution. While this may appear to be a rather strong assumption, it is important to note that the spatial distribution of climate is determined in large part by spatial differences in microgeographic characteristics, which remain fairly stationary within a given geological epoch. In contrast, global geological events (e.g., an ice age) predominantly affect worldwide climatic averages rather than the cross-sectional variation in climatic factors. Nevertheless, to relax the identifying assumption somewhat, the analysis also employs a new data series on historical temperatures between the years 1500 and 1899 (albeit for a smaller set of countries), and reveals findings that are qualitatively similar to those uncovered using temperature volatility in the last century.

The historical time-series data on temperature is obtained from the recent dataset of Luterbacher et al. (2006), who in turn compile their data from the earlier datasets of Luterbacher et al. (2004) and Xoplaki et al. (2005). These datasets make use of both directly measured data and, for earlier periods in the time series, proxy data from documentary evidence, tree rings, and ice cores to provide monthly (from 1659

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[24] This sequence of computations was specifically chosen to minimize the information loss that inevitably results from aggregation. Note that an alternative (but not equivalent) sequence would have been to perform the spatial aggregation to the country level first and then compute the intertemporal moments. To see why this alternative is inferior, consider the extreme example of a country comprised of two grid cells that have identical temperature volatilities but whose temperature fluctuations are perfectly negatively correlated. In this case, the alternative methodology would yield no volatility at all for the country, whereas the methodology adopted would yield the volatility prevalent in either of its grid cells.

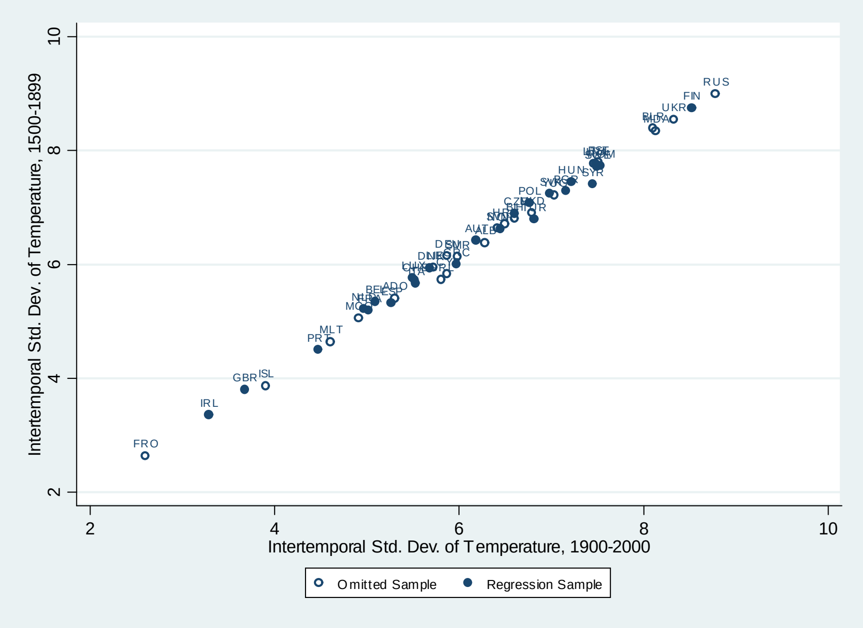

Figure 7: Historical and Contemporary Temperature Volatilities

Correlation Coefficients: 0.9977 (Full Sample); 0.9970 (Regression Sample)

onwards) and seasonal (from 1500 to 1658) temperature observations at a 0.5 degree resolution, primarily for the European continent. The current analysis then applies to this data the same aggregation methodology used to compute the contemporary measures of the intertemporal moments of temperature in order to derive the historical measures of the intertemporal mean and standard deviation of temperature at the country level. It should be noted that, while both historical and contemporary temperature data are available for 47 countries (as depicted in the correlation plots in Figures 7 and 8), only 25 of these countries appear in the 97-country sample actually employed by the regressions to follow. This discrepancy is due to the unavailability of transition timing data as well as data on some of the control variables employed by the regression analysis.[25]

Consistent with the assertion that the spatial variation in temperature volatility remains largely stable over long periods of time, temperature volatility in the 20th century and that in the preceding four centuries are highly positively correlated across countries, possessing a correlation coefficient of above 0.99. This relationship is depicted on the scatter plot in Figure 7, where it is important to note that the rank order of the vast majority of countries is maintained across the two time horizons. Moreover, as depicted in Figure 8, a similar correlation exists between the mean of temperature in the 20th century and that from the preceding four centuries, lending further credence to the identifying assumption that contemporary data on climatic factors can be employed as informative proxies for prehistoric ones.

The data on the timing of the Neolithic Revolution is the cross-country measure constructed by Putterman (2008), who assembles this variable using a wide variety of both regional and country-specific archaeological studies, as well as more general encyclopedic works on the Neolithic transition, including

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[25] The distinction between the 47- and 25-country samples is evident in Figures 7 and 8, where observations appearing only in the 25-country sample are depicted as filled circles.

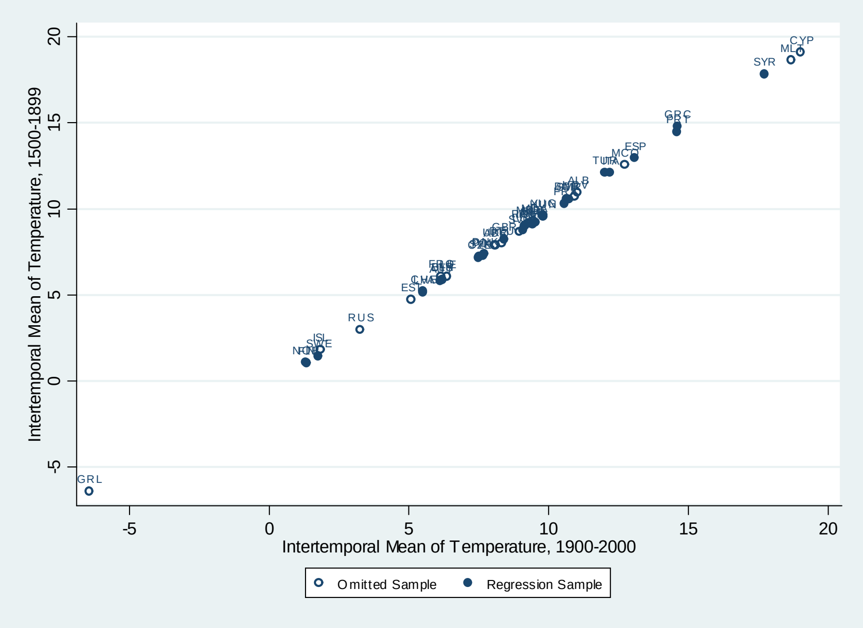

Figure 8: Historical and Contemporary Mean Temperatures

Correlation Coefficients: 0.9997 (Full Sample); 0.9997 (Regression Sample)

MacNeish (1992) and Smith (1995).[26] Specifically, the reported measure captures the number of thousand years elapsed, relative to the year 2000, since the earliest recorded date when people residing in an area within a country's present borders began practicing agriculture as the primary mode of subsistence.

Formally, the following quadratic specification is employed in order to assess the proposed non-monotonic impact of climate volatility on the timing of the transition to agriculture:

$$YST_i = \beta_0 + \beta_1 VOL_i + \beta_2 VOL_i^2 + \beta_3 TMEAN_i + \beta_4 LDIST_i + \beta_5 LAT_i + \beta_6 AREA_i + \beta_7 \Delta_i + \beta_8 \square_i + \varepsilon_i,$$

where YST_i is the number of thousand years elapsed since the Neolithic Revolution in country i, as reported by Putterman (2008); VOL_i is the temperature volatility prevalent in country i during either the contemporary (1900–2000) or the historical (1500–1899) time horizon; $TMEAN_i$ is the mean temperature of country i during the corresponding time horizon; $LDIST_i$ is the log of the great-circle distance to the closest Neolithic frontier, included here as a control for the spatial diffusion of agricultural practices[27]; LAT_i is the absolute latitude of the geodesic centroid of country i, and $AREA_i$ is the total land area of country i, as reported by the CIA World Factbook 2008; Δ_i is a vector of continental dummies; $\square_i$ is a vector of biogeographic variables employed in the study of Olsson and Hibbs (2005), such as climate, the size and orientation of the landmass, and the numbers of prehistoric domesticable species of plants and animals, included here as controls for the impact of biogeographic endowments as hypothesized by Diamond (1997); and, finally, ε_i is a country-specific disturbance term.

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[26] The reader is referred to www.econ.brown.edu/fac/Louis%5FPutterman/agricultural%20data%20page.htm for a detailed description of the primary and secondary data sources employed by the author in the construction of this variable.

[27] These are computed with the Haversine formula for geodesic distances, using the coordinates of modern country capitals as endpoints. The set of 7 global Neolithic frontiers, considered in the determination of the closest frontier for each observation, comprises Syria, China, Ethiopia, Niger, Mexico, Peru, and Papua New Guinea.

To fix priors, the reduced-form prediction of the theory – i.e., that intermediate levels of climatic volatility should be associated with an earlier onset of agriculture – implies that, in the context of the regression specification, the timing of the Neolithic Revolution, YST_i, and temperature volatility, VOL_i, should be characterized by a hump-shaped relationship across countries – i.e., $\beta_1 > 0$, $\beta_2 < 0$, and $VOL^* = -\beta_1/(2\beta_2) \in \left(VOL^{\min}, VOL^{\max}\right)$.[28]

8.1.1 Results with Contemporary Volatility

Table 1 reveals the results from regressions employing temperature volatility computed from contemporary data. Specifically, the measure of volatility used is the standard deviation of the monthly time series of temperature spanning the 1900–2000 time horizon.[29] For the sample of 97 countries employed in this exercise, the volatility measure assumes a minimum value of 0.541 (for Rwanda), a maximum value of 10.077 (for China), and a sample mean and standard deviation of 4.010 and 2.721 respectively. These descriptive statistics along with those of the control variables employed are collected in Table E.1 in Appendix E, with the relevant correlations appearing in Table E.2.

Consistent with the predictions of the proposed theory, Column 1 of Table 1 reveals a highly statistically significant hump-shaped relationship between the timing of the Neolithic Revolution and temperature volatility, conditional on mean temperature, log-distance to the closest Neolithic frontier, absolute latitude, land area, and continent fixed effects.[30] In particular, the first- and second-order coefficients on temperature volatility are both statistically significant at the 1% level, and possess their expected signs. The coefficients of interest imply that the optimal level of temperature volatility for the Neolithic transition to agriculture is 7.985, an estimate that is also statistically significant at the 1% level. To interpret the overall metric effect implied by these coefficients, a one standard deviation change in temperature volatility on either side of the optimum is associated with a delay in the onset of the Neolithic Revolution by 82 years.[31]

The following thought experiment places the aforementioned effect of temperature volatility into perspective. If Kenya's low temperature volatility of 1.161 were increased to Bulgaria's volatility of 8.094, which is in the neighborhood of the optimum, then, all else constant, agriculture would have appeared in Kenya by 7297 BP instead of 3500 BP, effectively closing the gap in the timing of the transition between the two countries by allowing Kenya to reap the benefits of agriculture 3797 years earlier. At the other end of the spectrum, lowering Mongolia's high temperature volatility of 14.032 to that of Bulgaria would have accelerated the advent of the Neolithic Revolution in the regions belonging to Mongolia today by 2981

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[28] These conditions ensure not only strict concavity, but also that the optimal volatility implied by the first- and second-order coefficients falls within the domain of volatility observed in the cross-country sample.

[29] This measure, that captures volatility from not only intergenerational fluctuations but intragenerational ones as well, may appear to be somewhat discordant with the model where the temporal fluctuations are purely intergenerational. This, however, is an innocuous artefact of the OLG setup of the model, chosen to convey the basic idea that fluctuations experienced by a hunter-gatherer society over a long expanse of time mattered for the pace of its transition to agriculture.

[30] An alternative interpretation for the observed hump-shaped relationship could be that the optimal temperature volatility regime proxies for the "ideal agricultural environment" so conditions away from this optimum, by increasing the incidence of crop failures, would reduce the incentive for hunter-gatherers to adopt farming. If this was the case, however, then agricultural suitability would exhibit a similar non-monotonic relationship with temperature volatility. Results, not shown, suggest that an index gauging the suitability of land for agriculture, constructed by Michalopoulos (2008) using spatially disaggregated data on climate and soil characteristics, is not systematically related to the intertemporal moments of temperature.

[31] Note that this is different from the marginal effect, which by definition would be 0 at the optimum. The difference between the marginal and metric effects arises from the fact that a one standard deviation change in temperature volatility does not constitute an infinitesimal change in this variable, as required by the calculation of its marginal effect. It is easy to show that the metric effect of a ΔVOL change in volatility at the level $\overline{VOL}$ is given by $\Delta YST = \beta_1 \Delta VOL + \beta_2 \left(2\overline{VOL} + \Delta VOL\right) \Delta VOL$. Evaluating this expression at the optimum for a one standard deviation change in volatility – i.e., setting $\Delta VOL = 1$ and $\overline{VOL} = -\beta_1/(2\beta_2)$ – then yields the relevant metric effect reported in the text.

Table 1: The Timing of the Neolithic Revolution and Contemporary Temperature Volatility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Dependent Variable is Thousand Years Elapsed since the Neolithic Revolution								
Temperature Volatility	1.302***	0.838***	1.020***	1.187***	1.064***	0.929***	0.956***	1.264***	1.300***
	(0.292)	(0.235)	(0.280)	(0.241)	(0.229)	(0.219)	(0.232)	(0.367)	(0.389)
Temperature Volatility Square	-0.082***	-0.053**	-0.073***	-0.085***	-0.075***	-0.064***	-0.072***	-0.090***	-0.099***
	(0.028)	(0.021)	(0.025)	(0.021)	(0.021)	(0.019)	(0.020)	(0.031)	(0.033)
Mean Temperature	0.018	0.071**	0.028	-0.019	-0.003	0.027	0.004	0.015	-0.014
	(0.042)	(0.029)	(0.037)	(0.036)	(0.035)	(0.028)	(0.033)	(0.066)	(0.071)
Log Distance to Frontier	-0.249***	-0.279***	-0.247***	-0.187***	-0.208***	-0.226***	-0.211***	-0.240***	-0.227***
	(0.079)	(0.044)	(0.066)	(0.055)	(0.058)	(0.043)	(0.054)	(0.050)	(0.062)
Absolute Latitude	-0.095***	-0.074***	-0.066**	-0.128***	-0.115***	-0.105***	-0.099***	-0.120***	-0.118***
	(0.024)	(0.022)	(0.028)	(0.018)	(0.019)	(0.019)	(0.020)	(0.032)	(0.032)
Land Area	0.029	0.101	0.090	0.202**	0.159*	0.196**	0.174**	0.187	0.147
	(0.065)	(0.066)	(0.056)	(0.099)	(0.086)	(0.098)	(0.081)	(0.114)	(0.090)
Climate		0.999***				0.573***		0.508**	
		(0.197)				(0.208)		(0.229)	
Orientation of Landmass		-0.575***				-0.876***		-0.869***	
		(0.202)				(0.227)		(0.265)	
Size of Landmass		0.038***				0.040***		0.039***	
		(0.010)				(0.009)		(0.010)	
Geographic Conditions			0.595***				0.278**		0.292
			(0.182)				(0.129)		(0.178)
Domesticable Plants				0.124***		0.111***		0.115***	
				(0.026)		(0.023)		(0.025)	
Domesticable Animals				-0.021		-0.150		-0.160	
				(0.119)		(0.100)		(0.107)	
Biogeographic Conditions					1.263***		1.136***		1.096***
					(0.264)		(0.259)		(0.285)
Mean Elevation								0.014	0.021
								(0.045)	(0.049)
Mean Ruggedness								-0.042	-0.120
								(0.117)	(0.131)
% Land in Tropical Zones								0.713	0.638
								(0.430)	(0.575)
% Land in Temperate Zones								0.680	0.696
								(0.441)	(0.497)
Small Island Dummy	No	No	No	No	No	No	No	Yes	Yes
Landlocked Dummy	No	No	No	No	No	No	No	Yes	Yes
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Optimal Temperature Volatility	7.985***	7.916***	6.981***	6.998***	7.071***	7.224***	6.648***	7.040***	6.596***
	(1.238)	(1.658)	(1.163)	(0.587)	(0.741)	(0.799)	(0.772)	(0.718)	(0.670)
F-test P-value	<0.001	0.001	0.002	<0.001	<0.001	<0.001	<0.001	0.002	0.005
Observations	97	97	97	97	97	97	97	97	97
R-squared	0.75	0.85	0.79	0.86	0.85	0.90	0.86	0.90	0.86

Notes: (i) Temperature volatility is the standard deviation of monthly temperatures across all months in the time period 1900–2000; (ii) Mean temperature is the average of monthly temperatures across all months in the time period 1900–2000; (iii) Geographic conditions is the first principal component of climate, and the size and orientation of the landmass; (iv) Biogeographic conditions is the first principal component of domesticable plants and animals; (v) The excluded continental category in all regressions comprises Oceania and the Americas; (vi) The F-test p-value is from the joint significance test of the linear and quadratic terms of temperature volatility; (vii) Heteroskedasticity robust standard error estimates are reported in parentheses; (viii) The standard error estimate for the optimal temperature volatility is computed via the delta method; (ix) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

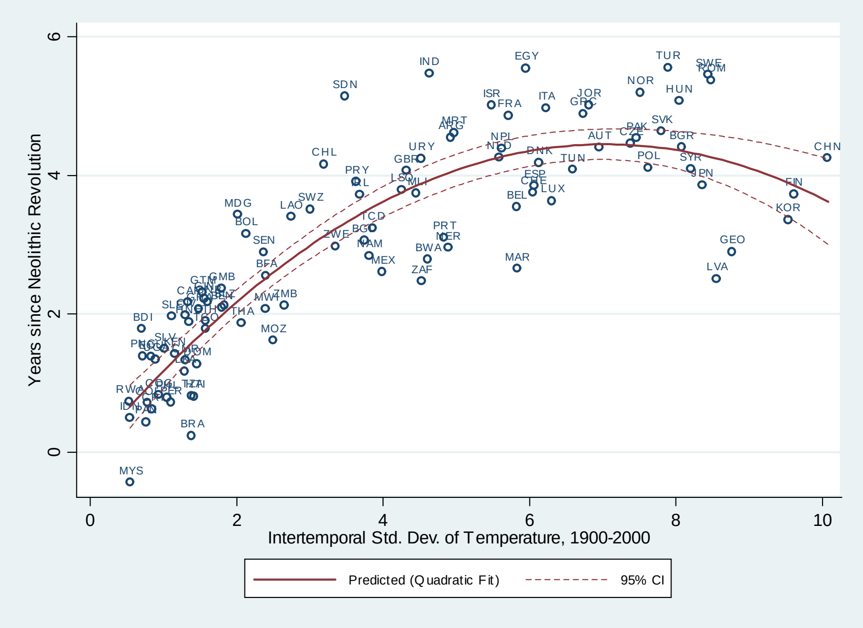


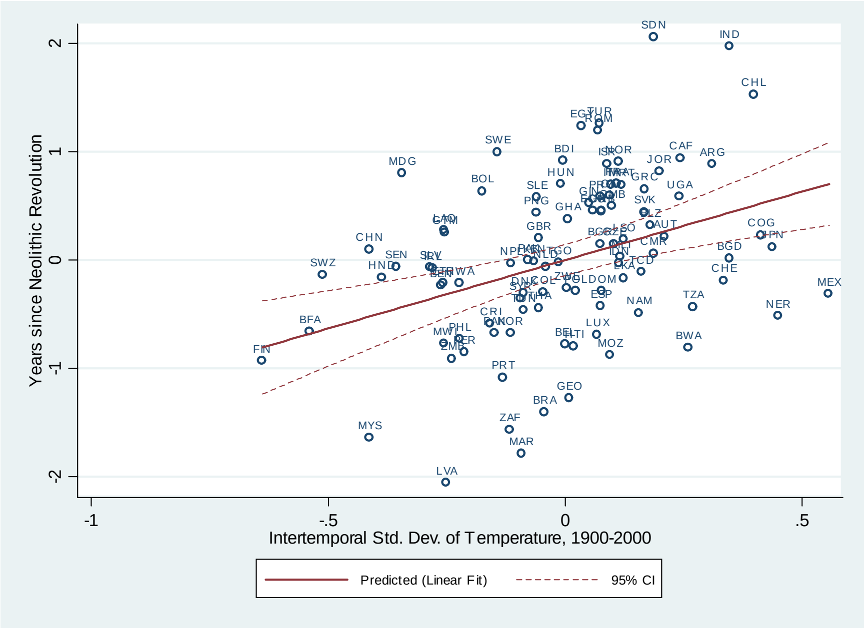
Figure 9: Contemporary Temperature Volatility and Transition Timing

Conditional on Mean Temperature, Distance to Frontier, Geographic and Biogeographic Factors, and Continent FE

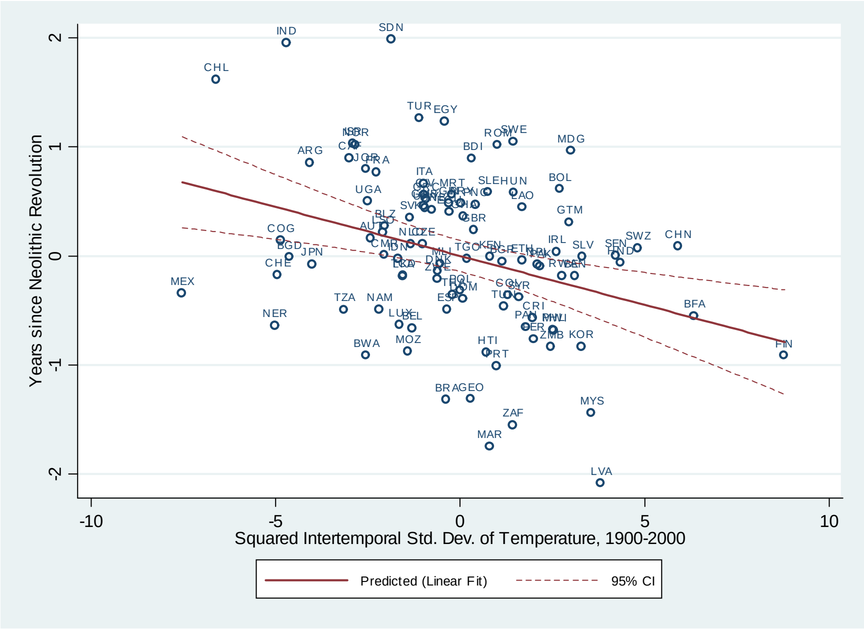
years. As for the control variables in the specification of Column 1, the significant negative coefficient on log-distance to the Neolithic frontier is a finding that is consistent with the spatial diffusion of agricultural practices, whereas the significant positive coefficient on land area is supportive of the findings of Kremer (1993) regarding the presence of scale effects throughout human history. Moreover, the coefficient on absolute latitude indicates that latitudinal bands closer to the equator are associated with an earlier transition to agriculture.

The remainder of the analysis in Table 1 is concerned with ensuring that the relationship between volatility and the timing of the Neolithic is not simply spurious, due to correlations between climatic volatility and other geographic and biogeographic endowments that have been deemed important for the transition to agriculture in the previous literature. Thus, Column 2 augments the preceding analysis with controls for geographic variables from the study of Olsson and Hibbs (2005), including an index gauging climatic favorability for agriculture, as well as the size and orientation of the landmass, which, as argued by Diamond (1997), played an important role by enhancing the availability of domesticable species and by facilitating the diffusion of agricultural technologies along similar environments. Column 3 repeats this analysis using the first principal component of the aforementioned geographic controls, a variable used by Olsson and Hibbs to demonstrate the validity of Diamond's hypothesis.

The baseline specification from Column 1 is augmented with controls for the numbers of prehistoric domesticable species of plants and animals in Column 4, while Column 5 replicates this same exercise using the first principal component of these biogeographic variables. The next two columns demonstrate robustness to the combined set of geographic and biogeographic controls from Olsson and Hibbs' empirical exercise, with the relevant controls entering the regression specification either as individual covariates in Column 6 or as principal components in Column 7. Finally, Columns 8 and 9 further augment the specifications from the



(a) The First-Order Effect



(b) The Second-Order Effect

Figure 10: The First- and Second-Order Effects of Contemporary Volatility on Transition Timing

Conditional on Mean Temperature, Distance to Frontier, Geographic and Biogeographic Factors, and Continent FE previous two columns with controls for elevation, a measure capturing the degree of terrain undulation, the percentages of land in tropical and temperate climatic zones, and small island and landlocked dummies that capture additional fixed effects potentially important for the diffusion and implementation of agricultural technologies.[32] The overall hump-shaped effect of temperature volatility on the timing of the Neolithic transition, conditional on the full set of controls in Column 8, is depicted on the scatter plot in Figure 9, while the associated first- and second-order partial effects of volatility – i.e., the regression lines corresponding to the first- and second-order coefficients – are depicted in Figures 10(a)–10(b).[33] As illustrated in Figure 9, the coefficients of interest from Column 8 imply that a one standard deviation change in temperature volatility on either side of the optimum is associated with a delay in the onset of the Neolithic Revolution by 90 years.

As is evident from Table 1, the hump-shaped effect of temperature volatility on the timing of the Neolithic Revolution revealed in Column 1 remains robust, both quantitatively and qualitatively, when subjected to a variety of controls for geographic and biogeographic endowments. With regard to the control variables, absolute latitude and log-distance from the Neolithic frontier appear to consistently confer effects across specifications that are in line with priors, whereas the effects associated with the geographic and biogeographic variables examined by Olsson and Hibbs (2005) are largely consistent with the results of their empirical exercise.

To summarize, the findings uncovered in Table 1, while validating the importance of technology diffusion and geographic and biogeographic endowments, provide reassurance that the significant hump-shaped effect of temperature volatility on the timing of the Neolithic Revolution is not simply a spurious relationship, attributable to other channels highlighted previously in the literature, but one that plausibly reflects the novel empirical predictions of the proposed theory.

Accounting for Seasonality One shortcoming of the measure of temperature volatility employed thus far is that, since it is derived using all months in the 1900–2000 time frame, it captures a systematic component of temperature volatility that is due to seasonality alone. Given that the theory assigns a bigger role to unanticipated fluctuations, and because seasonality is undoubtedly highly correlated with other geographical determinants of the timing of the Neolithic Revolution, if seasonality alone is driving the observed hump-shaped pattern, then the interpretation of the results as being supportive of the proposed theory becomes somewhat suspect. While the inclusion of absolute latitude as a control variable in the regression specifications partially mitigates the seasonality issue, it is far from perfect.

Hence, to rigorously address this issue, the analysis at hand constructs measures of temperature volatility by season, using data on season-specific months from the monthly temperature time series over the 1900–2000 time horizon while accounting for hemisphericity. Thus, temperature volatility in spring months is measured as the standard deviation of the sample comprising March, April, and May from each year in the 1900–2000 time frame for countries in the Northern Hemisphere, and the sample comprising September,

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[32] In terms of data sources for the additional controls, the data on mean elevation and terrain undulation (ruggedness) by country is obtained from the GECON database of Nordhaus (2006), while data on the percentages of land area in tropical and temperate climatic zones is taken from the dataset of Gallup et al. (1999). Finally, the island and landlocked dummies are obtained from the CIA World Factbook 2008.

[33] It should also be noted that Figures 9 and 11 are "augmented component plus residual" plots and not the typical "added variable" plots of residuals against residuals. In particular, the vertical axes in these figures represent the component of transition timing that is explained by temperature volatility and its square plus the residuals from the corresponding regression. The horizontal axes, on the other hand, simply represent temperature volatility rather than the residuals obtained from regressing volatility on the covariates. This methodology permits the illustration of the overall non-monotonic effect of temperature volatility in one scatter plot per regression, with the regression line being generated by a quadratic fit of the y-axis variable (explained above) on the x-axis variable (temperature volatility).

Table 2: The Timing of the Neolithic Revolution and Contemporary Temperature Volatility by Season

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is Thousand Years Elapsed since the Neolithic Revolution							
	Intertemporal Volatility and Mean of Monthly Temperature (1900-2000) Using Data on:							
	Spring Months		Summer Months		Fall Months		Winter Months	
Temperature Volatility	7.552***	5.449***	9.448***	9.269***	8.777***	7.225***	4.585***	4.041***
	(1.969)	(1.764)	(2.387)	(2.635)	(1.996)	(2.064)	(0.732)	(0.923)
Temperature Volatility Square	-2.250***	-1.877***	-4.747***	-5.450***	-2.547***	-2.346***	-1.040***	-0.871***
	(0.750)	(0.632)	(1.227)	(1.342)	(0.782)	(0.765)	(0.164)	(0.191)
Mean Temperature	-0.028	0.035	0.083**	0.040	0.046	0.074	-0.006	0.067
	(0.037)	(0.053)	(0.041)	(0.049)	(0.040)	(0.068)	(0.037)	(0.055)
Log Distance to Frontier	-0.238***	-0.183***	-0.265***	-0.188***	-0.233***	-0.190***	-0.245***	-0.171***
	(0.075)	(0.049)	(0.067)	(0.043)	(0.066)	(0.050)	(0.067)	(0.044)
Absolute Latitude	-0.067***	-0.077***	-0.010	-0.036*	-0.073***	-0.072***	-0.048**	-0.059**
	(0.025)	(0.027)	(0.022)	(0.020)	(0.022)	(0.025)	(0.023)	(0.025)
Land Area	0.033	0.138	0.035	0.121	0.021	0.117	0.017	0.104
	(0.068)	(0.087)	(0.066)	(0.078)	(0.066)	(0.094)	(0.078)	(0.092)
Geographic Conditions		0.447**		0.676***		0.394**		0.434***
		(0.177)		(0.168)		(0.185)		(0.156)
Biogeographic Conditions		1.113***		0.990***		0.961***		1.043***
		(0.297)		(0.274)		(0.277)		(0.279)
Mean Elevation		0.045		0.036		0.061		0.093**
		(0.042)		(0.039)		(0.049)		(0.045)
Mean Ruggedness		-0.140		-0.192		-0.105		-0.199
		(0.128)		(0.125)		(0.130)		(0.133)
% Land in Tropical Zones		-0.049		0.138		0.580		0.004
		(0.495)		(0.569)		(0.612)		(0.445)
% Land in Temperate Zones		1.045*		0.224		0.719		0.824
		(0.556)		(0.469)		(0.530)		(0.534)
Small Island Dummy	No	Yes	No	Yes	No	Yes	No	Yes
Landlocked Dummy	No	Yes	No	Yes	No	Yes	No	Yes
Continent Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Optimal Temperature Volatility	1.678***	1.452***	0.995***	0.850***	1.723***	1.540***	2.205***	2.320***
	(0.189)	(0.175)	(0.111)	(0.070)	(0.194)	(0.182)	(0.129)	(0.229)
F-test P-value	<0.001	0.011	0.001	<0.001	<0.001	0.003	<0.001	<0.001
Observations	97	97	97	97	97	97	97	97
R-squared	0.73	0.86	0.74	0.87	0.77	0.86	0.75	0.88

Notes: (i) Temperature volatility is the standard deviation of monthly temperatures across season-specific months in the time period 1900–2000; (ii) Mean temperature is the average of monthly temperatures across season-specific months in the time period 1900–2000; (iii) The seasonal compositions in the Nothern/Southern Hemisphere are defined as Spring/Fall (Mar-Apr-May), Summer/Winter (Jun-Jul-Aug), Fall/Spring (Sep-Oct-Nov), Winter/Summer (Dec-Jan-Feb); (iv) Geographic conditions is the first principal component of climate, and the size and orientation of the landmass; (v) Biogeographic conditions is the first principal component of domesticable plants and animals; (vi) The excluded continental category in all regressions comprises Oceania and the Americas; (vii) The F-test p-value is from the joint significance test of the linear and quadratic terms of temperature volatility; (viii) Heteroskedasticity robust standard error estimates are reported in parentheses; (ix) The standard error estimate for the optimal temperature volatility is computed via the delta method; (x) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 3: Wald Tests of the Impact of Volatility in Winter vs. Other Seasons

	(1)	(2)	(3)	(4)	(5)	(6)
	$\chi^2(1)$ Statistic from Testing the Null Hypothesis that the Effect of Volatility in Winter Months is not Different From the Effect in:					
	Spring Months		Summer Months		Fall Months	
	Baseline Model	Full Controls	Baseline Model	Full Controls	Baseline Model	Full Controls
Test on the First-Order Effect	2.98*	1.00	5.25**	5.83**	6.18**	4.18**
	[0.084]	[0.317]	[0.022]	[0.016]	[0.013]	[0.041]
Test on the Second-Order Effect	3.38*	3.97**	11.05***	16.55***	4.82**	5.64**
	[0.066]	[0.046]	[0.001]	[<0.001]	[0.028]	[0.018]

Notes: (i) p-values are reported in square brackets; (ii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

October, and November from each year in the 1900–2000 time frame for countries in the Southern Hemisphere. For temperature volatility in summer months, the relevant sample focuses on June, July, and August for countries in the Northern Hemisphere but December, January, and February for countries in the Southern Hemisphere, and so forth. The relevant descriptive statistics of the four seasonal volatility measures and their correlations with the control variables employed by the regressions to follow are reported in Appendix E in Tables E.3 and E.4 respectively.

Table 2 presents the results from regressions examining, at a time, each of the four seasonal temperature volatility measures as a non-monotonic determinant of the timing of the Neolithic Revolution. In particular, for each seasonal volatility measure, two specifications are considered, one with the baseline set of controls (corresponding to Column 1 of Table 1) and the other with the full set of controls (corresponding to Column 9 of Table 1). As is evident from the table, for each season examined, the regressions reveal a highly statistically significant and robust hump-shaped effect of volatility on the timing of the Neolithic. Specifically, the estimated first- and second-order coefficients on volatility not only appear with their expected signs, but also maintain statistical significance at the 1% level and remain rather stable in magnitude when subjected to the full set of controls for geographic and biogeographic endowments. This pattern is reassuringly reflected by the corresponding estimates of optimal volatility implied by these coefficients.

Comparing the magnitudes of the coefficients of interest across seasons, the regressions indicate a lower relative importance of temperature volatility during winter months. This pattern is more rigorously confirmed by Table 3, which collects the results from Wald tests conducted to examine whether the first- and second-order effects of winter volatility, as presented in Table 2, are significantly different from the corresponding effects of volatility in other seasons. Importantly, the relatively weaker impact of volatility during winter months, revealed in Table 2, is entirely consistent with the prior that knowledge accumulation in the hunter-gatherer regime is more likely to be useful for agriculture when the possibility of farming is present, which is less so during winter months.[34] This finding is also in line with the argument that the greater constraint on resource availability during these months would have been rationally anticipated by hunter-gatherers and, thus, accounted for in their food procurement activities. As such, temperature volatility in the winter months should be expected to play a smaller role in shaping the subsistence strategies and the associated specific human capital accumulation of hunter-gatherers towards the adoption of agriculture.

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[34] An alternative way to gauge the relative importance of the season-specific volatilities would have been to explicitly include all four seasonal measures in the same regression specification. However, given the high sample correlations between these respective measures, the resulting regression would be rather uninformative due to the well-known consequences of multicollinearity.

In sum, the results uncovered in Table 2, while being quantitatively different from those associated with the baseline measure of volatility in Table 1, establish the qualitative robustness of the baseline findings to the issue of seasonality. This lends support to the assertion that the significant and robust hump-shaped effect of temperature volatility on the timing of the Neolithic Revolution is not being driven by systematic intertemporal fluctuations due to seasonality, a finding that would otherwise have been at odds with the predictions of the proposed theory.

8.1.2 Results with Historical Volatility

As discussed earlier, the interpretation of the results obtained using contemporary measures of temperature volatility rests on the identifying assumption that the cross-country distribution of temperature volatility in the 20th century was not significantly different from that prior to the Neolithic Revolution. In an effort to relax this assumption, this section focuses on establishing qualitatively similar results using a measure of volatility computed from historical temperature data.

In particular, the measure of volatility employed by this exercise is the standard deviation of the seasonal time series of temperature from 1500 to 1899. As mentioned earlier, the sample considered here comprises 25 primarily European countries, selected based on the condition that these observations not only possess data on the standard set of control variables, but also appear in the 97-country sample considered earlier. This permits fair comparisons of the effects of contemporary versus historical measures of volatility in the same sample of countries.[35] In this modest 25-country sample, the historical measure of temperature volatility assumes a minimum value of 3.344 (for Ireland), a maximum value of 8.735 (for Finland), and a sample mean and standard deviation of 6.265 and 1.317 respectively. The reader is referred to Tables E.5 and E.6 in Appendix E for additional descriptive statistics and correlations pertaining to this 25-country sample.

Columns 1–4 of Table 4 reveal the results from regressions using the historical measure of volatility. In line with theoretical predictions, and despite sample size limitations, Column 1 shows a highly statistically significant hump-shaped relationship between the timing of the Neolithic Revolution and the historical measure of temperature volatility, conditional on mean historical temperature, log-distance to the closest Neolithic frontier, absolute latitude, land area, geographic factors from the Olsson and Hibbs (2005) exercise, and a Europe fixed effect.[36] Moreover, this non-monotonic effect, along with the estimate of optimal volatility, remains qualitatively and quantitatively robust when the specification is modified to use the first principal component of the geographic endowment variables in Column 2, and when it is further augmented to include controls for elevation, terrain quality, and a landlocked dummy in Columns 3 and 4.[37] The overall hump-shaped effect of historical temperature volatility on the timing of the Neolithic transition, conditional on the

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[35] While historical temperature data is available for some countries in North Africa and the Near East as well, the data is considered to be far more reliable for European countries where the number of weather stations is substantially larger and more uniformly distributed across space. In addition, there is no evidence of systematic climatic reversals amongst European countries since the Last Glacial Maximum, unlike, for example, in North Africa where expansions of the Sahara has resulted in increased desertification over time.

[36] Since Olsson and Hibbs (2005) report data on biogeographic endowments – i.e., the numbers of prehistoric domesticable species of plants and animals – at a macroregional level, and because the European continent is treated as one macroregion in their dataset, there is insufficient cross-sectional variation in these biogeographic variables within the 25-country sample being considered. As such, controls for biogeographic endowments are omitted from these regressions.

[37] The small island dummy is not considered here since there are no observations in the 25-country sample that are classified as small islands. While the British Isles are included in the sample, the fact that the UK and Ireland share a border prevents the strict qualification of these countries as small island nations. Relaxing this strict definition of a small island nation to treat the UK and Ireland as small islands does not significantly alter the results.

Table 4: The Timing of the Neolithic Revolution and Historical vs. Contemporary Temperature Volatility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable is Thousand Years Elapsed since the Neolithic Revolution							
	Intertemporal Volatility and Mean of Temperature in the:							
	Historical Period (1500–1899)				Contemporary Period (1900–2000)			
Temperature Volatility	5.370***	4.646***	4.976***	4.182***	4.610***	3.648***	3.887***	3.040***
	(0.768)	(0.711)	(0.952)	(0.793)	(0.867)	(0.744)	(1.032)	(0.790)
Temperature Volatility Square	-0.402***	-0.343***	-0.383***	-0.317***	-0.319***	-0.248***	-0.283***	-0.218***
	(0.061)	(0.053)	(0.077)	(0.061)	(0.062)	(0.050)	(0.072)	(0.052)
Mean Temperature	0.173**	0.145**	-0.022	-0.061	0.138**	0.096	-0.224	-0.256
	(0.061)	(0.067)	(0.300)	(0.242)	(0.059)	(0.072)	(0.319)	(0.274)
Log Distance to Frontier	-0.054	-0.100	-0.140	-0.198	-0.025	-0.107	-0.184	-0.266*
	(0.125)	(0.120)	(0.118)	(0.114)	(0.136)	(0.131)	(0.126)	(0.141)
Absolute Latitude	-0.096**	-0.096**	-0.198	-0.199	-0.107***	-0.110***	-0.296*	-0.291*
	(0.035)	(0.035)	(0.148)	(0.125)	(0.032)	(0.036)	(0.165)	(0.142)
Land Area	1.588	1.897*	2.613**	2.894**	1.200	1.680	2.329**	2.755**
	(1.170)	(1.006)	(0.900)	(1.055)	(1.325)	(1.115)	(0.843)	(1.145)
Climate	-0.940		-1.047		-1.037*		-1.055	
	(0.541)		(0.656)		(0.558)		(0.665)	
Orientation of Landmass	2.502***		2.591**		3.064**		2.708*	
	(0.808)		(1.001)		(1.084)		(1.317)	
Size of Landmass	-0.163***		-0.160***		-0.174***		-0.148**	
	(0.037)		(0.050)		(0.050)		(0.064)	
Geographic Conditions		-0.790***		-0.687***		-0.607**		-0.457**
		(0.214)		(0.218)		(0.216)		(0.211)
Mean Elevation			-0.280	-0.306			-0.352*	-0.371**
			(0.233)	(0.197)			(0.182)	(0.162)
Mean Ruggedness			0.309	0.409			0.241	0.332
			(0.294)	(0.253)			(0.262)	(0.242)
Landlocked Dummy	No	No	Yes	Yes	No	No	Yes	Yes
Europe Dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Optimal Temperature Volatility	6.680***	6.771***	6.489***	6.599***	7.231***	7.366***	6.860***	6.962***
	(0.236)	(0.214)	(0.276)	(0.239)	(0.269)	(0.284)	(0.398)	(0.415)
F-test P-value	<0.001	<0.001	0.001	0.001	<0.001	0.001	0.008	0.003
Observations	25	25	25	25	25	25	25	25
R-squared	0.94	0.93	0.95	0.94	0.93	0.92	0.95	0.93

Notes: (i) For the 1900–2000 time period, temperature volatility is the standard deviation of monthly temperatures across all months within this period, whereas for the 1500–1899 time period, it is the standard deviation of seasonal temperatures across all seasons spanning this period; (ii) For the 1900–2000 time period, mean temperature is the average of monthly temperatures across all months within this period, whereas for the 1500–1899 time period, it is the average of seasonal temperatures across all seasons spanning this period; (iii) Geographic conditions is the first principal component of climate, and the size and orientation of the landmass; (iv) Biogeographic conditions is the first principal component of domesticable plants and animals; (v) The excluded continental category in all regressions comprises Oceania and the Americas; (vi) The F-test p-value is from the joint significance test of the linear and quadratic terms of temperature volatility; (vii) Heteroskedasticity robust standard error estimates are reported in parentheses; (viii) The standard error estimate for the optimal temperature volatility is computed via the delta method; (ix) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

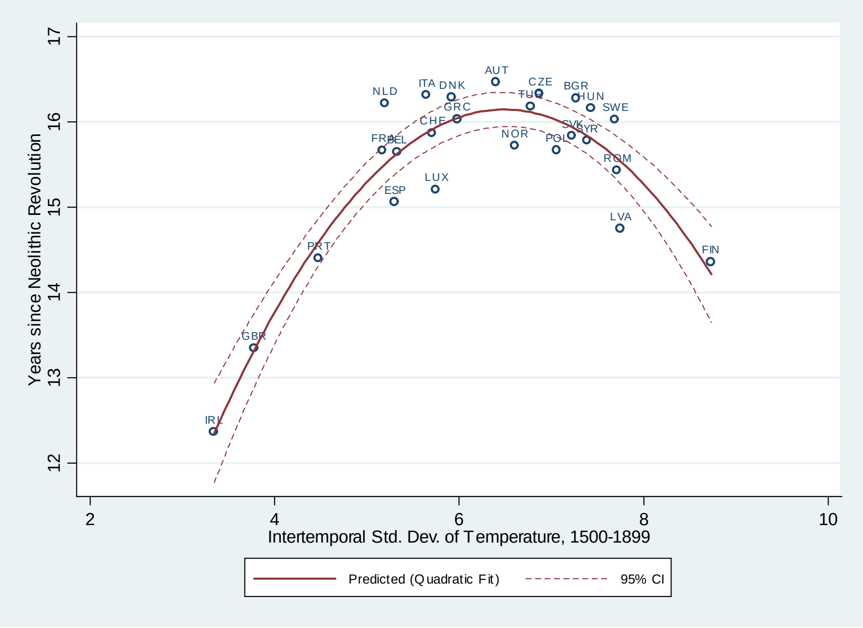


Figure 11: Historical Temperature Volatility and Transition Timing

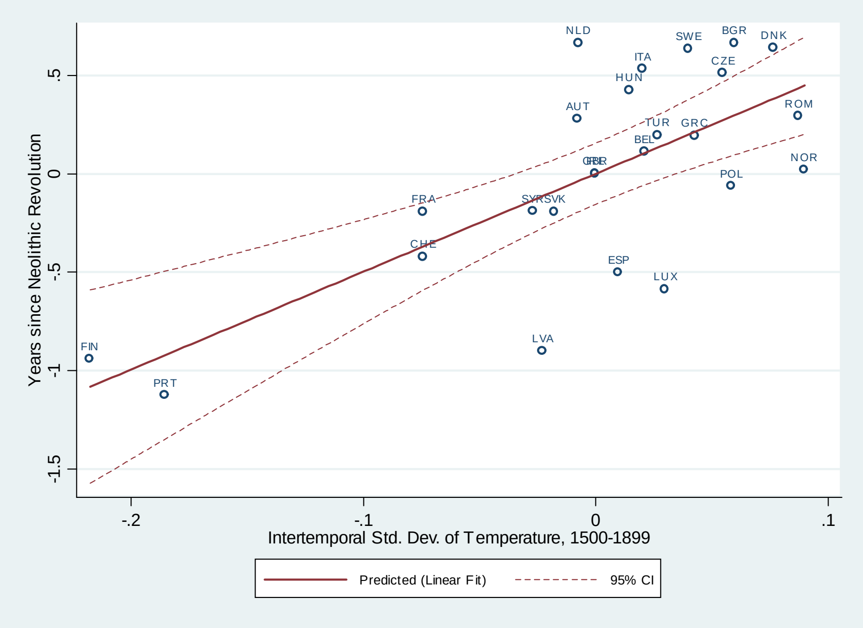
Conditional on Mean Temperature, Distance to Frontier, Geographic and Biogeographic Factors, and Continent FE

full set of controls in Column 3, is depicted on the scatter plot in Figure 11, while the associated first and second order partial effects of volatility – i.e., the regression lines corresponding to the first and second order coefficients – are depicted in Figures 12(a)–12(b). To interpret the associated metric effect, a one standard deviation change in historical temperature volatility at the optimal volatility level of 6.489 is associated with a delay in the onset of the Neolithic Revolution by 383 years.

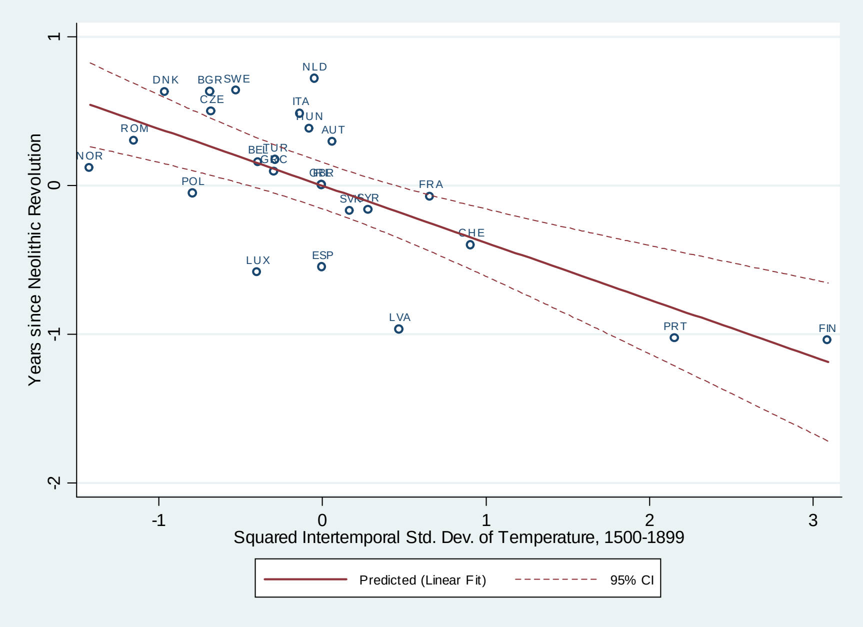
The final four columns of Table 4 repeat the preceding analyses using the contemporary rather than the historical measure of volatility in the 25-country sample. This permits a fair assessment of the identifying assumption that the cross-country distribution of temperature volatility remains stable over long periods of time and, therefore, that a contemporary cross-country distribution of temperature volatility may indeed be used to proxy for the unobserved prehistoric distribution. As is evident from Table 4, and as foreshadowed by the high correlation between the contemporary and historical measures of volatility, the results in Columns 5–8 do not substantially depart from those presented in Columns 1–4, thereby lending further credence to the identifying assumption underlying this exercise. Taken together, these empirical findings provide compelling evidence in support of the proposed theory, suggesting that spatial variation in climatic volatility was indeed a fundamental force behind the differential timing of the prehistoric transition to agriculture across regions of the world.

8.2 Cross-Archaeological Site Analysis

Precise estimates on the timing of the agricultural transition are obtained from the radiocarbon dating of archaeological excavations at early Neolithic sites. Thus, while Putterman's country-level estimates, based on standard archaeological sources and a multitude of country-specific historical references, provide a valuable and, indeed, the only source that covers a large cross-section of countries, this information is



(a) The First-Order Effect



(b) The Second-Order Effect

Figure 12: The First- and Second-Order Effects of Historical Volatility on Transition Timing

Conditional on Mean Temperature, Distance to Frontier, Geographic and Biogeographic Factors, and Continent FE undoubtedly a noisy proxy of the actual timing of the Neolithic Revolution. This section supplements the empirical investigation using a novel cross-archaeological site dataset. In particular, local climatic sequences are constructed from grid-level temperature data and combined with high quality data on radiocarbon dates for 750 early Neolithic settlements in Europe and the Middle East to explore the climatic determinants of the agricultural transition at the site level.

The site-level data on the timing of the Neolithic transition is obtained from the recent dataset compiled by Pinhasi et al. (2005). To construct their dataset, the authors selected the earliest date of Neolithic occupation for each of 750 sites in Europe and the Middle East, using uncalibrated radiocarbon dates that have standard errors of less than 200 radiocarbon years, and omitting all dates with higher error intervals as well as outlier dates. According to the authors, the resulting collection of sites and the corresponding dates provide a secure sample for the earliest appearance of each of the early Neolithic archaeological cultures in the regions covered.

As in the cross-country analysis, measures of the mean and standard deviation of temperature are constructed from Mitchell et al.'s (2004) monthly time series temperature data over the 1900–2000 time horizon.[38] Unlike the country-level measures, however, the site-level measures are constructed by averaging the intertemporal moments of temperature at the grid level across grids that fall within a 50km radius from each site. Thus, the volatility of temperature for a given site provides a measure of the volatility prevalent in the "average" grid within 50 kilometers of the site.

A quadratic specification similar to the one used in the cross-country analysis is employed to estimate the proposed non-monotonic effect of climate volatility on the timing of the transition to agriculture across sites:

$$YST_i = \delta_0 + \delta_1 VOL_i + \delta_2 VOL_i^2 + \delta_3 TMEAN_i + \delta_4 LDIST_i + \delta_5 LAT_i + \delta_6 \Delta_i + \delta_7 \square_i + \eta_i,$$

where YST_i is the number of thousand years elapsed since the earliest date of Neolithic occupation at site i, as reported by Pinhasi et al. (2005); VOL_i is the temperature volatility at site i during the contemporary (1900–2000) time horizon ; $TMEAN_i$ is the mean temperature at site i during this time horizon; $LDIST_i$ is the log of the great-circle distance of site i from Cayönü, one of the Neolithic frontiers identified by Pinhasi et al. (2005); LAT_i is the absolute latitude of site i; Δ_i is a Europe dummy; $\square_i$ is a vector of local microgeographic variables, including an index of climatic suitability for heavy-seed cultivation, elevation, and distance to the coast; and, finally, η_i is a site-specific disturbance term.[39] All control variables are site-specific, and are constructed using grid-level data at a 0.5 degree resolution, aggregated across grids located within a 50km radius from each site.[40] It should also be noted that these sites belong to countries that, according to the dataset of Olsson and Hibbs (2005), have identical biogeographic conditions in terms of the numbers of prehistoric domesticable species of plants and animals. Hence, the sample considered provides a

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[38] Given that the historical temperature data used in the cross-country analysis does not cover all the archaeological sites, the contemporary temperature data is employed instead.

[39] The standard errors are clustered at the country level to account for spatial autocorrelation in η_i. Applying the correction method proposed by Conley (1999), however, yields similar results.

[40] The site-level measure of climatic suitability for agriculture is constructed by applying the Olsson and Hibbs (2005) definition of this variable to grid-level data from Kottek et al. (2006) on the global distribution of Köppen-Geiger climate zones. Elevation is calculated using the TerrainBase, release 1.0 dataset from the National Oceanic and Atmospheric Administration (NOAA) and U.S. National Geophysical Data Center. Finally, distance from the sea is computed (after omitting the data on lakes) using the coastlines of seas, oceans, and extremely large lakes dataset published by Global Mapping International, Colorado Springs, Colorado, USA, version 3.0.

natural setup to explore whether heterogeneous climatic sequences generate differences in the timing of the transition to agriculture across regions that have access to common biogeographic endowments.

Table 5 collects the regression results of the cross-archaeological site analysis. The measure of volatility used in Columns 1 and 2 is the standard deviation of the monthly time series of temperature spanning the 1900–2000 time horizon. For the sample of 750 sites, the volatility measure has a sample mean and standard deviation of 6.264 and 1.416 respectively. These descriptive statistics along with those of the control variables employed are collected in Table E.7 in Appendix E, with the relevant correlations appearing in Table E.8.

Consistent with the predictions of the proposed theory, Column 1 of Table 5 shows a statistically significant hump-shaped relationship between the timing of the Neolithic Revolution and temperature volatility, conditional on mean temperature, log-distance to the Neolithic frontier, absolute latitude and a Europe fixed effect. In particular, the first- and second-order coefficients on temperature volatility are both statistically significant at the 5% level, and enter with their expected signs. The coefficients of interest imply that the optimal level of temperature volatility for the Neolithic transition in this sample of sites is 7.288. It is interesting to note that the magnitude of optimal volatility is almost identical to the optimum of 7.231 found in the sample of the 25 countries in Column 5 of Table 4. To interpret the overall metric effect implied by these coefficients, a unit change in the standard deviation of temperature at the optimum is associated with a delay in the onset of the Neolithic Revolution across sites by 50 years.

As for the control variables in Column 1, the significant negative coefficient on log-distance to the Neolithic frontier is consistent with the spatial diffusion of agricultural knowledge, while the coefficient on absolute latitude indicates that, conditional on climatic characteristics, hunter-gatherers at latitudinal bands closer to the poles experienced a delayed onset of farming. Column 2 augments the analysis by introducing site-specific controls for climatic favorability towards agriculture, distance to the sea, and elevation. Consistent with priors, Neolithic sites possessing climatic conditions more suitable for farming underwent an earlier transition, although the point estimate is insignificant. Moreover, the positive coefficient on distance to the sea implies that settlements closer to the coast experienced a later transition to agriculture. To the extent that distance from the coast captures the dependence of prehistoric hunter-gatherers on aquatic resources, this finding is consistent with the archaeological and ethnological record of cultures whose subsistence pattern, involving a heavier reliance on aquatic resources, resulted in a delayed adoption of farming.

The remaining columns of Table 5 address the issue of seasonality, discussed previously in the cross-country analysis, by constructing season-specific measures of temperature volatility at the site level. In particular, for each seasonal volatility measure, two specifications are considered, one with the baseline set of controls (corresponding to Column 1 of Table 5) and the other with the full set of controls (corresponding to Column 2 of Table 5). As is evident from the table, the regressions reveal a statistically significant and robust hump-shaped effect of seasonal volatility on the timing of the Neolithic transition. Specifically, the estimated first- and second-order coefficients on volatility appear with their expected signs and remain rather stable in magnitude when subjected to the full set of controls for geographic endowments. Note that consistent with the findings in the cross-country analysis, the impact of winter volatility is quantitatively less important, and incidentally also less precisely estimated, than volatility in the rest of the seasons. This pattern is more rigorously confirmed by the bottom panel of Table 5, which shows that the effects of winter volatility, as

Table 5: The Timing of the Neolithic Revolution and Temperature Volatility at the Site Level

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Dependent Variable is Thousand Years Elapsed since the Neolithic Revolution									
	Intertemporal Volatility and Mean of Monthly Temperature (1900–2000) Using Data on:									
	All Months		Spring Months		Summer Months		Fall Months		Winter Months	
Temperature Volatility	0.732**	0.752**	6.294***	6.315***	7.450***	7.720***	7.774***	8.318***	1.832*	1.717
	(0.322)	(0.323)	(1.195)	(1.334)	(2.562)	(2.752)	(1.367)	(1.815)	(1.067)	(1.092)
Temperature Volatility Square	-0.050**	-0.053**	-1.931***	-1.973***	-2.762**	-2.948**	-2.541***	-2.815***	-0.436*	-0.426*
	(0.025)	(0.026)	(0.383)	(0.439)	(1.094)	(1.141)	(0.489)	(0.670)	(0.228)	(0.238)
Mean Temperature	-0.042	-0.025	-0.030	-0.031	0.000	0.004	-0.009	-0.018	-0.040	-0.041
	(0.038)	(0.034)	(0.032)	(0.034)	(0.027)	(0.026)	(0.030)	(0.031)	(0.037)	(0.040)
Log Distance to Frontier	-0.791***	-0.744***	-0.617***	-0.585***	-0.726***	-0.628***	-0.551***	-0.535***	-0.739***	-0.713***
	(0.228)	(0.249)	(0.160)	(0.161)	(0.199)	(0.202)	(0.143)	(0.138)	(0.213)	(0.216)
Absolute Latitude	-0.077***	-0.078***	-0.096***	-0.103***	-0.083***	-0.092***	-0.092***	-0.105***	-0.092***	-0.097***
	(0.021)	(0.022)	(0.016)	(0.020)	(0.017)	(0.022)	(0.017)	(0.024)	(0.014)	(0.019)
Climate		0.148		0.097		0.160*		0.068		0.093
		(0.119)		(0.090)		(0.094)		(0.075)		(0.126)
Mean Elevation		0.003		-0.012		-0.006		-0.021		-0.012
		(0.030)		(0.029)		(0.026)		(0.029)		(0.031)
Distance to Coast		0.040		0.038		0.046		0.054*		0.041
		(0.044)		(0.030)		(0.028)		(0.027)		(0.029)
Europe Dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Optimal Temperature Volatility	7.288***	7.029***	1.629***	1.600***	1.349***	1.309***	1.530***	1.478***	2.102***	2.016***
	(0.773)	(0.982)	(0.044)	(0.051)	(0.091)	(0.070)	(0.053)	(0.052)	(0.224)	(0.247)
F-test P-value	0.050	0.055	<0.001	<0.001	<0.001	0.008	<0.001	<0.001	0.102	0.107
Observations	750	750	750	750	750	750	750	750	750	750
R-squared	0.69	0.69	0.72	0.72	0.71	0.71	0.73	0.73	0.69	0.69

$\chi^2(1)$ Statistic from Testing the Null that the Effect of Volatility in Winter Months is not Different From the Effect in:

			Spring Months		Summer Months		Fall Months			
Test on the 1st-Order Effect			44.11***	36.67***	7.75***	7.84***	35.96***	24.13***		
			[<0.001]	[<0.001]	[0.005]	[0.005]	[<0.001]	[<0.001]		
Test on the 2nd-Order Effect			43.39***	32.48***	5.90**	6.46**	31.12***	19.25***		
			[<0.001]	[<0.001]	[0.015]	[0.011]	[<0.001]	[<0.001]		

Notes: (i) In Columns 1–2, temperature volatility is the standard deviation of monthly temperatures across all months in the time period 1900–2000, while mean temperature is the average of monthly temperatures across all months spanning this time frame; (ii) In Columns 3–10, temperature volatility is the standard deviation of monthly temperatures across season-specific months in the time period 1900–2000, while mean temperature is the average of monthly temperatures across season-specific months spanning this time frame; (iii) Given that all the sites in the cross-site sample appear in the Northern Hemisphere, the month-level compositions by season are defined as follows: Spring (Mar-Apr-May), Summer (Jun-Jul-Aug), Fall (Sep-Oct-Nov), and Winter (Dec-Jan-Feb); (iv) The F-test p-value is from the joint significance test of the linear and quadratic terms of temperature volatility; (v) Heteroskedasticity robust standard error estimates (clustered by country) are reported in parentheses below the regression coefficients; (vi) The standard error estimate for the optimal temperature volatility is computed via the delta method; (vii) The p-values of the $\chi^2(1)$ statistics are reported in square brackets; (viii) *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

presented in the top panel of the table, differs systematically from the corresponding effects of volatility in other seasons.

To better gauge the quantitative impact of climatic volatility on the advent of farming across sites, consider the following scenario involving spring temperature volatility. Within Germany, the earliest Neolithic site is that of Klein Denkte, possessing a spring volatility of 1.620 and an estimated transition timing of 7930 BP. Note that Klein Denkte's spring volatility is close to the estimated optimum of 1.629, presented in Column 3 of Table 5. On the other hand, the German Neolithic sites of Uhyst and Bistroft both transited to agriculture around 5500 BP, but display significantly different spring volatilities. In particular, Uhyst has the highest spring volatility within Germany at 1.869, whereas Bistroft has the lowest at 1.438. Endowing the settlement at Uhyst with the spring volatility of Klein Denkte would have accelerated the advent of farming in the former by 110 years, whereas the same experiment for Bistroft would have given rise to agricultural dependence at this location 70 years earlier.

The analysis in this section employed data on the timing of Neolithic settlements in Europe and the Middle East to explore the role of local, site-specific climatic sequences in shaping the transition to farming across reliably excavated and dated archaeological entities. Consistent with the theoretical predictions, and in line with the systematic pattern revealed by the cross-country analysis, Neolithic sites endowed with moderate levels of climatic volatility transited earlier into agriculture, conditional on local microgeographic characteristics. The recurrent finding that climatic volatility has had a non-monotonic impact on the emergence on farming, across countries and archaeological sites alike, sheds new light on the climatic origins of the Neolithic Revolution.

9 Concluding Remarks

This research examines theoretically and empirically the origins of agriculture. The theory emphasizes the role of climatic sequences in determining society-specific knowledge and technological endowments in a hunter-gatherer regime. It argues that foragers facing volatile environments were forced to take advantage of their productive endowments at a faster pace. Consequently, as long as climatic shocks preserved the possibility of agriculture, differences in the frequency with which foragers were climatically propelled to exploit their respective habitats determined the comparative evolution of hunting and gathering societies towards sedentary farming.

In support of the theoretical predictions both qualitative and quantitative evidence is uncovered. On the qualitative front, detailed archaeological accounts on the role of climatic shocks in transforming the Natufian foraging culture towards farming, as well as on cases of other independent transitions to agriculture are consistent with the main predictions. Namely, in the archaeological and ethnological record, instances of environmental stress are correlated with the appearance of more sophisticated food extraction and processing techniques, and with a higher dependence on lower-ranked resources including potentially domesticable species. In the context of the theory, these climatic downturns in human history were necessary for augmenting hunter-gatherer human capital (i.e., the knowledge of efficiently acquiring underexploited species) and population density. The concomitant extensive exploitation of plants by hunter-gatherers, accelerated their accumulation of latent agricultural knowledge and brought them closer to the adoption of agriculture as subsequent climatic shocks occurred. On the other hand, static climatic conditions, by not compelling foragers to fully exploit the marginal resources available in their habitats, precluded the accumulation of knowledge relevant for farming. Moreover, occurrences of extreme environmental fluctuations eliminated any cumulative "beneficial" effect of the climatic past on hunter-gatherer dietary patterns and resource procurement practices. Such extreme climatic events essentially reset the process of development towards the emergence of agriculture.

The key theoretical prediction regarding a hump-shaped effect of climatic volatility on the advent of farming is empirically demonstrated. Conducting a novel empirical investigation at both cross-country and cross-archaeological site levels, the analysis establishes that, conditional on biogeographic endowments, climatic volatility has indeed conferred a non-monotonic effect on the timing of the transition to agriculture. Farming was undertaken earlier in regions characterized by intermediate levels of climatic volatility, with regions subject to either too high or too low intertemporal variability systematically transiting later. Reassuringly, the results hold at different levels of analysis and using alternative sources of climatic sequences. The findings provide compelling evidence in support of the proposed theory, suggesting that heterogeneity in climatic volatility was a fundamental force behind the differential timing of the prehistoric transition to agriculture both at a local and at a global scale.

Appendices

A Supporting Evidence for the Main Theoretical Elements

A.1 Climate Variability since the LGM

Various sources have been used to identify climatic histories since the LGM.[41] The general pattern shows that the LGM was followed by an increase in average temperatures and precipitation levels for several thousand years. This deglaciation period ended around 11,000 BP with the advent of the Holocene. However, this improvement in global climatic conditions was neither deterministic nor an irreversible trend. The millennia following the LGM were characterized by high climatic variability, evident in abrupt changes between warm and relatively cold periods. Different regional climatic sequences, however, show a common dramatic reversal known as the Younger Dryas (YD) around 13,000 BP (Berger, 1990).[42]

In the region of interest, i.e., Southwest Asia, there are several studies with often conflicting results regarding the timing of the occurrence of the YD. Wright, Jr. and Thorpe (2003) summarize and reconcile contradicting chronologies in the published record on the climatic sequence of the Levant. The authors firmly identify both the end of the LGM and the advent of the Younger Dryas, with the latter occurring around 13,000 BP.[43]

Figure A.1 shows the sequence of the oxygen-stable isotope ($\delta^{18}O$) composition of cave deposits in Soreq Cave in Central Israel, providing a proxy for the climatic sequence of the region since the LGM. Higher (less negative) values of the oxygen isotope are to be interpreted as reflecting cold and dry conditions.

The improvement in environmental conditions after the end of the LGM is evident in Figure A.1. The occurrence of the YD (an abrupt and large increase in oxygen isotope between 13,800 and 11,400 BP) is also well documented. Notably, the climatic improvement after the end of the LGM is substantially variable and relatively more so before the advent of the Holocene.

Prior to the Younger Dryas there also appears to be another short climatic reversal possibly correlated with a more global incident known as the Older Dryas. Direct evidence of harsh environmental conditions associated with Early Natufian settlements is provided by Leroi-Gourhan and Darmon (1991).[44] The emergence of the predominantly sedentary Early Natufian culture is identified by various authors (e.g., Bar-Yosef and Belfer-Cohen, 1989; Bar-Yosef, 1998) as a response to this short and cold abrupt crisis.

Madsen et al. (1996) review the climatic record of North Central China and find that the Pleistocene-Holocene transition was a time of considerable climatic and environmental flux. Moreover, Madsen et al. (1998) link this period of climatic variability with a transition to broad-spectrum foraging and seed processing

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[41] Polar ice cores, ocean and lake sediments, tree rings, and cave deposits, for example, have been employed in the determination of paleoclimatic sequences. A fairly reliable global assessment of the climatic past comes from the analysis of ice cores in Greenland.

[42] The Younger Dryas, which lasted for approximately 1,500 years, was associated with a rapid return to glacial conditions at higher latitudes of the Northern Hemisphere, and a general cooling and drying at lower latitudes.

[43] Their analysis is based on the pollen record from Ghab Marsh and lake Huleh, in the Jordan valley and Northern Israel respectively, as well as on the stable isotope analysis of cave deposits in Soreq cave in Central Israel. Additional evidence from lake Zeribar in Iran and lake Van from eastern Turkey corroborate the findings of the Levantine sequences.

[44] The authors, analyzing evidence from Early Natufian sites, particularly that of Wadi Judayid in Jordan, reveal a scarcity in the floral variety, which was dominated by a plant suited for cold and dry climates. A similar arid faunal pattern was present in the Hayonim terrace in Israel just before the first appearance of the Natufian culture in the record. In Figure A.1, this incident might be associated with point (a), occurring around 1,500 years before the advent of the YD.

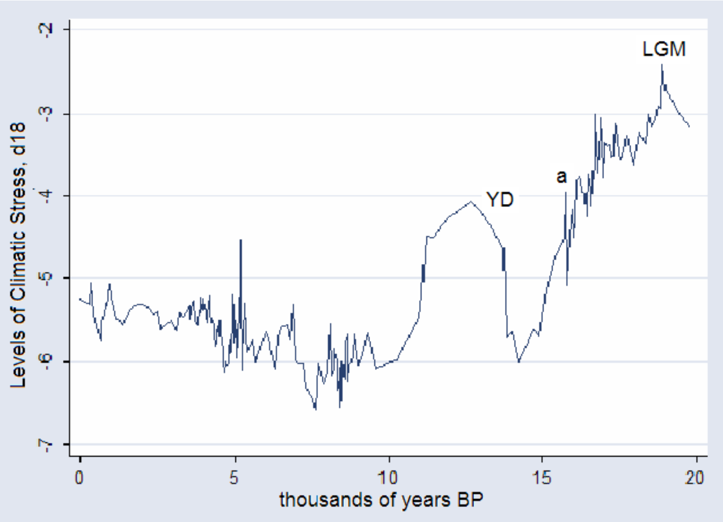

Figure A.1: Climatic Variability in Central Israel since the LGM

Source: ftp.ngdc.noaa.gov/paleo/icecore/greenland/summit/grip/chem/ca.txt

by hunter-gatherers in western and central China. Interestingly, there is no evidence indicating dietary changes for the cultures in the region prior to the YD.

The appearance of seeds with domesticated characteristics at Abu Hureyra occurred while the Younger Dryas was still in effect, around 13,000 BP (Hillman et al., 2001).[45] On the other hand, the transition to agriculture in Northern China occurred well after the end of the Younger Dryas although both regions seem to have been affected in a similar manner by the climatic reversal. The theory ascribes this heterogenous response to the greater investments in intermediate activities by the Natufians prior to the Younger Dryas. As already discussed, this lifestyle, encompassing investments in more diverse and efficient tools as well as a semi-sedentary infrastructure, was itself an outcome of earlier climatic shocks.

Additional evidence on the impact of climate on the lifestyle of hunter-gatherers comes from Higham (1995). The author suggests that sedentary settlements of the Peiligang culture in North China and Pengtoushan culture in South China, which eventually provide evidence of agricultural activities, were first occupied during a colder climate phase.

Such instances are indicative of the key role of climatic shocks in permanently affecting the degree of investments in intermediate activities (i.e., the overall subsistence and settlement strategies) of hunter-gatherer economies.

A.2 Climatic Stress and Food Procurement Patterns

Climatic changes have a direct impact on the available flora and fauna in a region. Indeed, maps of paleovegetation have been shown to change as climatic conditions fluctuate (Adams and Faure, 1997). This, in turn, implies that the availability and variety of food resources vary accordingly. To the extent that climatic changes alter the distribution of available resources, the presence of increased climatic harshness

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[45] In order to predict what would have happened in the absence of the YD, one would need to build the counterfactual climatic sequence. The prediction of the model is that, if climatic conditions were to remain completely static, then no agricultural activities would emerge. However, in the case of continuing mild climatic fluctuations farming would eventually arise. The YD therefore operated as a catalyst in a process that was already set in motion with the rise of the Early Natufian culture.

increases the risk of food acquisition. As a result foragers alter their dietary pattern by including lower-ranked species.[46] A similar hypothesis was initially proposed by Flannery (1969). He argued that subsistence diversification was pursued in West Asia, mainly by adding new species to the diet, in order to raise the population size sustainable in an environment increasingly constrained by climate instability at the end of the Pleistocene.[47]

As previously noted, the Natufian culture emerged as a reaction to a local short climatic reversal followed by favorable climatic conditions up until the occurrence of the Younger Dryas. Faunal remains and bones suggest that the Natufian diet comprised of a wide variety of plants and animals.[48]

The effect of the Younger Dryas on the dietary composition of the Natufian culture was not expansive, however, because they were already encompassing a wide variety of resources, ranging from animals such as gazelles, birds, hares, tortoises, and water fowls, to plants such as wild barley and wild einkorn (Bar-Yosef, 1998). Evidence from the site of Abu Hureyra (Hillman et al., 2001) suggests that hunter-gatherers further intensified their interventionist practices in response to the Younger Dryas, which caused a steep decline in the availability of wild plants (that served as staple foods for at least the preceding four centuries). This implies that the inhabitants of Abu Hureyra increased their investments in intermediate activities to improve the overall efficiency with which existing resources were obtained in response to changes in the availability of wild seeds.

From the anthropological record, Keeley's (1995) study of 96 ethnographic groups identifies the variables that were most likely to influence the adoption of cultivation. He concludes that increased dependence on plant foods could be an outcome of low precipitation, population pressure and low ecological productivity. The present theory recognizes both low ecological productivity and low precipitation as important dimensions of increased climatic stress.[49]

Hence, there appears to be ample evidence supporting the role of climatic stress in transforming the dietary patterns of prehistoric and modern hunter-gatherers towards a more efficient exploitation of existing and marginal resources and, ultimately, towards agriculture.

A.3 Food Procurement Patterns and Intermediate Investments

A central premise of the proposed theory is that the level of intermediate investments by hunter-gatherers is instrumental in coping with an increased risk of food acquisition. Specifically, the incorporation of previously ignored species, or a more efficient exploitation of those already being consumed, necessitates the application

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[46] Such dietary changes are, of course, possible under sufficiently mild increases in environmental harshness that do not result in the extinction of the underlying species. Expanding the dietary spectrum, however, is only one possibility of coping with increased risk. A climatically-induced efficiency increase in the exploitation of existing species is another way that risk may be alleviated.

[47] Weiss et al. (2004) present evidence on plant exploitation at the site of Ohalo II in Israel dated at 23,000 BP (the height of the LGM) that supports a broad consumption of wild seeds during a period of extreme climatic stress. The absence of specialized tools, however, suggests that the acquisition was relatively inefficient. This coupled with the facts that population density was very low and that wild cereals comprised a smaller fraction of total grasses consumed, as compared to subsequent cultures in the region, implies a low degree of latent agricultural knowledge accumulation (since small grain seeds are less susceptible to domestication).

[48] Smith (1991), investigating dental evidence within the Natufian culture, shows that both tooth size and dental disease patterns among the Natufians are intermediate between those of hunter-gatherers and agriculturalists. Additionally, she finds that, within the Natufian period, significant changes were taking place in dietary habits and food processing techniques. This leads the author to conclude that "the Natufians were eating a more abrasive and cariogenic diet than their Middle Paleolithic predecessors like large quantities of ground cereals."

[49] "At any latitude except those of polar deserts, a rich-coastal hunter-gather group experiencing either a decrease in precipitation, an increase in population density, or both, has little choice but to intensify its use of plant foods" (Keeley, 1995).

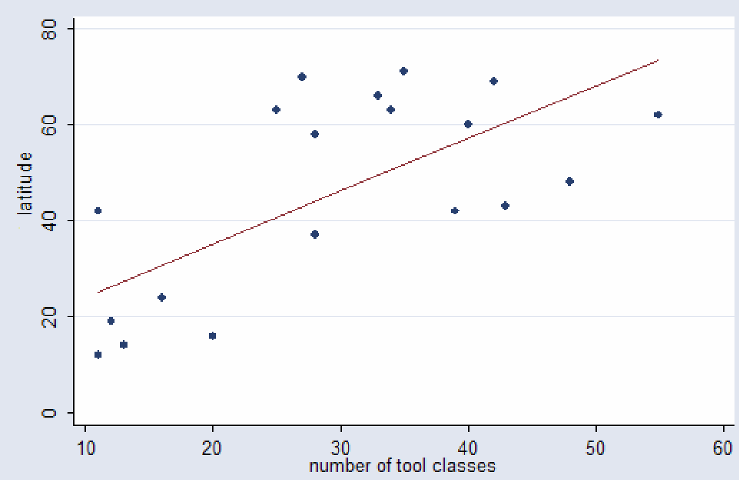

Figure A.2: Subsistence Risk and Tool Diversity

Source: Torrence (1983)

of a wider array of food extraction techniques. Hence, hunter-gatherer groups in environments characterized by a higher risk of resource procurement should employ, amongst other intermediate practices, a more diverse set of tools for food collection and processing.

Madsen et al. (1998) suggest that in Northern China a “technological transition occurred beginning in the Late Paleolithic, in which discoidal cores, flake points, blade tools, backed knives, and burins of the early Late Paleolithic were supplanted by a more diverse array of flake and blade tools, developed unifacial and bifacial tools, microliths, and, perhaps, milling stones and partially ground celts in the latest Paleolithic.” The authors maintain that this transition occurred precisely because the process of gaining access to new lower-ranked food resources was synonymous to developing higher-cost resource extraction and processing techniques.

Evidence for the need of richer tool assemblages to efficiently exploit existing resources is also readily discernible in the Natufian culture. Special tools that occurred for the first time among the Natufians were picks and sickle blades. The latter has been identified by various authors (e.g., Unger-Hamilton, 1989; Bar-Yosef, 1998) as a tool used in the harvesting of wild cereals either for consumption or for making roofs of primitive storage pits. Additionally, Natufian base camp sites have revealed ground stone tools such as bedrock mortars, cupholes, mullers, and pestles. Microscopic observations have demonstrated that these were employed primarily as food processing instruments.

The requirement for more diverse tools in gaining access to varied resources, so as to mitigate subsistence risk, implies a positive relationship between the extent of such risks and the number of different tool types in hunter-gatherer tool assemblages. Ethnographical evidence lends support in this regard. Based on data from Oswalt (1976) and Murdock (1967), Figure A.2 depicts the relationship between latitude and the diversity of tools employed by modern hunter-gatherers. Tool diversity is measured by the total number of tool classes such as instruments (e.g., pestles, mortars, etc.), weapons (like spears, bows, arrows, and throwing sticks), and facilities (i.e., traps, weirs, and hunting blinds). Torrence (1983) uses latitude as a proxy for subsistence risk due to greater seasonality associated with increasing distance from the equator. The correlation between latitude and tool diversity in Figure A.2 is large, positive (0.69), and statistically significant at 1% level.[50] The author succinctly states: “When the risk of failure to procure food is high, hunter-gatherers respond by increasing their overall investment in technology and in the diversity of tools” (Torrence, 1983). Such an interpretation highlights the role of harsher environments in influencing the intermediate practices of hunter-gatherer groups, which encompasses, amongst other activities, an increase in tool diversity.

Beyond the effects of climatic stress on tool-making, harsher environments stimulate increased investment in other intermediate technologies such as habitat management practices. Evidence from archaic cultures in Highland New Guinea supports this premise of the theory. According to Denham et al. (2004), at the end of the LGM, and prior to climate stabilization in the early Holocene, the Highland climate fluctuated considerably and was subject to greater variability as compared to that in the Lowland. These fluctuations stressed existing plant management practices in Highland New Guinea and necessitated more interventionist (i.e., greater ground preparation, tending and weeding of plants) and more extensive (i.e., greater disturbance of forest canopy to increase habitat diversity) plant exploitation strategies in order to maintain yields and a broad-spectrum diet.

A.4 Intermediate Investments and Sedentism

Archaeological evidence substantiates a direct relationship between the extent of intermediate technological investments, such as greater tool diversity, and the settlement patterns of hunter-gatherers towards more sedentary lifestyles. Madsen et al. (1996), in their study on settlement patterns and tool assemblages from the Pleistocene/Holocene transition in North/Central China, document an increase in tool diversity and a reduction in hunter-gatherer residential mobility over time beginning in the Late Paleolithic. Their findings suggest that an increasingly intensive use of marginal resources was associated with decreased mobility (possibly due to the need for more diverse tool assemblages).

Archaeological findings in the Levant also support the association between residential mobility and hunter-gatherer tool diversity. Wild cereal harvesting among the Natufians required the incorporation of specialized tools in their overall resource procurement strategies. According to Bar-Yosef (1998), the Natufian culture also practiced a high degree of sedentism, as suggested by the presence of human commensal remains (such as rats, house mice, and sparrows) at Natufian base camp sites.

In addition to the evidence from archaic foraging cultures, further support comes from anthropological studies of contemporary hunter-gatherer societies. Using data from Oswalt (1976) on modern hunter-gatherers, Shott (1986) finds a systematic relationship between mobility frequency, as measured by the number of residential moves per year (in Figure A.3, ln(MF) is the log of this variable), and tool diversity, as measured by the number of distinct portable tool types (i.e., instruments and weapons as described in the previous section) in the technological inventory. This relationship is shown in Figure A.3, where the depicted correlation is statistically significant at the 1% level.

A.5 Intermediate Activities and Intrinsic Agricultural Knowledge

Approaches from ecology stress concepts such as ‘people-plant interaction’ and ‘human-plant symbiosis’ in addressing long-run processes that determine the intrinsic accumulation of agricultural knowledge. Rindos

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[50] Bamforth and Bleed (1997), examining the same data, find that this correlation persists at the 10% level of significance after controlling for the percentage of aquatic resources in the dietary composition of each hunter-gatherer group in the sample.

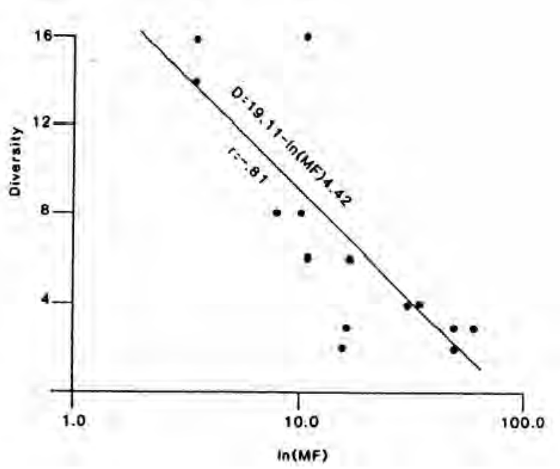

Figure A.3: Tool Diversity and Residential Mobility

Source: Shott (1986)

(1984), for instance, proposes that in areas that were shared by certain plant species and humans, the plants were unintentionally impacted by human interference with the environment in which they lived. This comprised a series of cause-and-effect ecological processes that resulted, over time, in the evolution of plants that were attractive for selection, causing them to become isolated and develop domesticable characteristics. Intermediate activities, in the examples provided so far, essentially act as the vehicle through which this interaction materializes, with larger intermediate investments positively affecting the accumulation of latent agricultural knowledge. Additionally, more sedentary lifestyles have been theoretically identified with a shift towards more intensive exploitation of marginal resources.

It should be noted that, unlike other approaches, the proposed theory does not ascribe to sedentism an independent role in generating agricultural knowledge. In fact, it is neither necessary nor sufficient. What matters is that the overall investment in intermediate activities is associated with the efficient exploitation of plants and domesticable seeds.

B Other Transitions and Non-Transitions

B.1 Other Transitions

As already discussed, the model developed in this paper draws evidence primarily from instances of the agricultural transition in the Levantine corridor, China, and New Guinea. The archaeological record, however, documents the independent domestication of wild species and the emergence of distinct agricultural economies in several other regions (see, e.g., Balter, 2007). Although each transition has its own unique characteristics, it is nonetheless beneficial to examine the developmental histories of these regions in a generalized framework. This appendix, therefore, briefly reviews evidence to ascertain the extent to which the proposed model is consistent with these other transitions.

Unlike the Near East, the archaeological record on the rise of African agriculture does not identify a single center of domestication.[51] Despite the non-centric nature of the African pattern, the paleoclimatological evidence does reveal an environment characterized by sporadic episodes of increased climatic stress in sub-Saharan Africa. According to Harlan (1995), the Sahara expanded and contracted since the end of the Pleistocene with rain conditions peaking at around 9,000 BP, followed by an abrupt and short arid phase at around 7,000 BP, which in turn was relieved by a 'Neolithic pluvial' in 6,500 BP. Dessication emerged again attaining current rainfall levels by about 4,500 BP. Researchers have suggested that it was during this period that the southward expansion of the desert displaced hunter-gatherer societies south, and forced innovations and experimentation that led to the initial domestication of millet and sorghum, (Smith, 1995).

The emergence of plant husbandry in the Eastern Woodlands of North America reveals similar patterns. Faunal remains recovered from archaeobotanical assemblages at numerous sites such as Ash Cave in Ohio, Russell Cave in Alabama, Marble Buff in Arkansas, and Napoleon Hollow in Illinois document the domestication of goosefoot, sumpweed, and sunflower in the region by 4,000–3,000 BP (Smith, 1992; 1995). Drawing parallels with the impact of the Younger Dryas climatic downturn in the Levantine corridor, Smith (1995) proposes that the trigger resulting in the domestication experience in eastern North America was a change in regional climatic conditions during the Middle Holocene (8,000–4,000 BP). Climatic stress and population growth, he argues, "heightened the ever-present fear of resource shortfall, even in times of abundance, pushing societies to increase the yield and reliability of some food resources, paving the way to domestication" (Smith, 1995).

B.2 Non-Transitions

Instances of non-transitions, expounded by the violation of one or more of the following conditions, help illustrate their crucial role for the adoption of agriculture, as prescribed by the theory: (a) the overall climatic volatility of a region; (b) the availability of potentially domesticable species; and (c) the incorporation of marginal species in response to climatic downturns.

The main prediction of the theory is that the absence of sufficient climatic variability will significantly delay the emergence of agriculture due to the slow transformation of foraging activities. Thus, hunter-gatherer economies in relatively stable environments may not experience pristine agricultural transitions. This prediction appears to be the case for cultures in the Amazon, Australia, and Southeast Asia, where, arguably, the tropical environment protected these cultures from major climatic fluctuations (Higham, 1995; Dow et al., 2009). Notably, the case of the emergence of agriculture in Highland New Guinea and not in the tropical Lowland, despite common access to similar endowments, is the prime example of a differential transition driven purely by differences in the degree of climatic fluctuations.[52]

Naturally, the availability of potentially domesticable species is a necessary requirement for an agricultural transition in the proposed theory. The lower the availability of such species, the slower is the accumulation of latent agricultural productivity for any level of intermediate investment. Examples of non-transition due to poor biogeographic endowments include regions such as Australia, California, Chile, and Argentina (Diamond, 1997). Moreover, a pristine transition may not occur if climatic stress does not induce

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[51] The evidence on African domestication is dispersed throughout the sub-Saharan belt from one side of the continent to the other (Harlan, 1992; 1995). Domesticated sorghum first appears in the record at the site of Adrar Bous in south central Sahara at around 4,000 BP, cultivated pearl millet is identified in the Dhar Tichitt region of southwestern Sahara by 3,000 BP, and African rice at the site of Jenne-Jeno on the Niger River bend is dated to about 200 AD (Smith, 1995).

[52] The Highland was more exposed to environmental changes compared to the Lowland (Bellwood, 2005).

an increased consumption of potentially domesticable species even when they are available. This is the case of the Jomon culture of Japan, dated from about 16,000 BP, which was characterized by early sedentism, but a late transition to agriculture (borrowed from the Mumum culture of Korea) at around 2,500 BP (Habu, 2004). The absence of a pristine transition in Japan has been attributed to the fact that the diversity of the Jomon diet, which was primarily composed of aquatic resources, remained relatively stable in the face of climatic downturns (Dow et al., 2009).

These instances of non-transition highlight the importance of the effect of climatic stress on the dietary set and the availability of domesticable species in shaping the final outcome.

C Proofs

Proof of Lemma 1. The first-order condition of (7) yields

$$\begin{aligned} F\left(s_t^{h*}, e_t, \zeta_t\right) &\equiv e_t\left[\left(1 - s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^2 + 1/\lambda s_t^{h*}\right]\left[\left(1 - s_t^{h*}\right)^{\rho} + \left(\zeta_t\lambda s_t^{h*}\right)^{\rho}\right] - \\ &\quad \alpha\left[1 - e_t\left(1 - s_t^{h*}\right)/\lambda s_t^{h*}\right]\left[\left(1 - s_t^{h*}\right)^{\rho - 1} - (\zeta_t\lambda)^{\rho}\left(s_t^{h*}\right)^{\rho - 1}\right] \qquad (C.1) \\ &= 0. \end{aligned}$$

Note that under no climatic stress, $e_t = 0$, (or, equivalently, when climatic harshness may not be mitigated) the optimal allocation to intermediate activities is $s_t^{h*}\ |_{e_t=0} = (\zeta_t\lambda)^{\frac{\rho}{1-\rho}}\left\{1 + (\zeta_t\lambda)^{\frac{\rho}{1-\rho}}\right\}^{-1}$. This, coupled with the assumption that $\zeta_t < \lambda^{-\frac{1}{\rho}}$, implies that $s_t^{h*}\ |_{e_t=0} < 1/(1+\lambda)$.

By assumption (A1), the second-order condition of the maximization in (7) is always negative (i.e., the objective function is globally concave):

$$\begin{aligned} F_s\left(s_t^{h*}, e_t, \zeta_t\right) &= -(\alpha + \rho)\, e_t\left[\left(1 - s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^2 + 1/\lambda s_t^{h*}\right]\left[\left(1 - s_t^{h*}\right)^{\rho - 1} - (\zeta_t\lambda)^{\rho}\left(s_t^{h*}\right)^{\rho - 1}\right] \\ &\quad - 2e_t\left[\left(1 - s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^3 + 1/\lambda\left(s_t^{h*}\right)^2\right]\left[\left(1 - s_t^{h*}\right)^{\rho} + \left(\zeta_t\lambda s_t^{h*}\right)^{\rho}\right] \qquad (C.2) \\ &\quad - \alpha(1 - \rho)\left[1 - e_t\left(1 - s_t^{h*}\right)/\lambda s_t^{h*}\right]\left[\left(1 - s_t^{h*}\right)^{\rho - 2} + (\zeta_t\lambda)^{\rho}\left(s_t^{h*}\right)^{\rho - 2}\right] \\ &< 0. \end{aligned}$$

Hence, since $F_s(s_t^{h*}, e_t, \zeta_t) \neq 0$, the uniqueness of s_t^{h*} follows immediately from the *Implicit Function Theorem.* For the properties of s_t^{h*}, note that

$$\begin{aligned} F_e\left(s_t^{h*}, e_t, \zeta_t\right) &= \frac{\left(\zeta_t\lambda s_t^{h*}\right)^{\rho}\left(1 - \alpha\left(1 - s_t^{h*}\right)\right) + \left(1 - s_t^{h*}\right)^{\rho}\left(1 + \alpha s_t^{h*}\right)}{\lambda\left(s_t^{h*}\right)^2} > 0; \qquad (C.3) \\ F_\zeta\left(s_t^{h*}, e_t, \zeta_t\right) &= \rho\,(\zeta_t\lambda)^{\rho - 1}\left(s_t^{h*}\right)^{\rho - 2}\left(\left(1 - \alpha\left(1 - s_t^{h*}\right)\right)e_t + \alpha\lambda s_t^{h*}\right) > 0, \qquad (C.4) \end{aligned}$$

which, along with $F_s(s_t^{h*}, e_t, \zeta_t) < 0$, completes the proof. ■

Proof of Lemma 2. It follows from (4) that

$$\begin{aligned}
\frac{\partial y_t^h}{\partial e_t} &= -\left[\left(1-s_t^h\right)/\lambda s_t^h\right]\left[\left(1-s_t^h\right)^{\rho}+\left(\zeta_t\lambda s_t^h\right)^{\rho}\right]^{\frac{\alpha}{\rho}}\left(L_t^h\right)^{\alpha-1}<0; && \text{(C.5)}\\
\frac{\partial y_t^h}{\partial \zeta_t} &= \alpha\left(\zeta_t\lambda s_t^h\right)^{\rho-1}\left[\lambda s_t^h-e_t\left(1-s_t^h\right)\right]\left[\left(1-s_t^h\right)^{\rho}+\left(\zeta_t\lambda s_t^h\right)^{\rho}\right]^{\frac{\alpha}{\rho}-1}\left(L_t^h\right)^{\alpha-1}>0; && \text{(C.6)}\\
\frac{\partial y_t^h}{\partial L_t^h} &= (\alpha-1)\left[1-e_t\left(1-s_t^h\right)/\lambda s_t^h\right]\left[\left(1-s_t^h\right)^{\rho}+\left(\zeta_t\lambda s_t^h\right)^{\rho}\right]^{\frac{\alpha}{\rho}}\left(L_t^h\right)^{\alpha-2}<0. && \text{(C.7)}
\end{aligned}$$

Noting (C.5) and (C.6), the first-order partials in parts 1 and 2 of the lemma follow from (A1) and the *Envelope Theorem*. The first-order partial in the last part of the lemma, however, follows immediately from (C.7), since the optimal allocation of labor to intermediate activities in the hunter-gatherer sector is independent of the size of the total labor force employed in that sector. For the same reason, the second-order partial with respect to the size of the total hunter-gatherer labor force follows from

$$\frac{\partial^2 y_t^h}{\left(\partial L_t^h\right)^2}=(\alpha-2)\frac{\partial y_t^h}{\partial L_t^h}\frac{1}{L_t^h}>0. \tag{C.8}$$

For the second-order partial with respect to the degree of environmental harshness, however, it is necessary to observe the dependence of the optimal allocation of hunter-gatherer labor to intermediate activities on environmental conditions. Specifically, (4) and Lemma 1 imply

$$\frac{\partial^2 y^h\left(e_t,\zeta_t,L_t^h\right)}{\left(\partial e_t\right)^2}=\frac{\partial^2 y_t^h}{\left(\partial e_t\right)^2}+\frac{\partial^2 s_t^h}{\left(\partial e_t\right)^2}\frac{\partial y_t^h}{\partial s_t^h}+2\frac{\partial s_t^h}{\partial e_t}\frac{\partial^2 y_t^h}{\partial s_t^h\partial e_t}+\left(\frac{\partial s_t^h}{\partial e_t}\right)^2\frac{\partial^2 y_t^h}{\left(\partial s_t^h\right)^2},$$

where all terms are evaluated at the optimal hunter-gatherer labor allocation choice. However, note that the first two terms both equal 0 due to the linear effect of the environment on hunter-gatherer output and the first-order condition for optimization in (7), respectively. In addition, the *Implicit Function Theorem* yields $\partial s_t^h/\partial e_t=-[\partial^2 y_t^h/\partial s_t^h\partial e_t]/[\partial^2 y_t^h/(\partial s_t^h)^2]$. Thus, upon simplification, the expression above reduces to

$$\frac{\partial^2 y^h\left(e_t,\zeta_t,L_t^h\right)}{\left(\partial e_t\right)^2}=\frac{-\left[\partial^2 y_t^h/\partial s_t^h\partial e_t\right]^2}{\left[\partial^2 y_t^h/(\partial s_t^h)^2\right]}>0, \tag{C.9}$$

where the positivity follows from the second-order condition for maximization in (7), thereby completing the proof. ■

Proof of Lemma 3. The uniqueness of $L^{LL}(e_t;\zeta_t)$ follows immediately, via the *Implicit Function Theorem*, from (24) and the fact that $y_L^h(e_t,\zeta_t,L_t)\neq 0$, as established in Lemma 2. Moreover, Lemma 2 further implies that

$$L_e^{LL}\left(e_t;\zeta_t\right)=-\frac{y_e^h\left(e_t,\zeta_t,L_t\right)}{y_L^h\left(e_t,\zeta_t,L_t\right)}<0,$$

and that

$$L_\zeta^{LL}\left(e_t;\zeta_t\right)=-\frac{y_\zeta^h\left(e_t,\zeta_t,L_t\right)}{y_L^h\left(e_t,\zeta_t,L_t\right)}>0.$$

For the second-order partial with respect to e_t, note that the independence of the optimal allocation of labor towards intermediate activities from the size of the total hunter-gatherer labor force implies that it is possible to define

$$y^h(e_t,\zeta_t,L_t) \equiv \Psi(e_t,\zeta_t)\, L_t^{\alpha \square 1} > 0, \tag{C.10}$$

where, as follows from the positivity of L_t and Lemma 2, $\Psi_{ee}(e_t,\zeta_t) > 0$. Hence, using (C.10), (24) yields

$$L^{LL}(e_t;\zeta_t) = \left[\frac{1 \square p}{\tilde{c}}\Psi(e_t,\zeta_t)\right]^{\frac{1}{1 \square \alpha}},$$

and therefore

$$\begin{aligned} L^{LL}_{ee}(e_t;\zeta_t) &= \frac{\alpha}{(1 \square \alpha)^2}\left[\frac{1 \square p}{\tilde{c}}\Psi(e_t,\zeta_t)\right]^{\frac{2\alpha \square 1}{1 \square \alpha}}\left[\frac{1 \square p}{\tilde{c}}\Psi_e(e_t,\zeta_t)\right]^2 \\ &\quad + \frac{1}{(1 \square \alpha)}\left[\frac{1 \square p}{\tilde{c}}\Psi(e_t,\zeta_t)\right]^{\frac{\alpha}{1 \square \alpha}}\frac{1 \square p}{\tilde{c}}\Psi_{ee}(e_t,\zeta_t) \\ &> 0, \end{aligned}$$

where the positivity follows directly from the sign of $\Psi_{ee}(e_t,\zeta_t)$, thereby completing the proof. ■

Proof of Lemma 4. Noting (25) define, for $e_t \in [0,\bar{e}]$, the function

$$(L_t,e_t,\zeta_t,A_t) \equiv y^h(e_t,\zeta_t,L_t) \square y^g(e_t,A_t) = 0, \tag{C.11}$$

where, as follows from Lemma 2,

$$_L(L_t,e_t,\zeta_t,A_t) = y^h_L(e_t,\zeta_t,L_t) < 0. \tag{C.12}$$

The uniqueness of $L^{yy}(e_t;\zeta_t,A_t)$ then follows immediately, via the *Implicit Function Theorem*, from (C.12). For the first-order partial with respect to e_t, observe that, under (A1), and along the Hunter-Gatherer Frontier, the differential impact of the environment on output per worker is larger for the agricultural sector than for the hunter-gatherer sector, since

$$\begin{gathered} y^h_e(e_t,\zeta_t,L_t) \square y^g_e(e_t,A_t) > 0 \Leftrightarrow \\ \square y^h(e_t,\zeta_t,L_t)\frac{\left[\left(1 \square s^{h*}_t\right)/\lambda s^{h*}_t\right]}{\left[1 \square e_t \; \square \; 1 \square s^{h*}_t\right)/\lambda s^{h*}_t\right]} + \frac{y^g(e_t,A_t)}{1 \square e_t} > 0 \Leftrightarrow \\ \frac{y^h(e_t,\zeta_t,L_t)}{1 \square e_t} > y^h(e_t,\zeta_t,L_t)\frac{\left[\left(1 \square s^{h*}_t\right)/\lambda s^{h*}_t\right]}{\left[1 \square e_t \; \square \; 1 \square s^{h*}_t\right)/\lambda s^{h*}_t\right]} \Leftrightarrow \\ 1 > \square \; 1 \square s^{h*}_t\right)/\lambda s^{h*}_t \Leftrightarrow s^{h*}_t > 1/(1+\lambda), \end{gathered}$$

where the first equivalence follows from (12) and (C.5), and the second equivalence from the fact that output per worker is equal in the two sectors along the *yy* frontier. Note that the last inequality is always satisfied under (A1), and it therefore follows that

$$_e(L_t,e_t,\zeta_t,A_t) > 0. \tag{C.13}$$

Hence, noting (C.12) and (C.13),

$$L_e^{yy}(e_t;\zeta_t,A_t) = -\frac{{}_{e}(L_t,e_t,\zeta_t,A_t)}{{}_{L}(L_t,e_t,\zeta_t,A_t)} > 0.$$

For the second-order partial with respect to e_t, note that

$$\begin{aligned} {}_{ee}(L_t,e_t,\zeta_t,A_t) &= y_{ee}^h(e_t,\zeta_t,L_t) > 0; \quad &\text{(C.14)}\\ {}_{eL}(L_t,e_t,\zeta_t,A_t) &= y_{eL}^h(e_t,\zeta_t,L_t) > 0, \quad &\text{(C.15)} \end{aligned}$$

where the positivity of the former follows from Lemma 2 and (12), and the positivity of the latter from (C.5) and the *Envelope Theorem*. Therefore, noting (C.12)-(C.15),

$$L_{ee}^{yy}(e_t;\zeta_t,A_t) = \frac{{}_{eL}\,{}_{e} - {}_{L}\,{}_{ee}}{({}_{L})^2} > 0.$$

Finally, for the first-order partials with respect to ζ_t and A_t, observe that

$$\begin{aligned} {}_{\zeta}(L_t,e_t,\zeta_t,A_t) &= y_{\zeta}^h(e_t,\zeta_t,L_t) > 0; \quad &\text{(C.16)}\\ {}_{A}(L_t,e_t,\zeta_t,A_t) &= -[y_A^g(e_t,A_t)] < 0, \quad &\text{(C.17)} \end{aligned}$$

where the positivity of the former follows from Lemma 2, and the negativity of the latter follows trivially from (12). Thus (C.12), (C.16), and (C.17) imply that

$$\begin{aligned} L_{\zeta}^{yy}(e_t;\zeta_t,A_t) &= -\frac{{}_{\zeta}(L_t,e_t,\zeta_t,A_t)}{{}_{L}(L_t,e_t,\zeta_t,A_t)} > 0;\\ L_{A}^{yy}(e_t;\zeta_t,A_t) &= -\frac{{}_{A}(L_t,e_t,\zeta_t,A_t)}{{}_{L}(L_t,e_t,\zeta_t,A_t)} < 0, \end{aligned}$$

which completes the proof. ■

D Assumptions in the Graphical Exposition

First, note that a climatic reversal experienced by generation t permanently affects the replacement frontier, LL, faced by all subsequent generations. Specifically, the harsher environment induces generation t to expand its intermediate activities beyond that of generation $t-1$. From (17), this increase in B_t over B_{t-1}, due to the increased climatic stress, confers generation $t+1$ with a higher productivity of intermediate goods, i.e., $\zeta_{t+1} > \zeta_t$. Following Lemma 3, this shifts the LL frontier faced by generation $t+1$ upwards since the economy is now permanently more productive and can, therefore, sustain a higher population in a Malthusian steady state. Consistent with historical evidence that a harsher environment accommodates lower steady-state levels of population, assumption (D.A1) is imposed. This guarantees that, if the economy is in a Malthusian steady state in period $t-1$, a permanent climatic reversal in period t will eventually result in a lower steady-state population (relative to that in period $t-1$), despite the improvement in the productivity of intermediate goods from period $t+1$ onward:

$$L^{LL}(e_{t-1};\zeta_t) > L^{LL}\left(e_t;\zeta_{t+1}\right), \forall\ e_t > e_{t-1}. \quad \text{(D.A1)}$$

Second, an increase in climatic stress occurring in period t also affects the hunter-gatherer frontier, yy, permanently. Unlike the LL frontier, however, the effect of the reversal on the yy frontier faced by generation $t+1$ is ambiguous. By Lemma 4, the increase in ζ_{t+1} over ζ_t, as a result of the reversal, tends to shift the yy locus upwards. At the same time, if the higher intensity of intermediate investments by generation t (relative to $t-1$) results in a positive growth rate of agricultural knowledge between t and $t+1$ (Case A in Proposition 2), the increase in A^h_{t+1} over A^h_t will tend to shift the yy locus downwards. Assumption (D.A2) assures that the net effect of a climatic reversal in period t on the yy locus is a downward shift of the frontier in period $t+1$:[53]

$$\frac{\partial L^{yy}\left(e_t;\zeta_{t+1},A^h_{t+1}\right)}{\partial\zeta_{t+1}}\frac{\partial\zeta_{t+1}}{\partial e_t}+\frac{\partial L^{yy}\left(e_t;\zeta_{t+1},A^h_{t+1}\right)}{\partial A^h_{t+1}}\frac{\partial A^h_{t+1}}{\partial e_t}<0. \tag{D.A2}$$

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[53] Clearly, the validity of this assumption is dependent on whether or not Case A of Proposition 2 holds true. If Case B holds instead, there would be no change in the level of latent agricultural knowledge following the reversal and, hence, no downward pressure on the yy locus. As such, assumption (D.A2) would end up violating the results of Lemma 4.

E Descriptive Statistics and Correlations

Table E.1: Descriptive Statistics for the 97-Country Sample

		Mean	SD	Min	Max
(1)	Temperature Volatility	4.010	2.721	0.541	10.077
(2)	Mean Temperature	18.652	7.616	0.829	28.194
(3)	Years since Transition	4.516	2.249	1.000	10.500
(4)	Log Distance to Frontier	7.066	2.070	0.000	8.420
(5)	Absolute Latitude	25.170	17.101	1.000	64.000
(6)	Land Area	0.629	1.338	0.003	9.327
(7)	Climate	1.577	1.049	0.000	3.000
(8)	Orientation of Landmass	1.530	0.687	0.500	3.000
(9)	Size of Landmass	30.752	13.608	0.065	44.614
(10)	Geographic Conditions	0.135	1.391	-2.138	2.132
(11)	Domesticable Plants	13.742	13.618	2.000	33.000
(12)	Domesticable Animals	3.845	4.169	0.000	9.000
(13)	Biogeographic Conditions	0.081	1.399	-1.097	1.988
(14)	Mean Elevation	5.803	4.902	0.211	27.296
(15)	Mean Ruggedness	1.217	1.102	0.036	5.474
(16)	% Land in Tropical Zones	0.349	0.414	0.000	1.000
(17)	% Land in Temperate Zones	0.299	0.415	0.000	1.000

Table E.2: Pairwise Correlations for the 97-Country Sample

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
(1)	Temperature Volatility	1.000															
(2)	Mean Temperature	-0.790	1.000														
(3)	Years since Transition	0.619	-0.441	1.000													
(4)	Log Distance to Frontier	-0.035	-0.106	-0.220	1.000												
(5)	Absolute Latitude	0.862	-0.900	0.497	0.155	1.000											
(6)	Land Area	0.068	0.031	0.105	-0.292	-0.096	1.000										
(7)	Climate	0.650	-0.720	0.655	0.139	0.748	-0.131	1.000									
(8)	Orientation of Landmass	0.609	-0.542	0.686	-0.014	0.569	-0.050	0.528	1.000								
(9)	Size of Landmass	0.571	-0.408	0.508	0.024	0.433	-0.055	0.367	0.672	1.000							
(10)	Geographic Conditions	0.734	-0.670	0.749	0.054	0.702	-0.092	0.752	0.908	0.814	1.000						
(11)	Domesticable Plants	0.742	-0.733	0.688	0.094	0.832	-0.213	0.826	0.639	0.511	0.792	1.000					
(12)	Domesticable Animals	0.776	-0.727	0.789	0.092	0.794	-0.086	0.809	0.749	0.525	0.842	0.890	1.000				
(13)	Biogeographic Conditions	0.781	-0.751	0.760	0.096	0.836	-0.154	0.841	0.714	0.533	0.840	0.972	0.972	1.000			
(14)	Mean Elevation	0.014	-0.147	0.000	-0.235	-0.147	0.210	-0.143	-0.038	0.119	-0.028	-0.174	-0.119	-0.151	1.000		
(15)	Mean Ruggedness	0.186	-0.354	0.221	0.007	0.174	-0.075	0.188	0.339	0.107	0.267	0.151	0.241	0.202	0.557	1.000	
(16)	% Land in Tropical Zones	-0.798	0.656	-0.414	0.065	-0.735	-0.029	-0.504	-0.323	-0.414	-0.489	-0.582	-0.548	-0.581	-0.167	-0.125	1.000
(17)	% Land in Temperate Zones	0.688	-0.828	0.414	0.197	0.863	-0.163	0.691	0.483	0.345	0.608	0.736	0.689	0.733	-0.194	0.124	-0.609

Table E.3: Descriptive Statistics for the Seasonal Variables

		Mean	SD	Min	Max
(1)	Temperature Volatility for Spring	1.056	0.444	0.362	2.212
(2)	Temperature Volatility for Summer	0.848	0.332	0.401	1.656
(3)	Temperature Volatility for Fall	0.964	0.437	0.362	2.117
(4)	Temperature Volatility for Winter	1.291	0.778	0.436	3.816
(5)	Mean Temperature for Spring	19.021	8.514	-0.738	31.246
(6)	Mean Temperature for Summer	22.740	4.773	10.568	32.966
(7)	Mean Temperature for Fall	19.006	7.309	1.402	28.583
(8)	Mean Temperature for Winter	13.839	10.734	-10.240	27.431

Table E.4: Pairwise Correlations for the Seasonal Variables

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	Temperature Volatility for Spring	1.000							
(2)	Temperature Volatility for Summer	0.901	1.000						
(3)	Temperature Volatility for Fall	0.955	0.942	1.000					
(4)	Temperature Volatility for Winter	0.940	0.889	0.943	1.000				
(5)	Mean Temperature for Spring	-0.761	-0.836	-0.821	-0.805	1.000			
(6)	Mean Temperature for Summer	-0.489	-0.603	-0.561	-0.597	0.878	1.000		
(7)	Mean Temperature for Fall	-0.756	-0.823	-0.812	-0.812	0.986	0.912	1.000	
(8)	Mean Temperature for Winter	-0.853	-0.880	-0.890	-0.864	0.968	0.769	0.961	1.000
(9)	Years since Transition	0.589	0.471	0.540	0.494	-0.461	-0.196	-0.405	-0.524
(10)	Log Distance to Frontier	0.027	0.091	0.051	0.066	-0.101	-0.176	-0.119	-0.061
(11)	Absolute Latitude	0.886	0.908	0.911	0.891	-0.899	-0.688	-0.887	-0.930
(12)	Land Area	-0.038	-0.045	-0.041	-0.043	0.048	0.092	0.026	-0.009
(13)	Geographic Conditions	0.743	0.671	0.712	0.713	-0.671	-0.456	-0.651	-0.721
(14)	Biogeographic Conditions	0.815	0.782	0.799	0.766	-0.773	-0.522	-0.723	-0.793
(15)	Mean Elevation	-0.107	-0.104	-0.088	-0.178	-0.115	-0.212	-0.159	-0.123
(16)	Mean Ruggedness	0.106	0.076	0.111	0.048	-0.357	-0.359	-0.348	-0.326
(17)	% Land in Tropical Zones	-0.728	-0.790	-0.778	-0.643	0.643	0.388	0.637	0.745
(18)	% Land in Temperate Zones	0.713	0.793	0.774	0.747	-0.839	-0.707	-0.821	-0.812

Table E.5: Descriptve Statistics for the 25-Country Sample

		Mean	SD	Min	Max
(1)	Hist. Temperature Volatility	6.265	1.317	3.344	8.735
(2)	Hist. Mean Temperature	8.630	4.152	0.981	17.787
(3)	Cont. Temperature Volatility	6.892	1.455	3.692	9.625
(4)	Cont. Mean Temperature	8.782	4.108	0.829	17.732
(5)	Years since Transition	6.492	1.666	3.500	10.500
(6)	Log Distance to Frontier	7.496	1.608	0.000	8.294
(7)	Absolute Latitude	48.927	7.672	35.000	64.000
(8)	Land Area	0.200	0.193	0.003	0.770
(9)	Climate	2.840	0.374	2.000	3.000
(10)	Orientation of Landmass	2.217	0.480	0.500	2.355
(11)	Size of Landmass	41.057	12.310	0.070	44.614
(12)	Geographic Conditions	1.790	0.907	-1.274	2.132
(13)	Mean Elevation	3.966	3.161	0.211	12.322
(14)	Mean Ruggedness	1.374	1.253	0.036	5.017

Table E.6: Pairwise Correlations for the 25-Country Sample

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1)	Hist. Temperature Volatility	1.000												
(2)	Hist. Mean Temperature	-0.335	1.000											
(3)	Cont. Temperature Volatility	0.993	-0.306	1.000										
(4)	Cont. Mean Temperature	-0.347	0.994	-0.325	1.000									
(5)	Years since Transition	0.045	0.781	0.089	0.738	1.000								
(6)	Log Distance to Frontier	-0.270	-0.528	-0.289	-0.508	-0.643	1.000							
(7)	Absolute Latitude	0.185	-0.907	0.156	-0.886	-0.854	0.493	1.000						
(8)	Land Area	0.111	0.059	0.189	0.024	0.376	-0.050	-0.126	1.000					
(9)	Climate	-0.482	0.594	-0.500	0.601	0.299	-0.109	-0.556	-0.259	1.000				
(10)	Orientation of Landmass	0.612	0.006	0.590	0.002	0.220	-0.137	-0.180	0.060	-0.128	1.000			
(11)	Size of Landmass	0.617	0.004	0.596	-0.000	0.224	-0.138	-0.179	0.070	-0.129	0.997	1.000		
(12)	Geographic Conditions	0.521	0.126	0.495	0.123	0.285	-0.160	-0.294	0.012	0.074	0.979	0.979	1.000	
(13)	Mean Elevation	0.095	0.110	0.128	0.048	0.452	-0.204	-0.472	0.325	0.072	0.262	0.264	0.279	1.000
(14)	Mean Ruggedness	-0.053	0.022	-0.034	-0.042	0.259	0.061	-0.365	0.089	0.058	0.200	0.202	0.214	0.879

Table E.7: Descriptve Statistics for the Cross-Site Sample

		Mean	SD	Min	Max
(1)	Temperature Volatility Overall	6.264	1.416	2.966	10.038
(2)	Temperature Volatility for Spring	1.431	0.276	0.478	2.294
(3)	Temperature Volatility for Summer	1.181	0.208	0.455	1.758
(4)	Temperature Volatility for Fall	1.367	0.255	0.465	2.003
(5)	Temperature Volatility for Winter	1.953	0.520	0.537	3.443
(6)	Mean Temperature Overall	11.662	4.447	3.764	28.601
(7)	Mean Temperature for Spring	10.680	4.406	2.761	28.198
(8)	Mean Temperature for Summer	19.402	4.775	11.327	35.178
(9)	Mean Temperature for Fall	12.576	4.783	4.598	28.880
(10)	Mean Temperature for Winter	3.991	4.664	-4.885	23.973
(11)	Years since Transition	6.322	1.279	4.500	10.890
(12)	Log Distance to Frontier	7.615	0.751	0.000	8.329
(13)	Absolute Latitude	44.936	8.365	13.900	58.530
(14)	Climate	2.558	0.868	0.000	3.000
(15)	Mean Elevation	3.997	3.168	0.181	28.719
(16)	Distance to Coast	1.793	1.663	0.093	11.929

Table E.8: Pairwise Correlations for the Cross-Site Sample

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1)	Temperature Volatility Overall	1.000														
(2)	Temperature Volatility for Spring	0.705	1.000													
(3)	Temperature Volatility for Summer	0.205	0.679	1.000												
(4)	Temperature Volatility for Fall	0.632	0.920	0.762	1.000											
(5)	Temperature Volatility for Winter	0.606	0.890	0.669	0.844	1.000										
(6)	Mean Temperature Overall	0.043	-0.429	-0.655	-0.524	-0.592	1.000									
(7)	Mean Temperature for Spring	0.064	-0.381	-0.636	-0.491	-0.534	0.989	1.000								
(8)	Mean Temperature for Summer	0.404	-0.150	-0.527	-0.257	-0.332	0.930	0.923	1.000							
(9)	Mean Temperature for Fall	0.067	-0.413	-0.656	-0.509	-0.591	0.995	0.975	0.934	1.000						
(10)	Mean Temperature for Winter	-0.379	-0.699	-0.686	-0.751	-0.806	0.907	0.882	0.692	0.893	1.000					
(11)	Years since Transition	0.500	0.121	-0.252	0.064	-0.103	0.556	0.539	0.688	0.590	0.303	1.000				
(12)	Log Distance to Frontier	-0.625	-0.205	0.311	-0.095	-0.047	-0.463	-0.434	-0.649	-0.512	-0.167	-0.744	1.000			
(13)	Absolute Latitude	-0.216	0.268	0.550	0.323	0.467	-0.892	-0.896	-0.891	-0.892	-0.728	-0.685	0.545	1.000		
(14)	Climate	-0.108	0.227	0.500	0.378	0.376	-0.756	-0.792	-0.718	-0.742	-0.638	-0.433	0.336	0.752	1.000	
(15)	Mean Elevation	0.454	0.135	-0.057	0.144	0.018	0.182	0.183	0.335	0.199	-0.027	0.499	-0.461	-0.475	-0.207	1.000
(16)	Distance to Coast	0.625	0.617	0.307	0.516	0.579	-0.150	-0.075	0.082	-0.167	-0.413	0.203	-0.240	-0.001	-0.032	0.300

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