The Climatic Origins of the Neolithic Revolution: A Theory of Long-Run Development via Climate-Induced Technological Progress

Quamrul Ashraf and Stelios Michalopoulos*

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Abstract

This research examines the transition from hunting and gathering to agriculture and sheds new light on the emergence of farming by focusing on the interplay among environmental conditions, investments in technology and population density. The study contributes to an understanding of the interaction between climatic sequences and technological progress, and analyzes the effect of environmentally triggered technological advancement on the evolution of population size in a foraging regime. It identifies the importance of an environment characterized by recurrent mild adversities as the driving force that enabled societies to make the transition from hunting and gathering to agriculture. The analysis suggests that differences in regional climatic sequences after the Last Glacial Maximum generated heterogeneous population densities. The associated variation in technological investment gave rise to disparities in the accumulation of intrinsic agricultural knowledge. This resulted in the differential timing of the transition to agriculture and, consequently, led to the observed contemporary divergence in income per-capita across countries.

Keywords: Hunter-gatherers, Agriculture, Agricultural Transition, Technological Progress, Climate, Population.

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

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 transition to agriculture from foraging occurred independently in several regions of the world between 12,000 and 5,000 years ago and is 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.

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Recent evidence suggests that contemporary comparative development can be linked to the timing of agricultural transitions. The differential timing of the emergence and subsequent adoption 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 states. Moreover, Bockstette et al. (2002) show that state antiquity, which increases with time elapsed since the transition to agriculture[1], is positively and significantly correlated with current outcomes such as political stability, institutional quality, income per capita and the rate of economic growth between 1960 and 1995. Similarly, Olsson and Hibbs (2005) show that geography and biogeography are remarkably strong in predicting contemporary levels of economic development through the differential timing of the transition to agriculture[2]. Despite compelling evidence on the long-run economic consequences of the Neolithic Revolution, the origins of this major transition remain relatively underexplored in the economic literature. Understanding the causal mechanism that led to the agricultural transition is the goal of the present study.

This paper sheds new light on the emergence of agriculture by examining the evolution of hunter-gatherer economies in a framework that focuses on the interplay among climatic sequences, technological investment and population density. Technological investment or investment in infrastructure is broadly defined as any intermediate activity that facilitates hunting and gathering. Such activities include the production of tools, the deliberate clearance of parts of forests to maintain soil fertility and the creation of more permanent settlements to secure access to specific resources[3].

The research contributes to an understanding of the impact of environmental stress on the expansion of intermediate activities, as evident in the varying diversity of tools (e.g., spears, bows and arrows, nets, traps, blades, pestles and mortars, etc.) in the tool assemblages of prehistoric and modern hunter-gatherers as well as in the degree of investment in settlements and plant interventionist practices. The theory highlights the permanent effect of environmentally triggered forces on such intermediate activities, conceptualizing the gradual transition of hunter-gatherers towards more efficient subsistence patterns. The latter may be verified by the observed inclusion of marginal species[4] in hunter-gatherer diets and the more efficient ex-

[1] Higher regional averages of state history in their paper closely map to regions of the world where agriculture emerged earlier. For example, Europe adopted agriculture very early due to its immediate adjacency to the region where agriculture first emerged, i.e. the Fertile Crescent.

[2] Reassuringly, Putterman (2006) uses country-specific estimates of the timing of the agricultural transitions to document that it is a significant determinant of incomes across countries today.

[3] The latter is associated with the degree of sedentism. A sedentary pattern of settlement, in contrast to a nomadic or residentially mobile lifestyle, refers to the long-term or permanent residence of a population in a single location.

[4] Specifically, given a resource ranking methodology based on calorific values net of costs of acquiring and processing, the broader diets entailed an increased dependence on lower-ranked plant and animal species, such as wild cereals and small game. Within the small game category, for example, slow-moving animals like tortoises are easy to acquire whereas faster animals like birds and hares require more tools for capturing and processing. Similarly, for plants, the tool requirements for fruit and wild seed consumption are different. Also, increased plant dependence may induce more interventionist plant management practises like tending and weeding of plants and/or active disturbance of forest canopy through fire to increase habitat diversity. Given calorific values, resources more dependent on intermediate activities for extraction and processing are thus referred to as marginal species. The terms "lower-ranked resources" and "marginal species" are used interchangeably

ploitation of resources over time. Both instances of dietary changes gave rise to what has been termed as "intensive foraging" among archaeologists.

According to the theory, this continuous transformation of the production activities of foragers was a necessary condition for the transition to agriculture. Consistent with this prediction, intensive foraging indeed predated agriculture in all known instances of pristine agricultural transition, as Table 1 suggests.

Area	Intensive Foraging	Agriculture
Centers of Domestication		
Near East: Bar-Yosef,, and Meadow 1995	15,000	11,500
North China: An 1991; Elston, et al. 1997	11,600	> 9,000
South China: An 1991	12,000?	8,000
Sub-Saharan Africa: Klein 1993	9,000	4,500
South Central Andes: Smith 1995	7,000	5,250
Central Mexico: Smith 1995	7,000	5,750
Eastern United States: Smith 1995	6,000	5,250

Numbers are thousand years before present

Intensive Foraging and Agriculture
Table 1 (Source: Richerson et al., 2001).

The proposed analysis links the need for a more efficient exploitation of resources, instigated by climatic variability, to the observed increased investment of foragers on intermediate activities. It illustrates why earlier episodes of environmental stress in human history did not lead to an agricultural transition highlighting the importance of those climatic downturns in augmenting the productivity of such intermediate activities and, consequently, bringing the respective cultures closer to the adoption of agriculture when subsequent climatic shocks occurred.

The channel illustrated by the theory is novel. It focuses on both the short and long run impact of climatic stress, explaining the gradual inclusion and, ultimately, efficient exploitation of marginal, and potentially domesticable, species in hunter-gatherer diets. The approach taken here does not center solely around the period of the transition to agriculture and, in fact, may be extended to conceptualize the forces behind the gradual technological evolution of mankind throughout prehistory towards more technologically intensive modes of production, thus providing new insights into the evolution of the foraging regime. Notably, 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)[5] as the

throughout the text.

[5] The radiocarbon dating of prehistoric events often diverges from their true calendar dates due to past variations in the amount of carbon-14 in the earth's atmosphere and appropriate calibrations are applied to reduce this discrepancy. Dates mentioned in this paper represent the calibrated radiocarbon dating method unless stated otherwise.

fundamental source of the observed differential timing of agricultural transitions in various parts of the world.

This research also, offers new insights regarding the important role of population changes behind the transition to agriculture (e.g., Boserup, 1965; Cohen, 1977). Specifically, the analysis reveals that population pressure is endogenous to the climatic history of a region. Additionally, unlike Olsson (2001), climatic stress here is assumed to impact hunting and gathering less severely than agriculture. Nevertheless, it is this climatic bias that leads to an increased dependence on plant resources, such as seeds and wild cereals, which in turn necessitates intermediate investments[6]. The resultant increase in the allocation of labor away from direct foraging and towards the production of intermediate goods facilitates a more efficient exploitation of the underlying habitat and consequently, enhances the accumulation of latent agricultural productivity by increasing human interaction with potentially domesticable species[7].

The model developed employs a deterministic, two-sector overlapping generations framework where individuals derive utility from consumption above a minimum subsistence requirement and the number of offspring. There are two modes (sectors) of production. One is hunting and gathering and the other is agriculture, which remains latent prior to the transition. In both sectors pure labor in the form of direct foraging or farming is combined with intermediate activities to produce the final output. The prevailing degree of environmental stress erodes output in both sectors. In the hunter-gatherer sector, however, this erosion is partially alleviated by incorporating previously ignored species in the diet or, equivalently, by increasing the efficiency with which existing resources are exploited. Both necessitate an expansion of intermediate activities, which in turn confers a permanent improvement in the productivity of these practices as applied in the production of food for subsequent generations of hunter-gatherers. The productivity of intermediate activities is defined as the knowledge regarding the extraction, processing and maintenance of different species or habitats. This knowledge, transmitted from one generation to the next, is cumulative and entails the use of various practices like tool making, settlement infrastructure and forest clearing. in acquiring species consumed by previous generations[8]. The agricultural sector is subject to endogenous technical progress, both before and after the transition. Prior to the transition, increased time investment in intermediate activities positively affects the growth rate of latent agricultural knowledge. Once agriculture is operative, technological progress in the agricultural sector is characterized by learning-by-doing dynamics.

Unlike previous research the model explicitly identifies several activities of hunter-gatherers like tool-making, settlement investments and habitat clearing as intermediate inputs in foraging production. Such investments enter the production function in both sectors. In the hunter-gatherer sector the trade-off between investment in intermediate practices and direct foraging (which includes mobility) is captured in a Constant-Elasticity-of Substitution production func-

[6] These may take the form of creation of new tools, i.e. sickle blades and grinding stones, and a more active disturbance of the underlying flora as a means of effectively managing plant diversity and soil fertility. Higher dependence on plant resources may also induce larger investments in permanent settlements in order to secure access to the main staples.

[7] Note that for foragers whose diet was insensitive to climatic fluctuations and/or poor in species amenable to domestication, the proposed accumulation of agricultural knowledge would not take place. Section 9 discusses such instances in more detail.

[8] Alternatively, the productivity of intermediate activities could be thought of as a "taste for food" parameter. The inclusion of previously unexploited species in the diet generates a taste for such resources for subsequent generations, effectively increasing the efficiency of existing intermediate inputs, like tools, in generating final output (or food).

tion where factor-specific productivities affect the optimal labor allocation. Consequently, the productivity of such intermediate activities and the degree of environmental stress together determine the allocation of labor between pure foraging and intermediate inputs over time[9]. As will become apparent, under intuitive assumptions regarding the degree of substitutability between intermediate inputs and direct foraging, an increase in the productivity of intermediate activities leads to larger investments in tool making, plant management practices and settlement infrastructure.

The positive effect of mild[10] climatic reversals on the accumulation of latent agricultural knowledge by hunter-gatherers is what triggers the emergence of agriculture. Latent agricultural knowledge increases as foragers come to depend more on the consumption of plants and seeds, thereby initiating a process by which the accidental but continuous selection of species leads to their domestication. The rate at which a habitat is "disturbed" depends crucially on both the investment in intermediate activities and the availability of domesticable species. The lower is intermediate investment, the more superficial is the exploitation of existing fauna and, consequently, the less likely it is that foragers will "disturb" their habitat sufficiently, leaving its potential for agriculture unexploited. In the current setup, it is the experience of climatic stress that induces hunter-gatherers to intensify intermediate practices (i.e., producing more diverse/effective tools, making larger investments in infrastructure to secure access to fields of wild plants, etc.) in order to procure available resources with greater efficiency. This is the driving force behind the accumulation of latent agricultural knowledge[11].

The theory predicts that in the absence of climatic reversals, groups remain indefinitely in a hunter-gatherer mode of production. Namely, if the environment is static, the level of output per hunter-gatherer will be stationary at the subsistence level with fertility at replacement. Similarly, continuously alleviating climatic stress will be counterbalanced by increases in steady-state population levels. This prediction is readily asserted by the distribution of contemporary hunter-gatherer societies to be found in either extremely poor areas like the poles, deserts or in rich coastal regions with little climatic variation. Examples include the Tiwi (Australia), the Semang (Indian Ocean), the Vedda (South India) and the Ainu (Japan) (Keeley, 1995).

Interestingly, the case of the earlier transition to agriculture in Highland New Guinea as compared to that in the Lowland, provides a unique setting where it is possible to disentangle the effect of differences in climatic fluctuations from differences in biogeographic endowments. More specifically, the two regions are endowed with roughly similar resources but the Highland, unlike the Lowland, was subject to considerable climatic fluctuations that prompted more interventionist and extensive plant management strategies among the Highland foragers, leading to an earlier emergence of agriculture (Denham et al., 2004)[12].

The evidence provided in this paper draws primarily from the Natufian culture of the Levant, the most extensively dated entity in the Near East (Bar-Yosef and Belfer-Cohen, 2000).

[9] The use of a Cobb-Douglas production function in the agricultural regime simplifies the analysis of time allocation between pure farming and the intermediate activities related to agriculture.

[10] Mild climatic shocks are to be contrasted to extreme climatic fluctuations that could lead to conditions under which agriculture is not feasible.

[11] Along this proposed line of thinking, Bellwood (2005), in reviewing the theories proposed by archaeologists on the transition to agriculture, notes that "a combined explanation of affluence alternating with mild environmental stress becomes increasingly a favored explanation among archaeologists." It is exactly these elements of affluence (gauged by population densities), environmental sequences and the interaction between the two that constitute the foundations of the present study.

[12] The timing of this transition is currently disputed in the literature with estimates ranging between 9000BP and 7000BP. For this reason, Highland New Guinean does not appear in Table 1.

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.

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 theoretical structure of the model. Sections 5 and 6 discuss the time-path of macroeconomic variables and the dynamical system. Various cases of transition and non-transition to agriculture generated by the model are examined in Section 7. Section 8 characterizes the post-transition long-run equilibrium of the model. Instances of foraging cultures associated with non transitions are examined in section 9. Finally, Section 10 concludes.

2 Related Literature

The Neolithic Revolution has been a long-standing subject of active research for archaeologists, historians and anthropologists, receiving relatively little attention from economists in spite of its economic significance. 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 Michalopoulos, 2006; Galor and Moav, 2002; Galor and Weil, 1999; Galor and Weil, 2000; Hansen and Prescott, 2002; Jones, 2001; Kögel and Prskawetz, 2001; Lagerlöf, 2003; Tamura, 2002). 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 economic literature 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[13].

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[14].

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) suggests that population growth, due to excessive hunting, resulted in smaller land-holdings per household and induced a more sedentary lifestyle, which favored farming over foraging.

More recently, Marceau and Myers (2005) revisit the institutional approach within a model of coalition formation under exogenous technological progress where individuals ratio-

[13] The reader is referred to Weisdorf (2005) for a comprehensive survey.

[14] Bulte et al. (2006) reexamine the causes behind the Pleistocene extinction of megafauna and attribute it to both human overkill and adverse climatic conditions. The authors suggest that human overkill of megafauna occurred as a result of increased specialization in the hunting of small animals.

nally form cooperative bands of foragers or farmers. At low levels of technology, their model sustains an equilibrium comprising of a grand coalition of foragers, which 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 and stimulated subsequent economic development by releasing labor from food-generating activities. Olsson (2001), on the other hand, theoretically revives Diamond'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[15].

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 work by Dow et al. (2005) within the economics literature. 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 and made agriculture more attractive in the short-run. This setup, however, cannot explain why earlier climatic reversals did not lead to agriculture and its relevance is limited to instances where the emergence of agriculture coincided exactly with a climatic downturn (only one such case is documented in the archaeological record i.e. the Natufian culture)[16]. Furthermore, models focusing only on the short-run impact of climatic stress are unfit to explain the observed gradual transformation of the foraging regime towards agriculture as evident in Table 1.

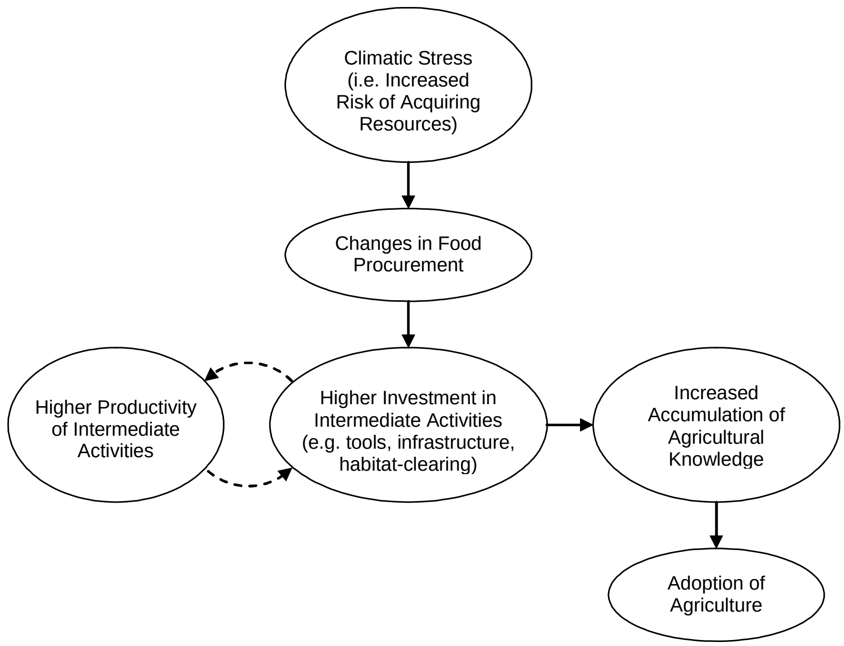
In contrast, the proposed unified theory overcomes these limitations by explicitly identifying the *short-run and long-run* impact of increased climatic stress on hunter-gatherer subsistence strategies.

[15] In addition, Olsson attributes the rise of agriculture to population pressure, cultural changes and external effects on agricultural productivity such as experimentation and experience accumulation.

[16] Furthermore, latest evidence regarding the speed of domestication (Tanno and Wilcox, 2006) shows that the domestication process of wild cereals is gradual and may well have taken over a millennium of cultivation before the emergence of domestic varieties. Such a gradual process implies that the few domesticated seeds found in Abu Hureyra in 12700 BP could not have been caused by the adverse climatic event of the Younger Dryas, which is dated at 13000 BP (since their course towards domestication should have started well before the climatic shock) thereby weakening the credibility of their thesis. Also, from a theoretical point of view their model may generate a transition in the event of a regionally biased climatic improvement. This casts doubt on the relevance of climatic downturns alone as the driving engine behind the transition to agriculture.

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 increases the risk of acquiring resources. This instigates hunter-gatherers to change their food acquisition patterns[17], necessitating the development of novel food extraction and processing techniques, which are accommodated by an increased investment in intermediate activities such as tool making, plant management practices or the building of a more sedentary settlement infrastructure.



Elements of the Proposed Theory
Figure 1.

The aforementioned increase in intermediate investment generates new knowledge regarding the collection and processing of resources. As such, a climatically induced temporary expansion in intermediate activities 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. We now proceed 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.

[17]Such changes encompass both the inclusion of new species in the diet, as well as increases in the efficiency with which currently exploited species are obtained.

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[18]. 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[19]

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

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

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

[19]Assuming a concave intermediate goods production function would not add any further insights and is imposed entirely for expositional simplicity.

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. 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[20]

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

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[21]. The productivity of intermediate goods represents knowledge (or taste for food) passed through from the 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[22].

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

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

In the agricultural production technology, the adverse impact of the environment may not be alleviated and land does not enter explicitly as a scarce factor in the production function[23]. 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[24]

[20] 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.

[21] 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.

[22] 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 hold given a sufficiently high elasticity of substitution between intermediate goods and physical labor.

[23] 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.

[24] Given the Cobb-Douglas structure, intermediate goods and physical labor have a unit elasticity of substitution in the agricultural production technology. This assumption is not crucial for the main results of the model and is imposed for expositional simplicity.

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

where A_t represents the TFP-augmenting agricultural technology[25] at time t and $\beta \in (0,1)$. Since land is not a binding factor in agricultural production this implies constant returns to labor[26]. 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 agriculturalist at time t is equal to the average product of labor employed in that sector at time t. Output per agriculturalist at time t, y_t^g, is

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

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

4.3 Optimization of 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[27]:

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

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[28].

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

[25] Note that if intermediate goods productivity, ζ_t, were allowed to affect agricultural output, this would appear be included in the TFP component. Doing so would not alter the qualitative predictions of the model.

[26] 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.

[27] 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.

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

Lemma 1 *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, that is*[29]

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

and is

1. *a monotonically increasing function of the degree of environmental harshness at time t, that is*
$$\frac{\partial s^h(e_t, \zeta_t)}{\partial e_t} > 0;$$
2. *a monotonically increasing function of the productivity of intermediate goods at time t, that is*
$$\frac{\partial s^h(e_t, \zeta_t)}{\partial \zeta_t} > 0.$$

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 and occurs precisely because an increase in the amount of intermediate goods per forager helps dissipate the adverse effect 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[30]. 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 results from the gross substitutability between intermediate goods and physical labor (or mobility) in the production technology, which implies that an increase in the productivity of intermediate goods will induce foragers to optimally substitute their labor away from direct foraging towards intermediate activities[31].

Let y_t^{i*} denote the maximal level of output per-worker in sector i. Lemma (1) implies that maximal output in the hunter-gatherer sector is implicitly defined by a unique single-valued

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

[30] 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.

[31] 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.

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 $y^h(e_t, \zeta_t, L_t^h)$) *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, that is*

$$\frac{\partial y^h\left(e_t, \zeta_t, L_t^h\right)}{\partial e_t} < 0 \text{ and } \frac{\partial^2 y^h\left(e_t, \zeta_t, L_t^h\right)}{\left(\partial e_t\right)^2} > 0;$$

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

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

3. *a monotonically decreasing, strictly convex function of the size of the labor force in that sector at time t, that is*

$$\frac{\partial y^h\left(e_t, \zeta_t, L_t^h\right)}{\partial L_t^h} < 0 \text{ and } \frac{\partial^2 y^h\left(e_t, \zeta_t, L_t^h\right)}{\left(\partial L_t^h\right)^2} > 0.$$

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 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 entry, 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), $t-1$, individuals consume a fraction, p, of their parent's wage income[32]. In the second period of life (parenthood), t, individuals are endowed with one unit of time, which they supply inelastically as labor to the relevant sector. They 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

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

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

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 expenditure on child-rearing and consumption c_t. Hence, the budget constraint faced by the individual in the second period of life (parenthood) reads as follows:

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

4.5 Optimization of Preferences

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

[32] Thus, the cost of child-rearing could equivalently be interpreted as time cost.

constraints. Substituting (14) into (13), the optimization problem of a member of generation t reads:

$$n_t^* = \underset{n_t}{argmax} \left\{(1-\gamma)\ln\left(y_t(1-pn_t)\right) + \gamma \ln\left(n_t\right)\right\} \tag{15}$$

subject to

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

The optimization implies that, as long as income is sufficiently high so as to ensure that $c_t > \tilde{c}$, a constant fraction γ of individual t's income is spent on child-rearing, whereas $1-\gamma$ 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., $\tilde{y} \equiv \tilde{c}/(1-\gamma)$. It follows that for $y_t \geq \tilde{c}$,

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

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 $1-\gamma$ to consumption. Moreover, as y_t increases (but remains below $\tilde{y}$), the individual will be able to maintain subsistence with 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 is a normal good.

Since the period we analyze 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[33]:

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

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, we outline the law of motion for the productivity of intermediate goods in the hunter-gatherer production 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

[33] A complete Malthusian model incorporates decreasing returns to labor in addition to having fertility as a normal good, ensuring the existence of a steady-state level of income with no population growth. The constancy of returns to labor in agriculture, however, implies that the existence of a Malthusian steady state is ensured in the model so long as the agricultural sector remains latent.

shock on either the dietary spectrum or, equivalently, the efficiency with which the current spectrum is exploited is 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 of exploitation of the existing resources. 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 proportion of marginal species incorporated and the higher the effectiveness of acquiring existing species[34].

Such climatically induced increases in intermediate investments improves the productivity of intermediate goods for subsequent generations, either because of direct technology 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[35].

Following the discussion above, the proposed law of motion for the productivity of intermediate goods in hunter-gatherer production reads[36]:

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

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. $F(.)$ 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[37]. 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

[34] This scale effect of population is essential in capturing the notion of technological progress in a Malthusian regime.

[35] Although the model does not explicitly account for research and development costs associated with intermediate goods productivity, this could be incorporated in the analysis by introducing a primitive research and development sector. The inclusion of an R&D sector would not affect the predictions of the theory but would complicate the exposition unnecessarily.

Nonetheless, we briefly sketch the elements of such a model: Consider a sector which is available at any point in time and has a time cost (friction) associated with its operation (not all experimentation is successful). Also, let the returns to investing in this sector be a positive function of the deviation of the current population above its Malthusian equilibrium. Intuitively harder times increase the marginal benefit of a given innovation. Such a set up would imply that sufficiently strong climatic stress, or mild climatic stress coupled with large population density, would induce investment in this primitive R&D sector and, hence, increase the productivity of intermediate goods for current and subsequent generations.

[36] 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 $\tilde{\zeta}$.

[37] 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.

group's aggregate investment in intermediate activities shape the productivity of intermediate goods that successive generations inherit[38].

The specified dynamics of the productivity of intermediates 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. As such, this law of motion captures how adverse climatic shocks instigated permanent changes in the production behavior of hunter-gatherers over time.

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 one when it is not. 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[39]. It is assumed that agricultural productivity in either regime evolves so long as environmental conditions are amenable to farming, that is, $e_t < \bar{e}$. Otherwise, the productivity parameter simply reverts to an initial, positive, irreducible level of agricultural knowledge $A_0 = A_{\min} > 0$. This restriction highlights the fact 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 transition. Hence, when agriculture is latent, we model the growth rate of agricultural knowledge between periods t and $t+1$ as a function of the allocation of hunter-gatherer labor to intermediate activities in period t, $s^h(e_t, \zeta_t)$[40].

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 were bound not to get fully assimilated into the next generation's stock of knowledge[41]. Moreover, an important implication of the 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

[38] Introducing random innovations that enhance the productivity of intermediate goods in the process of development would not affect the qualitative predictions of the model. The dynamics of ζ_t, as specified, essentially endogenizes the arrival rate of such innovations to the climatic variability of a region.

[39] Formally, $A_t \equiv A_t^h$, $\forall t$ such that $y^h(e_t, \zeta_t, L_t) > y^g(e_t, A_t)$ whereas $A_t \equiv A_t^g$, $\forall t$ such that $y^h(e_t, \zeta_t, L_t) \leq y^g(e_t, A_t)$.

[40] 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.

[41] Intuitively, this effect would have been exacerbated by adult mortality in a period of human history where adults transmitted knowledge from one generation to the next. Thus, adult mortality rates in archaic hunter-gatherer societies could well proxy for the type of intergenerational erosion of knowledge being proposed.

"eroding" the disturbance generated by the previous generation whose habitat, now in the absence of human intervention, reverts to its original "wild" state[42].

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

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

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_{t+1}^h, is, therefore,

$$g_{t+1}^h \equiv \left(A_{t+1}^h - A_t^h\right)/A_t^h = H\left(s^h\left(e_t, \zeta_t\right)\right) - \xi \equiv \tilde{H}\left(e_t, \zeta_t\right) - \xi, \tag{19}$$

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_t^h 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_{t+1}^h, and between periods $t+1$ and $t+2$, g_{t+2}^h. 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 absence of any climatic reversal the growth rate of knowledge would be identical and constant across generations. An increase in climatic stress of magnitude Δe in period t would increase g_{t+1}^h beyond the pre-reversal knowledge accumulation rate by[43]

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

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_{t+1}^h, by[44]

[42] This interpretation implies that the extent of knowledge erosion is endogenously determined by the degree of hunter-gatherer mobility. Although the erosion is not modelled as such, incorporating this effect would enhance the qualitative predictions of the model.

[43] This assumes a sufficiently small change in climatic stress, Δe, such that the second-order effect of the change operating through the concavity of H can be altogether ignored.

[44] 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. $g_{t+2}^h - g_{t+1}^h$, arises from the indirect effect of the climatic shock on the productivity of intermediate goods, ζ_{t+1}.

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

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* $A_t^h = A_{\min}$*, 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. $A_{t+1}^h > A_t^h \quad iff \quad \tilde{H}\left(e_{t-1},\zeta_t\right) + \Delta\tilde{H}_1 > \xi$

B. $A_{t+1}^h = A_t^h \quad iff \quad \tilde{H}\left(e_{t-1},\zeta_t\right) + \Delta\tilde{H}_1 \leq \xi$

C. $A_{t+2}^h > A_t^h \quad if \quad \tilde{H}\left(e_{t-1},\zeta_t\right) + \Delta\tilde{H}_1 + \Delta\tilde{H}_2 > \xi$ *or* $\tilde{H}\left(e_{t-1},\zeta_t\right) + \Delta\tilde{H}_1 > \xi$

D. $A_{t+2}^h = A_t^h \quad iff \quad \tilde{H}\left(e_{t-1},\zeta_t\right) + \Delta\tilde{H}_1 + \Delta\tilde{H}_2 \leq \xi$

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_{t+1}^h, 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 as determined by the degree of intermediate investment of the preceding generation, $\tilde{H}(e_{t-1},\zeta_t)$, is sufficiently large to overcome erosion between periods t and $t+1$. Otherwise, A_{t+1}^h will necessarily remain at the irreducible level of knowledge $A_{\min}$. Note that an increase in A_{t+1}^h necessarily implies an increase in the level of latent agricultural knowledge of generation $t+2$, A_{t+2}^h. However, even if A_{t+1}^h 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_{t+2}^h beyond $A_{\min}$.

Proposition (2) establishes the fundamental role of climatic histories coupled with current environmental conditions in governing the evolution of the 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[45]. 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 $t+1$,

[45] For simplicity, we assume that a subset of the productivity of intermediate goods, ζ_t, in the hunter gatherer sector can also be applied to agriculture. Its magnitude is normalized to 1.

A^g_{t+1}, is assumed to be a positive, increasing and concave function of the level of technology[46] at time t, A^g_t. Therefore,

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

where the function 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 $L_t = L^{h*}_t + L^{g*}_t$ is the population size in period t; $L^{h*}_0 > 0$, $L^{g*}_0 = 0$ and therefore $L_0 = L^{h*}_0$ 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), that is, if both sectors in the economy are active in period t, output per capita and, thus, fertility choices are identical across sectors.

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, and embodied knowledge of agriculture. The dynamic path of the economy is fully determined by the sequence $\{e_t, L_t, \zeta_t, A_t\}^{\infty}_{t=0}$ that satisfies equations (17), (23) and either (18) or (22) in every period t. This describes the time path of the degree of environmental harshness, e_t[47], the size of the population, L_t, the productivity of intermediate goods in the hunter-gatherer sector, ζ_t, and the stock of agricultural knowledge, A_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., $L_t = L^h_t$, 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^L_t, is a unique single-valued function of e_t,*

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

[46] The assumption of diminishing returns is theoretically close to the epistemological framework of technology proposed by Olsson (2000; 2005) where new knowledge is created through convex combinations of existing ideas and the rate at which it grows is subject to diminishing returns in absence of paradigm shifts.

[47] The trajectory may be either deterministic or stochastic. It is not explicitly described since in the current set up the dynamic analysis focuses on the effect one time shocks contingent on different climatic histories.

where L_t^L *is*

1. *monotonically decreasing and strictly convex in* e_t*, that is*

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

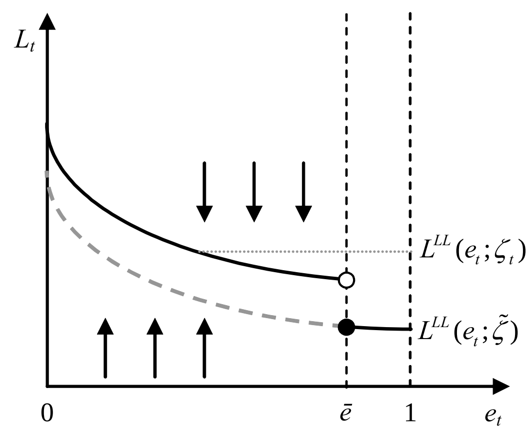
2. *monotonically increasing in* ζ_t*, that is*

$$\frac{\partial L^{LL}\left(e_t;\zeta_t\right)}{\partial \zeta_t} > 0.$$

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* $y^h(e_t,\zeta_t,L_t) > y^g(e_t,A_t)$*,*

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



LL frontier given $y^h > y^g$ for all $e_t \in [0,1]$
Figure 2.

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 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 of generation t is indifferent between supplying his labor to the hunter-gatherer and agricultural sectors. Thus[48],

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

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 size of the population indifferent between agriculture and hunting and gathering* L_t^y *is a unique single-valued function of* $e_t \in [0, \bar{e}]$,

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

where L_t^y *is*

1. *monotonically increasing and strictly convex in* e_t*, that is*

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

2. *monotonically increasing in* ζ_t*, that is*

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

3. *monotonically decreasing in* A_t*, that is*

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

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,

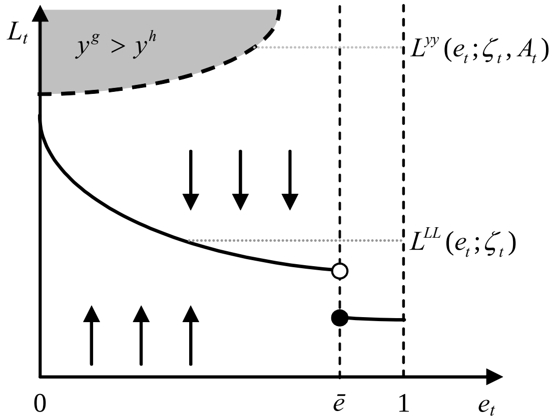
$$y^h\left(e_t, \zeta_t, L_t^h\right) - y^g(e_t, A_t) \gtreqless 0 \quad \text{if and only if} \quad L_t^h \lesseqgtr L^{yy}(e_t; \zeta_t, A_t).$$

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* $L_t^{g*} = L_t - L^{yy}(e_t; \zeta_t, A_t)$.

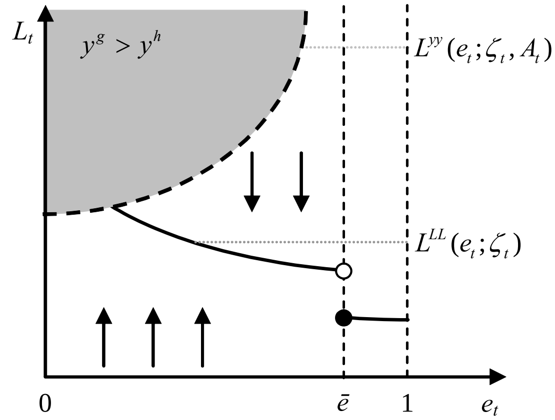
The Hunter-Gatherer Frontier, as depicted in Figures 3a-3b[49], is therefore a strictly convex, upward sloping curve in (e_t, L_t) space where, given e_t and an arbitrary L_t, the fraction of the total labor force residing above (below) the frontier will be employed in the agricultural (hunter-gatherer) 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.

[48] 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.

[49] The replacement frontiers in Figures 3a and 3b have been drawn such that $\zeta_t > \tilde{\zeta}$.



yy and LL frontiers for relatively low A_t
Figure 3a.



yy and LL frontiers for relatively high A_t
Figure 3b.

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. These are determined both by the magnitude of the reversal as well as the climatic history experienced by the foraging group. Consequently, the exposition shows how the model may account for different cases of the transition (or non-transition) to agriculture 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 mild increases in climatic stress may fail to give rise to agriculture, highlighting 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.

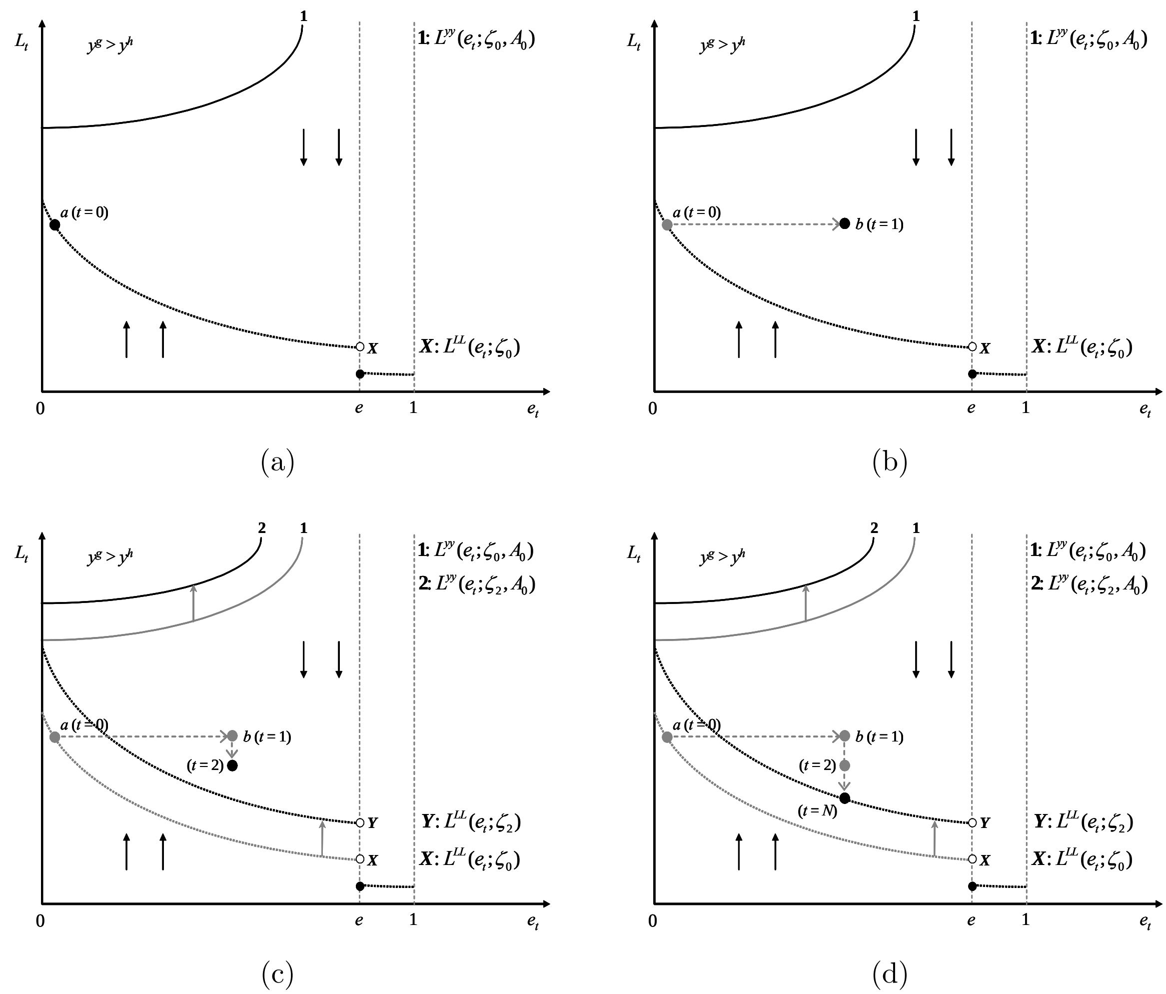
Figures 4a-4d depict the case of non-transition given a permanent mild climatic reversal. Note that such a scenario occurs under Case D of Proposition (2)[50].

The interpretation of Figures 4a-4d is as follows. Corresponding to Figure 4a, 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 a mild adverse climatic shock, $e_0 < e_1 < \bar{e}$, and moves to point b (Figure 4b). Generation 1, responds to the harsher environment by simultaneously increasing it's intermediate activities and reducing fertility (relative to generation 0). By (17),

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

the increased intermediate activities of generation 1 improves 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 4c. 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 4c, the yy locus simply shifts up (when the intermediate goods productivity increases from ζ_0 to ζ_2) and remains there. Subsequently, as Figure 4d illustrates, the economy gradually moves under Malthusian dynamics to eventually settle on its new steady-state in period N.



Non-transition during a Climatic Reversal
Figure 4.

This example offers a novel insight regarding non-transitions. In particular, a reversal may fail to set in motion the growth of latent agricultural knowledge either because the shock is not sufficiently large[51] or the rate at which the habitat is disturbed (i.e. proxied by the level of intermediate investments) prior to the shock is not substantial enough.

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 "racheting" 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 mild 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 of understanding the observed evolution of mankind in the foraging regime towards more technologically advanced modes of food acquisition, independent of the Neolithic Revolution.

7.2 Transition during a Climatic Reversal

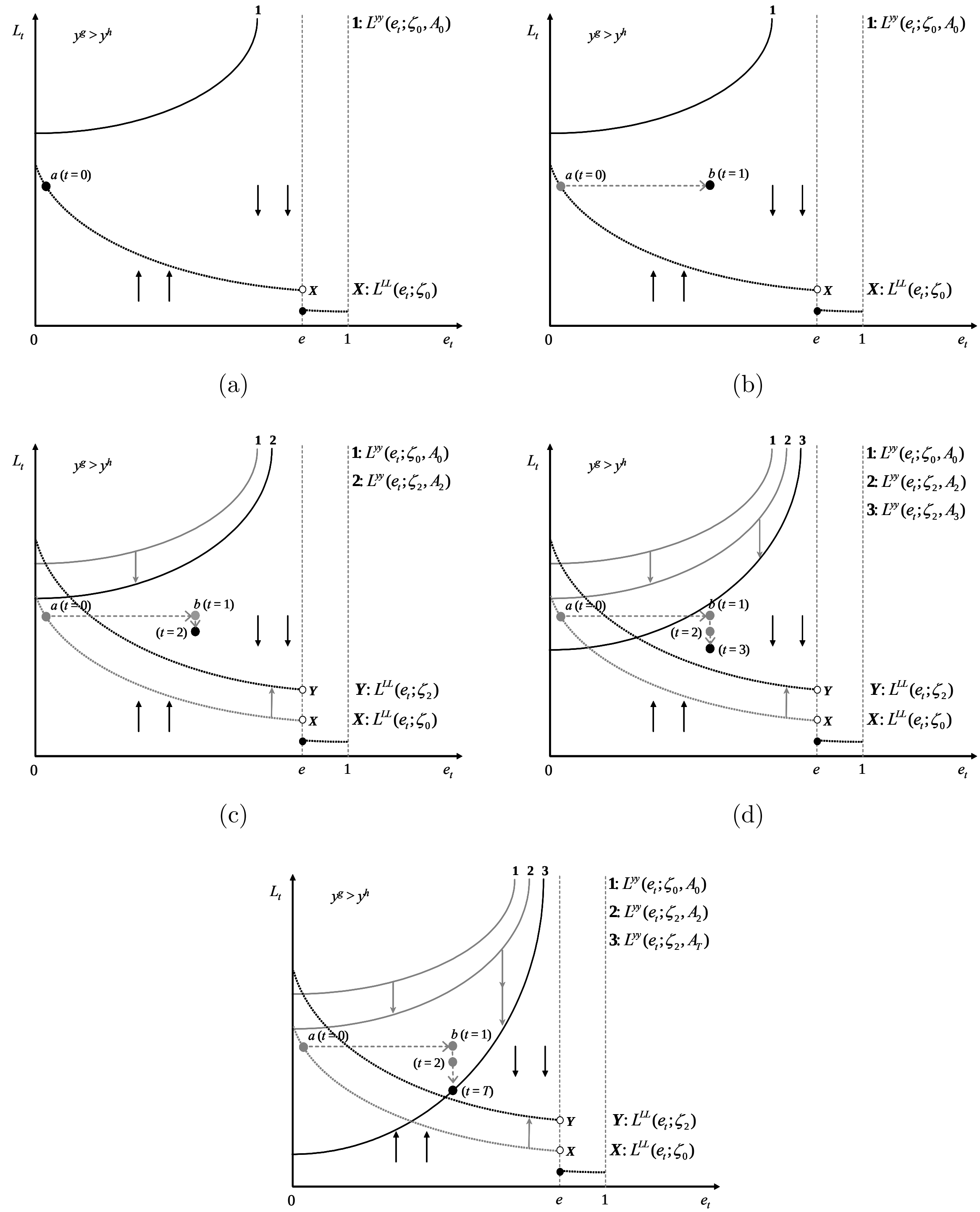
The scenario of the transition to agriculture during a period of increased climatic stress illustrates the experience at Abu Hureyra. For the theory to give rise to such a case it suffices to assume that there is either no climatic recovery following the reversal or that the recovery occurs after the transition has already taken place[52]. Figures 5a-5e 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 5a-5e may be interpreted as follows. Suppose, as shown in Figure 5a, 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 5b. 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 5c. 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 to ensure that the yy locus starts shifting down for subsequent generations. Figure 5d shows that this is the case for all generations beyond that in $t = 1$. Finally, as shown in Figure 5e, the downward shifting yy locus 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 could induce high 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 cultures.

[51] Alternatively, it could be the case that the shock is so large, i.e. $e_1 > \bar{e}$, that both the levels of latent agricultural knowledge and the productivity of intermediate goods revert to their initial primitive values (figure not shown).

[52] The graphical assumption (G-A2) is employed in this case.



Transition during a Climatic Reversal
Figure 5.

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. Nonetheless, as will become evident from the example, it is a preceding climatic reversal that plays the key role.

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.,

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

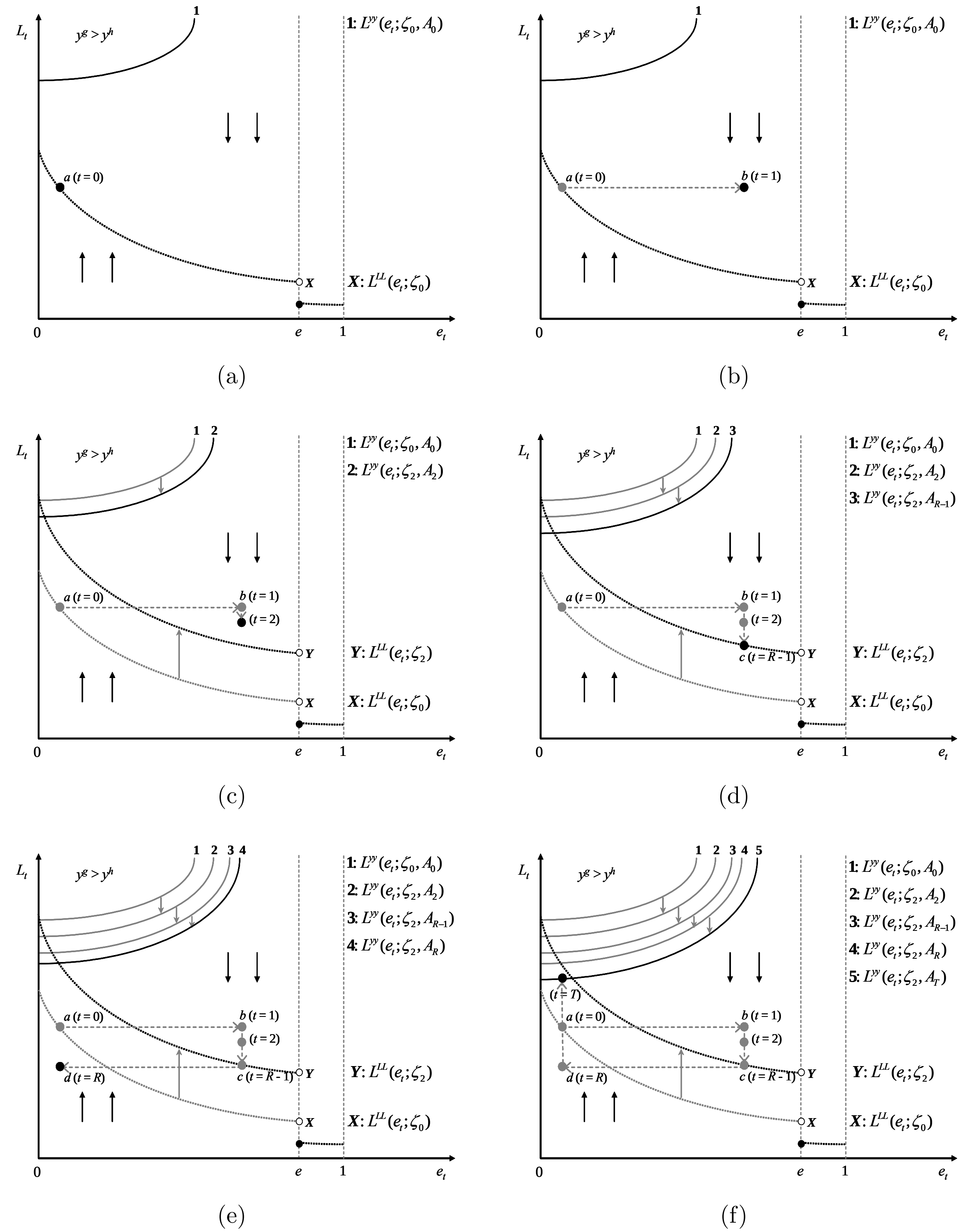
Figures 6a-6f illustrate this scenario and, for simplicity, are depicted under the graphical assumptions in Appendix D in addition to the case specific assumptions (A3) and (A4).

The interpretation of Figures 6a-6f is as follows. Corresponding to Figure 6a, 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 (Figure 6b). 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 corresponds to Figure 6c).

Meanwhile, the initial reversal has set in motion the accumulation of latent agricultural knowledge, which, as illustrated in Figure 6c, shifts the yy locus downward[53]. Over time, given no changes in environmental conditions, the economy settles in the new steady-state denoted by point c (Figure 6d). 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 6e. 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 (the move from curve 3 to 4 in Figure 6e). 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 6f, the economy's upward trajectory meets the downward shifting frontier in period T. At this point the economy transits into agriculture[54].

[53] Note that, by the graphical assumption (G-A2), the yy locus faced by generation 2 (curve 2) resides below the initial frontier (curve 1).

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

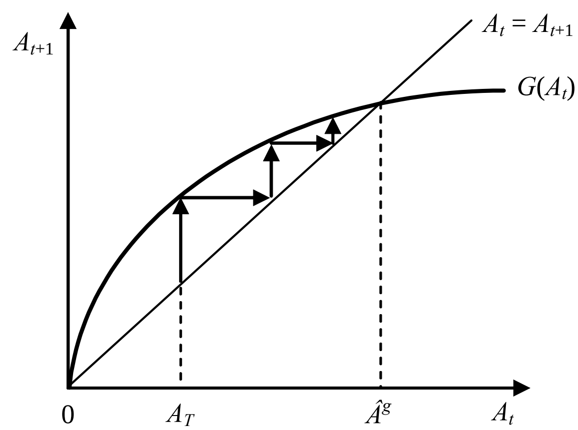


Transition following a Climatic Recovery
Figure 6.

This example illustrates the significance of the permanent effect of climatic reversals on the productivity of intermediate goods in the hunter-gatherer sector. Specifically, in its absence 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, this case 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 and exemplifies Bellwood's (2005) assertion that "if climatic reversal was the trigger, it took a while to go off."

8 The Post-Transition Long-run Equilibrium

Once the transition to agriculture occurs, the global concavity of the function G in the learning-by-doing dynamics of agricultural technology, as specified in (22) and depicted in Figure 7, assures the existence of a unique, positive and globally stable steady-state. As long as A_t^h increases, an increasing fraction of the total population joins the agricultural sector. This reallocation of labor keeps incomes equal across the two sectors. In this section we examine 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[55].



Post-transition Dynamics of A_t
Figure 7.

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, as follows directly from Proposition (1), the steady-state level of per-capita income 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

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

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 agricultural population continues to increase in every period at the steady-state[56]. This occurs because although hunter-gatherers of any generation t in the steady-state have the same fertility as the agriculturalists, their offspring in excess of $\hat{L}^h$ join the agricultural population in the next period[57].

9 Non-Transitions

The discussion in Appendix A and B illustrates that the proposed model is in line with evidence from the archaeological literature regarding instances of pristine transition to agriculture for the cases summarized in Table 1. Interestingly, the theory may also be applied to understand cases of non-transition where one or more of the following conditions, crucial for the potential adoption of agriculture, are violated: (a) the overall climatic volatility of the 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., 2005). 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 a prime example of differential transition driven purely by differences in the degree of climatic fluctuations[58].

Naturally, the availability of potentially domesticable species is a necessary requirement for an agricultural transition in our 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, pristine transition may not occur if climatic stress does not induce 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 is 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 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., 2005).

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.

[56] Although this result runs contrary to the belief that agricultural populations historically behave in a Malthusian manner, one may appeal to the notion of Boserupian dynamics to justify the result. Alternatively, the model could be modified to introduce decreasing per-worker returns to labor in agriculture beyond an arbitrary level of population engaged in agriculture. This, however, would unnecessarily complicate the model, which is primarily meant to provide an understanding of the transition to agriculture as opposed to the long-run equilibrium behavior of agricultural populations.

[57] This is an artifact of the assumed free mobility of labor across sectors.

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

10 Concluding Remarks

Persistent differences across regions in the pattern of climatic variation over time differentially affected the process of development. This research provides a unified theory that links climatic variability with the evolution of the foraging regime. It suggests that the climatically triggered transformation of foraging activities played a pivotal role in the transition to agriculture. Specifically, considering cultures indigenous to the Fertile Crescent, favorable climatic conditions after the LGM coupled with mild environmental shocks led to increased investment in intermediate activities such as tool-making and the building of semi-permanent settlements. These changes facilitated the efficient exploitation of a wide array of marginal species. Greater tool diversity, active intervention in maintaining fields of wild cereals and the associated dietary expansion were all intimately linked to the increased sedentary lifestyle of the Natufians.

A subsequent climatic reversal, i.e., the Younger Dryas, made the transition to agriculture a technologically viable alternative to either reverting to more mobile foraging or continuing a partial dependence on wild cereal harvesting. According to the proposed theory, this transition was feasible due to the pre-reversal rate of wild cereal exploitation attained by the Natufians, which on it's own was an outcome of earlier climatic shocks. Increased intermediate investments in the form of sedentism and tool-making positively affected the accumulation of latent agricultural knowledge which encompasses both a pseudo-farming experience and the domestication process of the available species.

This research focuses directly on the interaction of environmental conditions and production decisions regarding the allocation of labor between intermediate activities and pure foraging which includes the mobility pattern of hunter-gatherers. The theory internalizes the permanent effect of mild environmental stress on intermediate input investments, shedding light on the gradual transition of foragers towards more sophisticated food extraction and processing techniques. The model explains why earlier climatic downturns in human history did not lead to agriculture highlighting, however, their importance in fostering the productivity of intermediate activities (i.e., knowledge of efficiently acquiring underexploited species) and, consequently, population density. In several instances the result was the adoption of a more sedentary lifestyle by hunter-gatherers, which when coupled with extensive exploitation of plants, accelerated their accumulation of latent agricultural knowledge and brought them closer to the adoption of agriculture later in the climatic sequence. Interestingly, the theory captures that there need not be a tight contemporaneous link between the emergence of agriculture and an adverse climatic event, a common criticism to models predicting otherwise.

Mild environmental adversities are therefore essential in shaping the foraging regime towards the agricultural transition, implying that heterogeneity in past regional climatic sequences, conditional on biogeographic endowments, played a crucial role in generating the differential timing of agricultural transitions and, consequently, the observed contemporary differences in income per capita across countries. On the other hand, occurrences of extreme environmental stress (e.g., a return to glacial or arid conditions), however, eliminated any cumulative "beneficial" effect of the climatic past on the dietary and intermediate investment patterns of foragers, essentially resetting the process of development towards the emergence of agriculture.

The characteristics of cases of independent transition to agriculture reviewed in detail in Appendix A and B are consistent with the main predictions of the theory. This places past and current climatic stress at the center of understanding the evolution of subsistence economies of archaic hunter-gatherers towards agriculture.

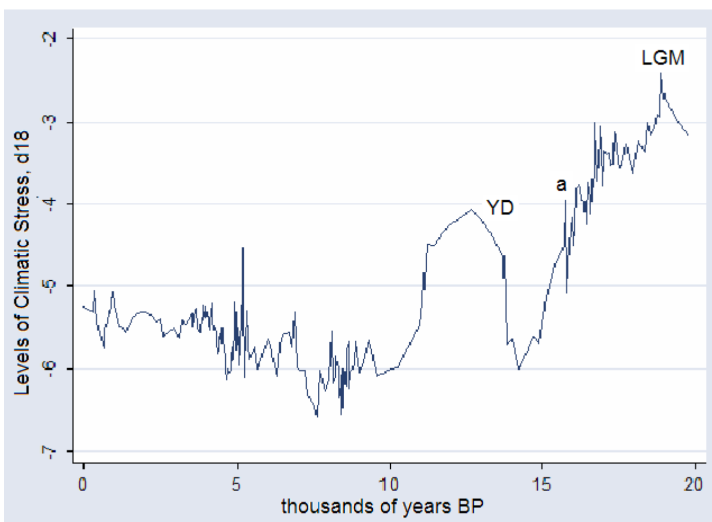
Appendix A - Supporting Evidence

Climate Variability since the LGM

Various sources have been used to identify climatic histories since the LGM[59]. 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 was terminated at about 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)[60] around 13,000 (Berger, 1990).

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, the latter occurring around 13,000 BP[61].

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.



Climate Variability in Central Israel since the LGM
Figure A-1[62].

[59]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.

[60]This event, 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.

[61]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.

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

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 13,8 and 11,4 BP) is also well documented. Notably, this climatic improvement is substantially variable and relatively more so before the advent of the Holocene. The impact of this climatic pattern on the evolution of subsistence strategies of cultures native to the Levant, is the focus of the theory.

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)[63]. The emergence of the predominantly sedentary Early Natufian culture is identified by various authors (e.g., Bar-Yosef, 1998; Bar-Yosef and Belfer-Cohen, 1989) 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 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)[64]. 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. This lifestyle, encompassing investments in more diverse and efficient tools as well as a semi-sedentary infrastructure, arose due to instances of climatic stress experienced earlier (already discussed above).

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 documented climatic stress in permanently affecting the degree of investments in intermediate activities (i.e., the overall subsistence and settlement strategies) of hunter-gatherer economies.

Climatic Stress and Food Procurement Patterns

Climatic changes have a direct impact on the available flora and fauna in a region. Maps of paleovegetation change as climatic conditions fluctuate (Adams and Faure, 1997). This, in turn,

[63] 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) which is around 1500 years before the advent of the YD.

[64] 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 initiated by the rise of the Early Natufian culture.

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 increases the risk of food acquisition. As a result foragers alter their dietary pattern by including lower-ranked species[65]. 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[66].

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[67].

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 gazelle, birds, hares, tortoise 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[68].

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 an efficient exploitation of existing and marginal resources and ultimately towards agriculture.

[65] Such dietary changes, as discussed earlier, are 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.

[66] 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).

[67] 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."

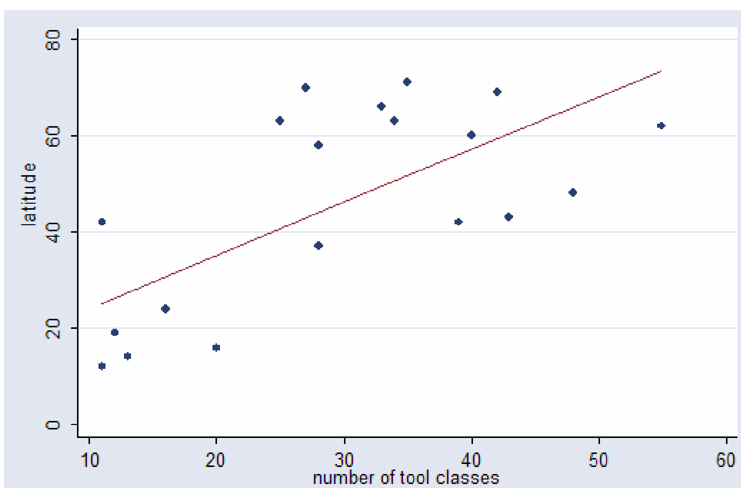
[68] "At any latitude except those of polar deserts, a rich-coastal hunter-gather group experiencing either a decrease in precipitation, an increase in population density, or both, has little choice but to intensify its use of plant foods" (Keeley, 1995).

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 more efficient exploitation of those already being consumed necessitates the application of a wider array of food extraction techniques. Hence, hunter-gatherer groups in environments characterized by higher risks 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 exactly because the process of gaining access to new lower-ranked food resources was synonymous to developing higher-cost 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.



Subsistence Risk and Tool Diversity
Figure A-2 (Source: Torrence, 1983).

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 residing in different latitudes. 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[69]. 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 for 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.

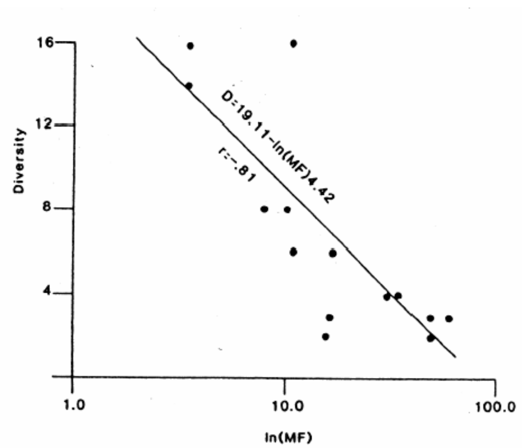
Intermediate Investments and Sedentism

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 because of 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 the figure, 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. The correlation in Figure A-3 is statistically significant at the 1% level.

[69] 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.



Tool Diversity and Residential Mobility
Figure A-3 (Source: Shott, 1986).

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 (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[70].

It should be noted that, unlike other approaches, our 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.

[70]Bender (1978) suggests that sedentism caused certain sociocultural processes to operate within communities that led to concerns with social status, prestige and, ultimately, power. This, he argues, had to be met by generating a food surplus that permitted a redistribution of wealth necessary to achieve a position of power. However, in order to generate wealth, more diverse forms of exploitation were required and this led to intensive plant collection and, eventually, to cultivation.

Appendix B - 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 as depicted in Table 1. 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[71].

Unlike the Near East, the archaeological record on the rise of African agriculture does not identify a single center of domestication[72]. 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 archaeological record on the emergence of agriculture in Central America shows evidence of domesticated maize and common beans appearing at San Marcos and Coxcatlán Caves in the Tehuacán Valley of central Mexico at around 4,700 BP and 2,300 BP, respectively (Smith, 1995)[73].

Consistent with the theory, archaeologists (e.g., MacNeish, 1971; Flannery, 1986; McClung de Tapia, 1992) have interpreted the Tehuacán and Oaxaca Valley sequences along the lines of environmentally triggered dietary expansion leading to the eventual domestication of plants in central Mexico. MacNeish (1971) argues that in the earliest Ajuereado phase of the Tehuacán sequence (10,000 - 7,000 BC), small nomadic bands gradually acquired a close familiarity with local "microenvironments" in a knowledge accumulation process that coincided with Late Pleistocene climatic variation, which substantially altered the regional environment. Specifically, as larger animals became scarce due to increased climatic stress, the lack of sufficient meat resources led to an increased exploitation of small game and plant foods. During the succeeding El Reigo phase (7,000 - 5,000 BC), the subsistence-settlement pattern was characterized by larger semi-nomadic groups with intensive plant collection. This gave way to the Coxcatlán phase (5,000 - 3,400 BC) where domesticated maize first appears in the archaeological record[74].

[71] The dates mentioned in this section reflect uncalibrated radiocarbon dates and, therefore, appear as being different from those mentioned in Table 1.

[72] 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 4000 BP, cultivated pearl millet is identified in the Dhar Tichitt region of southwestern Sahara by 3000 BP, and African rice at the site of Jenne-Jeno on the Niger River bend is dated to about 200 AD (Smith, 1995).

[73] Moreover, remains of *Cucurbita* squash at Guilá Naquitz Cave in the Oaxaca Valley have been dated, albeit controversially, to as early as 9,800 BP (Flannery, 1986; Marcus and Flannery, 1996).

[74] Flannery (1986) provides a similar interpretation for the Oaxaca Valley sequence and argues that the early

Regarding south central Andes, research conducted by Rick (1980) has shed light on the domestication of high-altitude species of plants and animals in South America. The earliest evidence of domestication in this region appears in Panaulauca and Pachamachay caves in the Lake Junin basin of south central Andes and comprises the grain crop quinua and the llama. Both instances are dated between 5,000 and 4,000 BP. In an interpretation of sequences akin to that offered for central Mexico, Smith proposes that domestication in the Andean highlands became inevitable once "hunter-gatherer societies began to intervene in the life cycle of a few selected wild food sources in their efforts to make life more predictable in an often changing environment" (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 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).

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cultivation of maize, beans and squash in central Mexico was a logical consequence of hunter-gatherer efforts to increase the predictability of subsistence resources in an environment where resource abundance varied from one year to another.

Appendix C - Proofs

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

$$\begin{aligned} F\left(s_t^{h*}, e_t, \zeta_t\right) &\equiv e_t\left[\left(1-s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^2+1/\lambda s_t^{h*}\right]\left[\left(1-s_t^{h*}\right)^\rho+\left(\zeta_t\lambda s_t^{h*}\right)^\rho\right]- \\ &\quad \alpha\left[1-e_t\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]\left[\left(1-s_t^{h*}\right)^{\rho-1}-(\zeta_t\lambda)^\rho\left(s_t^{h*}\right)^{\rho-1}\right] \qquad (26) \\ &= 0. \end{aligned}$$

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 $s_t^{h*}\mid_{e_t=0}= (\zeta_t\lambda)^{\frac{\rho}{1-\rho}}\left\{1+(\zeta_t\lambda)^{\frac{\rho}{1-\rho}}\right\}^{-1}$. This, coupled with the assumption that $\zeta_t < \lambda^{-\frac{1}{\rho}}$, implies that $s_t^{h*}\mid_{e_t=0}< 1/(1+\lambda)$.

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

$$\begin{aligned} F_s\left(s_t^{h*}, e_t, \zeta_t\right) &= -(\alpha+\rho)\,e_t\left[\left(1-s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^2+1/\lambda s_t^{h*}\right]\left[\left(1-s_t^{h*}\right)^{\rho-1}-(\zeta_t\lambda)^\rho\left(s_t^{h*}\right)^{\rho-1}\right] \\ &\quad -2e_t\left[\left(1-s_t^{h*}\right)/\lambda\left(s_t^{h*}\right)^3+1/\lambda\left(s_t^{h*}\right)^2\right]\left[\left(1-s_t^{h*}\right)^\rho+\left(\zeta_t\lambda s_t^{h*}\right)^\rho\right] \qquad (27) \\ &\quad -\alpha(1-\rho)\left[1-e_t\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]\left[\left(1-s_t^{h*}\right)^{\rho-2}+(\zeta_t\lambda)^\rho\left(s_t^{h*}\right)^{\rho-2}\right] \\ &< 0. \end{aligned}$$

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

$$F_e\left(s_t^{h*}, e_t, \zeta_t\right) = \frac{(\zeta_t\lambda s_t^{h*})^\rho\left(1-\alpha\left(1-s_t^{h*}\right)\right)+\left(1-s_t^{h*}\right)^\rho\left(1+\alpha s_t^{h*}\right)}{\lambda\left(s_t^{h*}\right)^2} > 0; \qquad (28)$$

$$F_\zeta\left(s_t^{h*}, e_t, \zeta_t\right) = \rho(\zeta_t\lambda)^{\rho-1}\left(s_t^{h*}\right)^{\rho-2}\left(\left(1-\alpha\left(1-s_t^{h*}\right)\right)e_t+\alpha\lambda s_t^{h*}\right) > 0, \qquad (29)$$

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

$$\frac{\partial y_t^h}{\partial e_t} = -\left[\left(1-s_t^h\right)/\lambda s_t^h\right]\left[\left(1-s_t^h\right)^\rho+\left(\zeta_t\lambda s_t^h\right)^\rho\right]^{\frac{\alpha}{\rho}}\left(L_t^h\right)^{\alpha-1} < 0; \qquad (30)$$

$$\frac{\partial y_t^h}{\partial \zeta_t} = \alpha\left(\zeta_t\lambda s_t^h\right)^{\rho-1}\left[\lambda s_t^h-e_t\left(1-s_t^h\right)\right]\left[\left(1-s_t^h\right)^\rho+\left(\zeta_t\lambda s_t^h\right)^\rho\right]^{\frac{\alpha}{\rho}-1}\left(L_t^h\right)^{\alpha-1} > 0; \qquad (31)$$

$$\frac{\partial y_t^h}{\partial L_t^h} = (\alpha-1)\left[1-e_t\left(1-s_t^h\right)/\lambda s_t^h\right]\left[\left(1-s_t^h\right)^\rho+\left(\zeta_t\lambda s_t^h\right)^\rho\right]^{\frac{\alpha}{\rho}}\left(L_t^h\right)^{\alpha-2} < 0. \qquad (32)$$

Noting (30) and (31), 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 (32) 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

$$\frac{\partial^2 y_t^h}{\left(\partial L_t^h\right)^2} = (\alpha - 2)\frac{\partial y_t^h}{\partial L_t^h}\frac{1}{L_t^h} > 0. \tag{33}$$

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

$$\frac{\partial^2 y^h\left(e_t, \zeta_t, L_t^h\right)}{\left(\partial e_t\right)^2} = \frac{-\left[\partial^2 y_t^h/\partial s_t^h \partial e_t\right]^2}{\left[\partial^2 y_t^h/(\partial s_t^h)^2\right]} > 0, \tag{34}$$

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

$$y^h\left(e_t, \zeta_t, L_t\right) \equiv \Psi\left(e_t, \zeta_t\right) L_t^{\alpha-1} > 0, \tag{35}$$

where, as follows from the positivity of L_t and Lemma 2, $\Psi_{ee}(e_t, \zeta_t) > 0$. Hence, using (35), (24) yields

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

and therefore

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

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

$$
\Omega\left(L_t,e_t,\zeta_t,A_t\right) \equiv y^h\left(e_t,\zeta_t,L_t\right) - y^g\left(e_t,A_t\right) = 0, \tag{36}
$$

where, as follows from Lemma 2,

$$
\Omega_L\left(L_t,e_t,\zeta_t,A_t\right) = y_L^h\left(e_t,\zeta_t,L_t\right) < 0. \tag{37}
$$

The uniqueness of $L^{yy}(e_t;\zeta_t,A_t)$ then follows immediately, via the *Implicit Function Theorem*, from (37). 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 the the hunter-gatherer sector, since

$$
\begin{aligned}
& y_e^h\left(e_t,\zeta_t,L_t\right) - y_e^g\left(e_t,A_t\right) > 0 \Leftrightarrow \\
-y^h\left(e_t,\zeta_t,L_t\right)&\frac{\left[\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]}{\left[1-e_t\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]} + \frac{y^g\left(e_t,A_t\right)}{1-e_t} > 0 \Leftrightarrow \\
\frac{y^h\left(e_t,\zeta_t,L_t\right)}{1-e_t} &> y^h\left(e_t,\zeta_t,L_t\right)\frac{\left[\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]}{\left[1-e_t\left(1-s_t^{h*}\right)/\lambda s_t^{h*}\right]} \Leftrightarrow \\
1 &> \left(1-s_t^{h*}\right)/\lambda s_t^{h*} \Leftrightarrow s_t^{h*} > 1/\left(1+\lambda\right),
\end{aligned}
$$

where the first equivalence follows from (12) and (30), 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

$$
\Omega_e\left(L_t,e_t,\zeta_t,A_t\right) > 0. \tag{38}
$$

Hence, noting (37) and (38),

$$
L_e^{yy}\left(e_t;\zeta_t,A_t\right) = -\frac{\Omega_e(L_t,e_t,\zeta_t,A_t)}{\Omega_L\left(L_t,e_t,\zeta_t,A_t\right)} > 0.
$$

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

$$
\begin{aligned}
\Omega_{ee}(L_t,e_t,\zeta_t,A_t) &= y_{ee}^h\left(e_t,\zeta_t,L_t\right) > 0; \qquad (39)\\
\Omega_{eL}(L_t,e_t,\zeta_t,A_t) &= y_{eL}^h\left(e_t,\zeta_t,L_t\right) > 0, \qquad (40)
\end{aligned}
$$

where the positivity of the former follows from Lemma 2 and (12), and the positivity of the latter from (30) and the *Envelope Theorem.* Therefore, noting (37)-(40),

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

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

$$\begin{aligned}\Omega_\zeta(L_t,e_t,\zeta_t,A_t) &= y^h_\zeta(e_t,\zeta_t,L_t)>0; &(41)\\ \Omega_A(L_t,e_t,\zeta_t,A_t) &= -\left[y^g_A(e_t,A_t)\right]<0, &(42)\end{aligned}$$

where the positivity of the former follows from Lemma 2, and the negativity of the latter follows trivially from (12). Thus (37), (41) and (42) imply that

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

which completes the proof. ■

Appendix D - Assumptions on 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 (G-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:

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

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 (G-A2) assures that the net effect of a climatic reversal in period t on the yy locus results in a downward shift of the frontier in period $t+1$[75]:

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

[75] 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, (G-A2) would end up violating the results of Lemma (4).

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