THE TRANSITION TO AGRICULTURE:
CLIMATE REVERSALS, POPULATION DENSITY,
AND TECHNICAL CHANGE

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Abstract: Until about 13,000 years ago all humans obtained their food through hunting and gathering, but thereafter people in some parts of the world began a transition to agriculture. Recent data strongly implicate climate change as the driving force behind the agricultural transition in southwest Asia. We propose a model of this process in which population and technology respond endogenously to climate. The key idea is that after a lengthy period of favorable environmental conditions during which regional population grew significantly, an abrupt climate reversal forced people to take refuge at a few ecologically favored sites. The resulting spike in local population density reduced the marginal product of labor in foraging and made agriculture attractive. Once agriculture was initiated, rapid technological progress through artificial selection on plant characteristics led to domesticated varieties. Farming became a permanent part of the regional economy when this productivity growth was combined with climate recovery.

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1. Introduction

Anatomically modern humans have existed for almost 200,000 years (McDougall, Brown, and Fleagle, 2005), and judging from artwork, funeral practices, and tool design, cognitively modern humans have existed for at least 50,000 years. Yet until about 13,000 years ago, all humans obtained their food by hunting animals or gathering wild plants. The shift to domesticated plants and animals began at this time in southwest Asia. Independent points of origin also included north China, south China, sub-Saharan Africa, Mexico, the Andes, and the eastern U.S., with subsequent diffusion to most parts of the globe. This transition was arguably the most consequential case of rational economic choice in human history. It was necessary for the existence of cities, states, and writing, and with relatively few exceptions for specialized crafts, inequality, hierarchy, and organized warfare.

How can one explain the long lag between the evolution of modern humans and the shift to agriculture? Why did farming emerge when and where it did? Several authors have recently pointed to climate change as a leading suspect behind the agricultural transition. For example, Richerson et al. (2001) assert that agriculture was "impossible" in the most recent Ice Age because prevailing climatic conditions--low temperatures and atmospheric CO_2 levels, extreme aridity, and high-amplitude fluctuations on time scales of a decade or less to a millennium--severely limited the expected returns on investments in agriculture. In their view, the relatively warm, wet, and stable conditions after the Ice Age encouraged cultural evolution toward heavy reliance on specialized plant resources, leading eventually to agriculture. The empirical problem with this perspective, however, is that archaeologists have not yet found evidence for agriculture anywhere in the world during the initial warming phase following the last glacial, even though this interval lasted almost two millennia.

Warmer conditions indeed led to abundant wild resources, substantial population growth, and a sedentary lifestyle in southwestern Asia. This idyllic period was interrupted by an abrupt climate reversal (the Younger Dryas) during which cooler and drier conditions again prevailed. Many hunting and gathering sites became less attractive and the population either returned to a nomadic lifestyle or took refuge in a few areas that remained relatively hospitable. It is only during this harsher period that agriculture is first detected.

Our model accounts for the puzzling observation that a climate reversal was needed to initiate the transition. The key idea is that forcing a large regional population through a small geographic bottleneck led to a spike in labor supply at the best food production sites. Under reasonable technological assumptions there is a population threshold beyond which some labor is optimally allocated to agriculture. The climate reversal in southwest Asia propelled local densities beyond this threshold at a few particularly favorable locations.

If technology had been constant and the climate deterioration had been permanent, falling living standards would have lowered region-wide population, reducing pressure on the best sites. Eventually local densities would have dropped below the minimum needed for agriculture, and farming would have been a temporary expedient on the way back to a foraging lifestyle. However, two factors intervened. Once agriculture began, productivity grew rapidly through (possibly unintentional) artificial selection on genetic characteristics of plants and through the domestication of animals that were complementary to farming. Second, the climate reversal was temporary. After temperatures rose significantly, the new package of domesticated plants and animals spread, population growth resumed, and settled agriculture became the norm.

Due to the vast scale of the relevant literature we focus our review mainly on recent contributions by economists, although attention is also given to some important ideas from archaeology and anthropology. It is convenient to organize the discussion in terms of the variable believed by each author to be the prime mover behind the transition (for related surveys, see Pryor, 1983, 2004; Locay, 1989; Weisdorf, 2005). We will not address the role of culture as an explanatory variable (for a discussion, see Pryor, 2004).

Technology. Agriculture is sometimes portrayed as a technological innovation analogous to the light bulb. In this view, agriculture was invented by an astute group of pioneers and diffused rapidly once its benefits were recognized by others. This scenario is no longer taken seriously for several reasons. First, anthropologists stress that people in foraging societies are knowledgeable botanists and it is inconceivable that they would not grasp the feasibility of planting seeds in order to obtain a harvestable crop. Second, there are numerous examples of foragers who lived near farmers or traded with them but did not adopt farming themselves. Third, the hypothesis does not explain why agriculture arose in specific places at specific times, or why it took many millennia to invent it.

There are, however, more sophisticated theories in which technological change is the driving force behind the transition. Olsson and Hibbs (2005) develop a model of long run growth in which the pace of innovation in a particular region is an increasing function of that region's biogeographic endowment, including its suite of potentially domesticable plants and animals. Weisdorf (2004) combines exogenously improving food production with satiation in food consumption to model the abrupt emergence of a non-food-producing sector, which he identifies with the creation of food surpluses under agriculture. Finally, Marceau and Myers (2005) suggest that modest foraging capabilities are compatible with a grand coalition that restrains overharvesting of wild resources. Once technology advances to a certain point the grand coalition collapses, overharvesting prevails, and it is profitable for smaller coalitions to abandon foraging in favor of agriculture. Although these theories capture various aspects of the transition, none accounts in detail for its location or timing.

Population. Starting with Boserup (1965) and Cohen (1977), population pressure became the dominant explanation for the agricultural transition among archaeologists and anthropologists. Archaeological evidence, however, is now regarded as inconsistent with this approach for two reasons. First, increasing population pressure implies a gradual decline in living standards prior to the agricultural transition, which is not found in the data (Cohen and Armelagos, 1984). Second, world population grew extremely slowly prior to agriculture but exploded immediately after the transition (Kremer, 1993; Livi-Bacci, 1997).

Some economists have also assigned a direct or indirect role to population, often in the context of natural resource depletion. Smith (1975) links the agricultural transition to overhunting of Pleistocene megafauna, which he associates with human migration into new territory. But even if the megafaunal extinctions in North America and Australia resulted from human intervention rather than climate change, an issue subject to much debate, these events do not line up well with the location and timing of early agriculture.

North and Thomas (1977) claim that foraging was initially characterized by an open access property regime that failed to restrain overuse of wild resources. This problem was exacerbated by population growth, to the point where a transition to private property rights under agriculture became attractive. But property rights in foraging societies are extremely diverse, ranging from open access to community rights to private property, a fact that tends to undercut broad generalizations of this sort (Kelly, 1995; Baker, 2003).

Most economists dislike the use of population as an exogenous variable in the very long run, suspecting that it likely reflects a degree of choice by the people involved. This argument is supported by anthropologists who have identified several population control strategies among foragers, including sexual abstinence, long periods of breast-feeding, and infanticide. However, some demographers continue to maintain that foragers had little control over their fertility (Caldwell and Caldwell, 2003).

Climate. According to the classic "oasis" theory of V. Gordon Childe (1951: 67-72), increased aridity in southwest Asia forced humans, plants, and animals to retreat to a few oases where water remained available. This led to locally high population densities in close proximity to domesticable species, which led to agriculture. The oasis hypothesis was eventually abandoned by archaeologists and anthropologists in favor of theories involving population pressure, in part because good climate data were lacking (Binford, 1968).

As better data became available, interest in environmental explanations revived. Bar-Yosef and Meadow (1995) argue that cold and dry conditions during the Younger Dryas caused yields from wild cereal stands to decrease in southwest Asia and thus provided incentives for cultivation. Similarly, Hillman et al. (2001) suggest that the Younger Dryas drove foraging populations to cultivate caloric staples. Our analysis grows out of this interpretation from archaeology, while providing the requisite theoretical structure and incorporating population and technical change as endogenous variables.

Among economists, Morand (2002) has recently asserted that a climate reversal in southwest Asia caused people to take refuge at locations where water was available. He attributes agriculture mainly to a climate bias that reduced foraging productivity. Morand's formal model focuses on issues of human capital and intra-household bargaining that play no role in our analysis. His model also implies that people will choose either foraging or agriculture rather than using a combination of both, as is common during a transition.

Olsson (2001) constructs a model in which several factors could induce a transition to agriculture, including climate changes biased toward agriculture or against foraging; an exogenous increase in population; a change in preferences; or exogenous improvements in agricultural productivity as a by-product of foraging. Regarding climate, Olsson favors the view that environmental conditions in southwest Asia deteriorated less for agriculture than for foraging. We depart from Morand and Olsson by dropping the idea that climate change was directly biased in favor of agriculture. Instead, we stress an indirect channel running from climate to local population density and then to production decisions.

Several authors have explored the incidence of agriculture empirically using cross-sectional anthropological data (Pryor, 1986, 2004; Keeley, 1995; Locay, 1997). For our purposes, one difficulty with these studies is that recent or contemporary foraging societies are found in rain forests, deserts, or the Arctic, and there are no data indicating that early agriculture evolved in such environments. In any case, our theory concerns sequences of events involving climate change, population, and technology. A cross-sectional approach is unsuitable in this context and thus we rely instead on data-based historical narrative.

` Section 2 describes global climate from the last Ice Age to the Holocene. Section 3 defines agriculture and sketches its emergence in southwest Asia. The model is developed in section 4 and used to explain events in southwest Asia in section 5. Section 6 surveys other instances of pristine agriculture--that is, cases for which the emergence of agriculture cannot be explained by diffusion from societies where it already existed--as well as some important non-transitions, including the failure of agriculture to evolve in the last Ice Age.

Section 7 summarizes our key contributions to the literature on agricultural origins. First, we show that several commonly discussed factors are unnecessary for a transition (biased climate change, sedentism, and resource depletion). Second, we identify important but previously neglected factors (heterogeneity of production sites and migration). Finally, we endogenize two variables often treated as exogenous (population and technology).

2. Global Climate History

Climate reconstruction (paleoclimatology) involves observations on polar ice, alpine glaciers, ocean and lake sediments, tree rings, calcite precipitated on the walls of caves, growth bands in corals, and the chemistry of marine shells. Polar ice cores have more than 40 distinct climate-related properties and provide data on temperature, rainfall, ice volume, and atmospheric CO_2 concentrations. Ice cores from Dome C in eastern Antarctica allow inference of climatic conditions going back 740,000 years (Wolff et al., 2004; McManus, 2004), and confirm observations from Vostok in east Antarctica (going back 400,000 years), Greenland (80,000 years), and Atlantic ocean sediments (800,000 years).

These climate histories reveal a series of glacial periods (Ice Ages) lasting 100,000 years on average, interrupted by interglacial periods lasting 10,000 years on average. The glacial periods are characterized by low concentrations of CO_2, cold and dry conditions, high variability in weather, and low sea levels. Interglacial periods manifest opposite conditions. Relative to the current interglacial, the last Ice Age involved a 30% reduction in atmospheric CO_2 concentrations, a decrease in global mean annual temperature of 5 to 10 degrees Centigrade, and a drop of 125 meters in sea level (Cronin, 1999).

The last glacial maximum (LGM) occurred around 21,000 BP (before present). By 19,000 BP the great ice sheets had begun to melt, by 16,000 BP the climate exhibited large variations in temperature and rainfall, and shortly after 15,000 BP there was a dramatic increase in temperature that brought the Ice Age to an end. From 13,000 BP to 11,600 BP an abrupt climate reversal occurred in which conditions returned to those characterizing the LGM. This event, the Younger Dryas, is detected throughout the northern hemisphere (Cronin, 1999: 202-221), although the precise timing varies by region. The very cold and dry conditions of the Younger Dryas gave way to a second dramatic increase in temperature and rainfall. Except for significant declines in temperature around 8200 BP and 5000 BP, which may be relevant for some pristine cases discussed in section 6, the earth's Holocene climate has been relatively stable. Figure 1 provides a graph of recent temperature data.

3. Agricultural Origins in Southwest Asia

We take agriculture to mean harvesting of crops grown from previously harvested seeds. This rules out many "proto-agricultural" practices found among foragers, such as starting fires to induce seed germination or weeding "wild gardens". Planting seeds from previous harvests is vital because this is the process that leads, intentionally or otherwise, to artificial selection on the genetic traits of plants. We ignore animal domestication, even though the same principle of artificial selection through breeding applies, because (except for dogs) it followed plant domestication in most of the cases we consider.

For cereals, peas, lentils, bitter vetch, and chickpeas--the early domesticates in southwest Asia--a key difference from wild varieties is that domesticated crops cannot re-seed themselves. Thus if domesticated seeds are found, this indicates the existence of agriculture because the seeds in question must have been both planted and harvested, not just harvested. Details on morphological markers indicating domestication are provided in Harlan (1995), Smith (1998), and Moore et al. (2000). Artificial selection takes time so there is a lag between the point at which agriculture begins and the point at which it results in observable domestication. For the crops of greatest interest here, with suitable harvesting techniques, this lag is thought to have an upper bound of roughly 200 years and may be much shorter (Hillman and Davies, 1990).

At the LGM much of southwest Asia was thinly populated or unoccupied. People lived in small campsites in groups ranging from one to five families. Their lifestyle was nomadic and food was obtained by hunting and gathering. One such camp is Ohalo II, dating from 23,000 BP, which was submerged under the Sea of Galilee and discovered in 1989 after water levels dropped dramatically. The inhabitants of Ohalo II gathered a broad range of grains (Weiss et al., 2004). A significant portion of their diet consisted of small-grained grasses, far smaller than wild cereals (which were utilized as well). These grasses grew on short plants that demanded more stooping and bending to harvest than wild wheat and barley. Separating the seeds from the husks was also highly labor-intensive.

Between the Ice Age and the Younger Dryas, Natufian communities flourished in southwest Asia during a warm and wet period (for a summary and bibliography, see Bar-Yosef, 2002a, 2002b). Population grew substantially and people became sedentary. Food was plentiful, and the skeletal evidence shows few signs of trauma. There is little evidence of conflict between groups. Migration of people and settlement patterns closely followed changes in biomass, which in turn was largely determined by the amount and distribution of winter rains. This way of life lasted more than 1500 years.

The earliest domesticated seeds have been found at Abu Hureyra, located on the ecotone between the Euphrates Valley and the woodland-steppe in what is today northwest Syria (data are from Moore et al., 2000; see also Hillman et al., 2001). This village was founded around 13,500 BP. Excavation has uncovered two superimposed settlements. Abu Hureyra 1 was inhabited by sedentary foragers. The remains of food plants at 13,500 BP reflect a diverse diet typical of hunter-gatherer societies. There is no evidence for the cultivation of crops here or at any other Natufian site before the advent of the Younger Dryas, which for this region is dated around 13,000 BP.

The use of several wild foods, including some caloric staples, diminished rapidly in the early stages of the Younger Dryas, and the sequence in which individual species declined is consistent with advancing desiccation. The decline in wild cereals was immediately followed by a rapid rise in a weed flora typical of arid-zone cultivation involving substantial tillage. Charred seeds provide direct evidence that the villagers at Abu Hureyra cultivated domestic rye at this time. There are also indications of other domestic grains and possibly legumes after 13,000 BP. These observations of domestication pre-date all others for southwest Asia by one thousand years. According to Hillman (2000a: 420-1), this series of events suggests that cultivation was precipitated by the decline in wild cereals and that environmental change was the trigger.

Population in the village grew to perhaps 100 – 300 people at its maximum during this period even though population levels in southwest Asia as a whole were contracting, with many sites abandoned. The poorer climate probably decreased fertility and increased mortality for the existing inhabitants of Abu Hureyra, so population growth suggests that people were migrating from other sites in the region. The lack of evidence for violence or fortifications at Abu Hureyra also suggests that any such migration was relatively peaceful.

Abu Hureyra was also exceptional for its continuous occupation during this period. The Younger Dryas resulted in a return to a nomadic way of life across most of southwest Asia (Bar-Yosef, 2002a, 2002b). Both regional contraction in population and increased nomadism for the region as a whole are consistent with the decline in health accompanying climate deterioration (Smith, 1991). Abu Hureyra was an outlier in this regard as well. Analysis of skeletal remains indicates that nutrition levels remained constant during the Younger Dryas (Molleson, 2000).

Around 12,000 BP, the approximate end of the Younger Dryas at Abu Hureyra, population in the village declined, indicating an out-migration to previously arid locations.

Charred remains dated to this period include evidence of free-threshing wheats and bread wheat as well as domestic einkorn, barley, lentils, field weeds, and gazelle bones. Abu Hureyra 2 is dated from roughly 11,400 BP. The villagers were farmers who also collected some wild plants and hunted game, but eventually became wholly dependent on their crops and domesticated animals. Population increased rapidly to levels more than twenty times the population of Abu Hureyra 1 and surpassed in size almost all other contemporary sites in southwest Asia. All told, the life span of the village exceeded four thousand years of continuous occupation.

A number of geographical factors help explain the relatively large size and longevity of Abu Hureyra. It was particularly well situated with regard to surface water; it had easy access to a wide range of foods due to its location at a juncture of two environmental zones; it was close to the gazelle migration route; and it had extensive open land with easily tilled soils and adequate rainfall for dry farming. This combination was rare in the region.

Abu Hureyra is the only site in southwest Asia at which it is possible to observe the entire transition from foraging to agriculture. Other sites such as Mureybet, Tell Aswad, and Jericho provide data that, while consistent with the general story from Abu Hureyra, are less informative and less certain. Conditions at these other sites were also unusually favorable. Tell Aswad was located on a lakeshore surrounded by marshes, and Jericho had a permanent spring. Other early agricultural sites were on river flood plains or alluvial fans (Smith, 1998). Thus far, the presence of domesticated seeds during the Younger Dryas has only been documented for Abu Hureyra, but analysis of wild seed assemblages at Mureybet (dating from 12,500 BP) "suggests that the morphologically wild-type einkorns, ryes, and barley were already under predomestication cultivation" (Hillman, 2000b: 378). Elsewhere, domestication is first observed later in the warmer and wetter Neolithic period.

4. The Formal Model

This section defines short and long run equilibria for a model involving technology, climate, and population. The analysis can be generalized in various ways, but we confine attention to simple functional forms in order to highlight the main causal mechanisms.

Technology. Consider a production site with two sources of food: wild (obtained by foraging) and cultivated (obtained by agriculture). These foods are perfect substitutes in consumption. The production functions are

$$\text{(1)} \qquad \text{foraging:} \quad F(n_f,w) = wn_f^{\alpha} \qquad (0 < \alpha < 1)$$

$$\text{agriculture:} \quad G(n_g,k,w) = g(w)n_g^{\eta}k^{1-\eta} \qquad (0 < \eta < 1)$$

where n_f is foraging labor, n_g is agricultural labor, k is seeds, and w is weather. Foraging has decreasing returns because variable labor is applied to the fixed harvestable resources provided by nature (the input of seeds from nature is normalized at unity). Agriculture has constant returns because it involves seed inputs that can be scaled up as desired. Early in an agricultural transition suitable land is abundant and can be ignored. These assumptions are standard in the economic literature on agricultural origins (Weisdorf, 2005).

The adult population (n) allocates labor to maximize total output, taking account of the fact that agriculture requires a flow of seeds as an input. Thus (n_f,n_g,k) solves

$$\text{(2)} \qquad \max \quad F(n_f,w) + G(n_g,k,w) - k$$

$$\text{subject to } n_f \geq 0,\ n_g \geq 0,\ k \geq 0, \text{ and } n_f + n_g = n$$

As will be explained below, we take a time period to be the length of one human generation rather than an annual cycle. From this perspective it makes sense to regard seed inputs and food outputs as contemporaneous flows, and thus (2) does not incorporate time subscripts. After maximizing in (2) with respect to seeds, the problem reduces to

$$\text{(3)} \qquad \max \quad F(n_f,w) + (n-n_f)h(w) \quad \text{subject to } 0 \leq n_f \leq n$$

where $h(w) \equiv [\eta/(1-\eta)][g(w)(1-\eta)]^{1/\eta}$

Next, define $n^a > 0$ by equating marginal products so that $F_n(n^a,w) \equiv h(w)$. This leads to the situation in Figure 2. It is easy to see that the following behavior is optimal:

(i) If $n \leq n^a$ then use all labor for foraging ($n_f = n$, $n_g = 0$). Food per person is $y(n,w) = F(n,w)/n = wn^{\alpha-1}$ (the average product curve in Figure 2 for $0 \leq n \leq n^a$).

(ii) If $n > n^a$ then set $n_f = n^a$ and $n_g = n - n^a$. Food per person is $y(n,w) = h(w) + [F(n^a,w) - n^a h(w)]/n$ (the average product curve in Figure 2 for $n^a < n$).

Output per capita declines continuously as n increases, with a kink at the boundary $n = n^a$ where the transition to positive agricultural labor occurs. This framework implies that the share of total labor devoted to agriculture approaches one as population goes to infinity.

Good weather need not favor foraging over agriculture or vice versa. We will say that weather is neutral between the two activities if

$$(4) \qquad g(w) = \gamma w^{\eta} \qquad \text{for some constant } \gamma > 0.$$

From the definition of h(w) in (3), equation (4) gives $h(w) = \beta w$ where $\beta > 0$ is a constant. Per capita output thus becomes

$$(5) \qquad y(n,w) \equiv wz(n) = (w/n)\ \{\max n_f^{\alpha} + (n-n_f)\beta \text{ subject to } 0 \leq n_f \leq n\}$$

$$\text{where (i)} \quad z(n) = n^{\alpha-1} \qquad \text{for } n \leq n^a = (\alpha/\beta)^{1/(1-\alpha)}$$

$$\text{and (ii)} \quad z(n) = \beta + \delta/n \qquad \text{for } n > n^a = (\alpha/\beta)^{1/(1-\alpha)} \qquad \text{with } \delta > 0.$$

In the neutral case weather has a multiplicative effect on food per capita but does not affect the allocation of labor or the population threshold n^a required for an agricultural transition. Neutrality is assumed in sections 4 and 5; biased effects will be discussed in section 7.

Climate. We consider a large geographic area with a continuum of production sites whose total mass is unity. In our population model one time period is a human generation

(15-25 years), so weather refers to the average environmental conditions prevailing at a site over such an interval. Annual and seasonal variations are ignored.

Sites are divided into two quality types. In each period a fraction π of all sites have good weather w^+ and the remaining $1-\pi$ sites have bad weather w^-, where $w^+ > w^-$. It does not matter for our analysis whether quality is a permanent feature of a site (e.g. resulting from a lakeshore location), or a random variable that can change over time (e.g. weather in the strict sense). It is only important that under a given climate regime, the fraction of good sites π remains constant over time for the region as a whole. The term 'climate' refers to the parameters (w^+,w^-,π) rather than the weather at a particular site in a particular period. The model can easily be extended to allow many site qualities, but only the best sites play a substantive role in the analysis (these are the places where population density is greatest and therefore where agriculture occurs first).

Population. We use an overlapping generations framework where all adults have the utility function $U[c,R(e)]$, with c denoting food consumption by the adult, e denoting food consumption by children, and $R(e)$ the number of children who survive to adulthood. Utility is maximized subject to $c + e = y$. The number of surviving children per adult as a function of available food is $r(y) \equiv R[e(y)]$, which is increasing if R is increasing and e is a normal good. Leisure is ignored for the moment but will be discussed in section 7.

Let the number of adults at a given site s at the beginning of period t be n_{st}^o. In each period, events occur in the following sequence.

1. The weather w_{st} is determined for each site. All adults observe the weather at every site in the region.
2. Each adult decides whether to stay at her current site or move somewhere else. These decisions determine new levels of population at each site denoted by n_{st}.
3. The adults at site s obtain food by allocating labor to foraging and agriculture as in the production model. Food is shared equally at the site, yielding y_{st} per adult.
4. Each adult at site s allocates the food y_{st} between herself and her children.

5. The current adults die at the end of period t. At the beginning of period t+1 the initial population at site s is $n_{s,t+1}^0 = r(y_{st})n_{st}$ and the process repeats.

Because utility is increasing in y, adults prefer sites with more food per adult. We assume an open access property regime where incumbents cannot exclude newcomers. If there are no mobility costs and each adult regards the post-migration population at each site (n_{st}) as parametric, then in each period food per adult (y_{st}) must be equalized across sites. Thus every site s has the same rate of population change $r(y_{st})$ in period t.

The open access assumption is a convenient way to generate a positive short run relationship between weather quality and population density across sites, as we explain below, but a similar relationship can arise under more complex property rights systems that impede full utility equalization. For example, foragers can often move to better locations by exploiting kinship networks, creating a tendency for population to concentrate at good sites (Kelly, 1995). Our qualitative results survive as long as this tendency exists. As noted in section 3, circumstantial evidence suggests that migration increased the size of Abu Hureyra during the Younger Dryas, indicating that some mobility was possible. Similarly, Bar-Yosef (2002a: 116) suggests that as marginal areas became drier in this period, kinship-based relocation caused population to rise in the fertile belt of the Levant.

Short run equilibrium. Equal food per adult across sites implies that in each period t there is a y_t such that $y_t = w_{st}z(n_{st})$ for all s where z(n) is defined in (5). Because z(n) is a decreasing function, sites with better weather w_{st} must have higher population densities n_{st}. Inverting z and integrating over sites gives the short run equilibrium condition

$$(6) \qquad N_t = \pi z^{-1}(y_t/w^+) + (1-\pi)z^{-1}(y_t/w^-)$$

where $n_t^+ = z^{-1}(y_t/w^+)$ and $n_t^- = z^{-1}(y_t/w^-)$ are the population densities at good and bad sites in period t and N_t is total regional population (fixed in the short run). Since the mass of sites is unity, N_t is also the population density for the region as a whole. The structure of short run equilibrium is shown in Figure 3. Equation (6) yields the middle curve y(N), which determines y_t as a function of the given N_t. The left curve shows the population density n^- for a bad site as a function of y and the right curve shows the corresponding density n^+ for a good site.

Long run equilibrium. Because all sites have the same population growth rate and migration does not affect aggregate population, we can write $N_{t+1} = r[y(N_t)]N_t$. A non-trivial steady state requires $r[y(N^*)] = 1$. Under the reasonable assumptions $r(0) = 0$ and $r(+\infty) > 1$, continuity and monotonicity of r imply that there is a unique $y^* > 0$ with $r(y^*) = 1$. There is a unique N^* such that $y(N^*) = y^*$ if and only if $y^* > \beta w^+$, which we will assume below. Finally, assume $r[y(N)]N$ is increasing in N so the positive direct effect of N_t on $N_{t+1} = r[y(N_t)]N_t$ outweighs the negative indirect effect through y and r. This implies that $\{N_0, N_1 \ldots\}$ converges monotonically to N^* from any initial population N_0. All long run equilibria have the same food per adult y^* because this is determined by $r(y^*) = 1$. The local densities are $n^+ = z^{-1}(y^*/w^+)$ and $n^- = z^{-1}(y^*/w^-)$, and the regional population N^* is obtained by substituting y^* for y_t in (6).

5. The Effects of Climate Change

This section applies the model to the case of southwest Asia discussed in section 3.

Initial Warming. The absence of agriculture in the last Ice Age indicates that w^+ was low enough to keep the long run population density $n^+ = z^{-1}(y^*/w^+)$ below the threshold n^a even at the best sites. We take this long run equilibrium as a starting point.

Any climate improvement that increases the weather quality at good sites (w^+), the weather quality at bad sites (w^-), or the fraction of good sites (π) will shift up the y(N) function in Figure 3. In the short run this raises food per capita (y) while total population N_{IA}^* stays at its Ice Age level (a jump from point A to B in Figure 4, yielding $y_B > y^*$). Assuming the new climate parameters stay in place, in the long run population will grow to N_{WA}^* and food per capita will eventually return to y^* (a move from B to C in Figure 4).

In principle such a climate shift could induce a transition to agriculture in the short run, but this is unlikely. To see why, multiply the weather outcomes (w^+,w^-) in (6) by the same scalar $\lambda > 0$, holding π fixed. Because N remains constant in the short run, y rises by the factor λ and both local densities n^+ and n^- are unchanged. However, an agricultural transition requires that n^+ rise. This can occur in the short run only if w^+ improves not just absolutely but also relative to the weather outcomes at other sites. The same holds a fortiori if π rises simultaneously, because then y rises further and all local population densities fall (equilibrium is maintained because there are more good sites).

For southwest Asia it is implausible that the initial warming improved the best sites disproportionately. The critical role of climate change was to enhance water availability through increased precipitation. The greater precipitation would not have provided a large marginal benefit at those sites endowed with permanent water sources (rivers, lakeshores, marshes, or springs), but it would have been significant at less desirable locations. Thus weather, in our broad sense, improved proportionately more at bad sites than at good ones. This is consistent with the observed migration of people into previously arid landscapes.

Figure 5 shows how an abrupt warming at the end of the Ice Age that compressed the distribution of weather outcomes would also have compressed the short run distribution of population across sites (shrinking the gap between n^- and n^+). Despite better conditions throughout the region, agriculture did not arise because the maximum local density (n^+) declined as a result of population dispersal.

The scenario of the preceding paragraphs cannot rule out a shift to agriculture in the long run on purely theoretical grounds. Once food per capita returns to y^* the maximum local density becomes $n^+ = z^{-1}(y^*/w^+)$, which depends solely on w^+. Thus in the long run only the absolute quality of weather at the best sites matters, not relative weather quality. If the rise in w^+ is large enough, $n^+ > n^a$ holds and agriculture will get underway. However, agriculture did not arise among the early Natufians, even though their sedentary lifestyle lasted for more than 1500 years. Figure 5 thus has n^+ approaching an asymptote above its Ice Age value but below the level n^a needed for agriculture.

Climate Reversal. Now consider an abrupt climate deterioration (in the southwest Asian case, the Younger Dryas). This lowers the weather quality at good sites, the weather quality at bad sites, the fraction of sites that are good, or a combination of the three. The y(N) function therefore shifts down in Figure 4, moving the system from C to D. Because conditions did not fully revert to Ice Age levels, the new y(N) curve is placed between the curves for initial warming and the Ice Age.

The short run reduction in food per capita from y^* to y_D must increase the density at the best sites (n^+) if conditions at these sites (w^+) do not deteriorate. The reason is clear: refugees fleeing worsening conditions elsewhere will take sanctuary in favored locations. Even if w^+ does fall, a local population spike still occurs if poor quality sites deteriorate proportionately more than the best sites (holding π constant). Any decline in π magnifies the short run spike in n^+ because fewer good sites are available to refugees.

This scenario, which reverses the effect of the initial warming described above by increasing the heterogeneity of site qualities, is consistent with the fact that many sites were abandoned during the Younger Dryas, and also with the fact that the sites in continuing use (such as Abu Hureyra) were those that depended less on rainfall. As noted in section 3, the population of Abu Hureyra actually grew in this phase, probably due to in-migration from increasingly arid locations elsewhere. This local effect, which runs counter to the regional population decline induced by the Younger Dryas, is likewise consistent with our theory.

Figure 5 is drawn so that the short run jump in n^+ is large enough to bring about agriculture at the best sites ($n^+ > n^a$). Whether this occurs depends on the total population N_{WA}^* inherited from the warming phase. Using (5) and (6), the climate reversal triggers a transition to agriculture in the short run if and only if

$$(7) \qquad N_{WA}^* > N^a \equiv (\alpha/\beta)^{1/(1-\alpha)} \left[\pi + (1-\pi)(w^-/w^+)^{1/(1-\alpha)}\right]$$

where N_{WA}^* is the steady state population in the initial warming phase and parameters on the right hand side refer to values during the climate reversal. It follows that agriculture is more likely if the warming phase supported a large regional population; if most sites during the reversal phase are low quality; and if sites with bad weather are substantially worse than sites with good weather. The productivity of agriculture (β) influences the prospects for a transition only through the height of the hurdle $n^a = (\alpha/\beta)^{1/(1-\alpha)}$.

If the reversal had been permanent and nothing else had changed, total population would have dropped due to lower region-wide food output, reaching a new equilibrium at point E in Figure 4. At best n^+ would return to its level at the end of the initial warming if w^+ did not fall in the reversal, and it would go still lower if the good sites deteriorated. Agriculture would thus have been only a temporary response to the short run population spike at the best locations (see the dashed continuation of the n^+ curve in Figure 5).

In reality, the onset of agriculture in southwest Asia led to increases in productivity through artificial selection on the genetic features of plants and perhaps other improvements in agricultural technology, culminating eventually in full domestication. In our model, this shows up as an increase in β. If these productivity gains occur rapidly enough relative to the declining local population density n^+, agriculture can become permanent at the high-quality sites even during a climate reversal.

The maximum value of β compatible with pure foraging for a given y is obtained by setting $n^+ = n^a$, which yields $\beta = \alpha y/w^+$. Equations (5) and (6) determine the short run per capita food consumption y for an arbitrary regional population N given pure foraging: $y(N) = \{(1/N)[\pi(w^+)^{1/(1-\alpha)} + (1-\pi)(w^-)^{1/(1-\alpha)}]\}^{1-\alpha}$. Combining these results yields the relationship

$$(8) \qquad \beta^a(N) = (\alpha/w^+)\{(1/N)[\pi(w^+)^{1/(1-\alpha)} + (1-\pi)(w^-)^{1/(1-\alpha)}]\}^{1-\alpha}$$

where $\beta > \beta^a(N)$ implies that some agriculture is undertaken, at least at the good sites, and $\beta \leq \beta^a(N)$ implies universal foraging. This locus is depicted in Figure 6.

Under pure foraging, the long run population N^* is obtained from (6) using $z(n) = n^{\alpha-1}$ in (5) and $y = y^*$. The resulting N_{RV}^* is independent of β as shown in Figure 6. With positive agricultural labor, however, β affects N^*. The upward sloping part of the locus $N^*(\beta)$ in Figure 6 is derived from (6) using $z(n) = \beta + \delta/n$ in (5) and $y = y^*$. This locus has an asymptote at $\beta = y^*/w^+$; for agricultural technologies more productive than this, no steady state population exists.

Now suppose that in any period where agriculture is practiced, its productivity level increases. This gives the upward arrows in Figure 6 for points above the zero-agriculture boundary $\beta^a(N)$. Technology is assumed to remain static below this curve.

Consider a trajectory starting from the initial point P corresponding to population N_0 and technology β_0. If improvements in technology are slow relative to the rate at which population falls, the system trajectory hits the zero-agriculture locus between R and Q, pure foraging is restored, no further increase in β occurs, and population approaches N_{RV}^* in the long run. But if agricultural productivity grows rapidly enough, β exceeds the critical value β_{RV}^* while population is still above N_{RV}^*. In this situation it is impossible to reach the zero-agriculture boundary because $\beta^a(N)$ lies to the left of the population locus $N^*(\beta)$. The result is a perpetually improving technology, which is only compatible with finite long run population if there is a ceiling β_{max} on agricultural productivity with $\beta_{max} < y^*/w^+$.

Under these conditions, the system converges to point S in Figure 6 where long run population is larger than N_{RV}^*. Agriculture becomes a permanent feature of production at the good sites, even under the adverse conditions of the climate reversal. The improvement in agricultural productivity shifts the $y(N|RV)$ curve in Figure 4 rightward to the dashed curve $y(N|RV')$, so the new long run equilibrium occurs at F rather than E.

Climate Recovery. Finally, suppose climate recovers. In combination with a better agricultural technology this yields a $y(N)$ curve superior to the one for initial warming as in Figure 4. In the short run the system moves from F to G and in the long run it settles at H, with a higher regional population than under any previous regime.

We have already derived conditions under which endogenous technical change in the reversal phase makes agriculture permanent at good sites. The same will be true in the recovery phase provided that n^+ does not drop too much in the short run due to population dispersal. The minimum local density required for agriculture falls from n^a to a lower value n_{min}^a due to technical progress during the reversal, and agriculture remains viable during the recovery phase provided that $n^+ > n_{min}^a$ holds (see Figure 5). In the case of Abu Hureyra, we observe a relatively brief period of population decline at the end of the Younger Dryas (about 12,000 BP), with renewed population growth accompanying the increased dominance of agriculture in Abu Hureyra 2 (dated about 11,400 BP).

6. Other Transitions and Non-Transitions

Even if it is granted that our theory captures some central features of the transition in southwest Asia, one might wonder whether it can be applied to other pristine transitions and whether it can account for the absence of agriculture in seemingly favorable contexts. This section briefly surveys selected cases of each type. The available data are inconclusive but we are not aware of evidence that directly contradicts the framework developed in section 5.

North China. Most authorities now agree that there were two largely independent centers of pristine agriculture in China, one in the north in the Huanghe River valley and a second in the south in the Yangzi River valley (all data on China are from Lu, 1999, except where stated). In the plain north of the Huanghe, evidence for domesticated millet comes from the Cishan assemblage, dated to roughly 8000-7700 BP. South of the Huanghe, the Peiligang culture gives evidence of millet cultivation during 8500-7500 BP. In general, the data for this region are incomplete and genuinely transitional sites have not been identified. However, Smith (1998: 133-140) stresses the favorable ecological features of the early farming villages, while Higham (1995: 134) argues that the Peiligang settlements were first occupied during a colder climate phase also experienced in the Yangzi valley. It may be relevant that the known dates for agriculture in north China roughly coincide with those for the global cooling event around 8200 BP (see section 2).

South China. The key crop in the south was rice, for which there is some evidence of domestication in the middle Yangzi valley dating to 9000-8000 BP. This is associated with the Pengtoushan culture. The nearby site of Bashidang provides good evidence of domesticated rice by 8000 BP. Both were located on alluvial plains, and Bashidang likely reflects an "initial stage of domestication" (Lu, 1999: 93). Higham suggests that settlement began at Pengtoushan during "a period that experienced a reduction in temperature following 1,500 years of progressive warming" (1995: 133) and argues that climate deterioration encouraged the domestication of rice and millet (1995: 147). After the climate recovered, rice cultivation spread widely in the south (1995: 153-4).

Africa. Unlike southwest Asia and (perhaps) China, domestication in Africa does not seem to have been concentrated in a few focal locations. Rather, it occurred in a broad band running along the southern margin of the Sahara Desert, from the tropical region of west Africa to Chad, Sudan, and Ethiopia in the east (Harlan, 1995).

Around 14,000 BP there were freshwater lakes, ponds, and swamps in the central Sahara, but rainfall began to diminish around 10,000 BP. This period was associated with greater use of wild grasses and proto-domestication of wild sheep. Shortly after 9000 BP, cattle were likely domesticated in the eastern Sahara independently of events in southwest Asia (Mithen, 2003: 492-8). Recent ice core data from the summit of Mt. Kilimanjaro have revealed that between 10,000-5000 BP East Africa was wetter and warmer than today. A decades-long drought occurred around 8300 BP and another occurred between 5000 and 4000 BP (National Research Council, 2002: 34; Mithen, 2003: 453-4; note the temperature dip in Figure 1 around 5000 BP).

Unfortunately the archaeological record is quite thin, but Smith (1998: 100) cites dates of 4000 BP for domesticated sorghum and 3000 BP for pearl millet. Smith remarks that various researchers believe "the timing of initial domestication of millet and sorghum was tied to the southward expansion of the desert, which intensified about 4000 years ago, displacing people south" (1998: 110). He goes on to remark that African rice may also fit this model (1998: 112). Finally, Smith observes that settlements in the savanna zone from 5000-3000 BP were located on the shores of permanent lakes, that fish were an important food source, and that wild rice, millet, and sorghum were probably harvested at such sites. This seems compatible with a 'refuge' role for these locales at a time of desert expansion.

Mexico. Recent research has dated the first domestication of squash to the region of Oaxaca about 10,000 BP (Flannery, 1986; Marcus and Flannery, 1996; Smith, 2001). Maize from the same site has been dated to 6300 BP although there is genetic evidence that domestication may have occurred earlier (see Matsuoka et al., 2002). The earliest known domestic beans are from the Tehuacan Valley and date only to 2300 BP.

Given this diversity of dates it is difficult to tie domestication to any specific climate event. The evidence on climate change is not robust in any case, but the region likely had a moderated version of the Younger Dryas (National Research Council, 2002). Flannery (1986) has argued, consistent with our model, that water was the limiting resource in the region. During the drought of the Younger Dryas, the population might have congregated at caves such as Guila Naquitz, the site of the earliest domesticated squash plants found in the New World. Flannery's theory has, however, been criticized by Hayden (1990).

The Andes. Pachamachay Cave, site of the earliest known settlement in the region, provides evidence of habitation by human foragers starting around 12,500 BP (Rick, 1980; Mithen, 2003). Over time, foraging was supplanted by domestication of animals (llamas and alpacas) and cultivation of a cereal crop (quinoa) at Pachamachay as well as Panaulauca (Mithen, 2003). Rick (1980) dates both plant and animal domestication to about 7000 BP. The potato was also domesticated in the region but there is no evidence of it at this date.

The Younger Dryas occurred well before the earliest evidence of domestication, but another periodic climate event appears to have begun at the same time that agriculture was emerging in the Andes. The first paleoclimatic record of an El Niño episode is also from

7000 BP. El Niño, which persists today, is the cyclic warming of the ocean in the south Pacific. It leads to heavy rainfall along the Pacific coast of South America, and droughts in Australia and elsewhere. Archaeological evidence from the coast shows that major debris slides wiped out foraging villages, and El Niño also decimated fish populations due to the migration of fish to cooler water. The causal connection with domestication in the Andean highlands is speculative, but some of the coastal population may have migrated to higher elevations, raising population densities there and pushing the region toward agriculture.

We next consider selected instances of 'non-transition'. Such cases provide weaker evidence because there are several necessary conditions for agriculture, any one of which could explain its absence. For example, Diamond (1997) argues that seemingly promising regions such as California, southwestern and southeastern Australia, southern Africa, and Chile and Argentina were disqualified by poor endowments of potentially domesticable species (a low value of β in our model). In addition to its modest biological endowment, Australia was an unlikely candidate because it had a low regional population density. The Amazon and southeast Asia were probably disqualified by their tropical locations, which buffered them from global climate shifts (on the southeast Asian case, see Higham, 1995).

We briefly review two other cases: the Jomon of Japan and the coastal people of northwestern North America. Both societies make the point that a good natural setting, a sedentary lifestyle, and a high regional population are insufficient to bring about a farming economy. Moreover, both had severe Younger Dryas events and experienced the global cooling of 8200 BP, making them especially relevant for the questions of interest here.

The Jomon period in Japan is dated from about 16,000 BP (all information is taken from Habu, 2004). It is characterized by advanced technology (pottery) from a very early date, sedentism, and general prosperity, but a late transition (around 2500 BP) to full-scale rice farming. When agriculture finally arrived it appears to have been borrowed, along with other cultural characteristics, from the Mumun culture of the Korean peninsula. It is unclear whether this involved major population flows from Korea itself.

During the Younger Dryas period, the Jomon people were hunter-gatherers whose diet included marine mammals and fish, especially in summer; plant foods (primarily nuts) in autumn; land-based mammals in winter; and shellfish year round but especially in late winter and early spring before other important food sources became available. This pattern continued subsequently through more sedentary periods. It is possible that the Jomon may have eventually domesticated buckwheat, but this was not a major food item. The standard explanation for the late transition to agriculture is that most of the Jomon diet was relatively insensitive to climate. This highlights the fact that what matters in our model is not just the sheer size of a climate reversal. If the reversal does not have a major effect on food output and the spatial distribution of population, it is unlikely to stimulate a transition.

The coastal inhabitants of the Pacific northwest in North America are often used as the textbook example of a complex society not based on agriculture (see Johnson and Earle, 2000: 204-217). Fishing was a central food source, especially the rich seasonal runs of salmon and eulachon. Many other wild foods were available, such as shellfish, waterfowl, marine and land mammals, roots, and berries, but by 8000 BP salmon was the dominant food. Fish, berries, and other foods were stored for winter use. People were sedentary in winter, had high population densities, and possessed quite sophisticated technologies and infrastructure. Their societies also had features not often found among foragers including craft specialization, inequality, hierarchy, and (pre-contact) slavery and warfare.

Despite a promising environment with mild temperatures and ample precipitation, agriculture never became a core part of the economy. Several food plants were cultivated at the time of European contact, but these seem to have been supplemental rather than primary dietary components, and full domestication apparently did not occur (Deur, 1999, 2002). We conjecture that fresh water and marine resources cushioned these societies from climate shocks, averting a shift to agriculture despite the prevailing high population densities. Good production sites may also have been less scarce during climate reversals as compared with southwest Asia and other pristine cases, dampening local population spikes.

The most notable non-transition of all is the absence of agriculture anywhere before 13,000 BP. Climate theories are sometimes criticized for failing to explain why agriculture did not arise during past interglacial periods, but cognitively modern humans probably did not exist during the last interglacial, which occurred around 130,000 BP. While cognitive ability is not an explicit variable in our model, we share the common view that the emergence of cognitively modern humans was an additional prerequisite for agriculture, distinct from climate and resource endowments.

The more interesting puzzle is why modern humans did not develop agriculture between about 50,000 BP and 13,000 BP. Richerson et al. (2001) attribute this to the low mean and high variance of weather during the last Ice Age, which forestalled long-term investments in agriculture. Our theory suggests a different view: climate instability ruled out lengthy mild periods during which large regional populations could accumulate. Before the Holocene there was no precedent for the 1500 years or more in which Natufian society took root in southwest Asia. Without such large pre-existing populations, climate reversals would not cause a sufficient spike in local densities at the best sites and the agricultural threshold would never be crossed.

A final piece of evidence supporting our theory is the very small number of pristine transitions to agriculture. Consider the conditions that must hold in order for our model to predict agriculture as a long run equilibrium. A period of ‘good’ climate must last long enough for population to expand sufficiently; the diet of the population must be sufficiently dependent on wild plants that are vulnerable to a climate shift; a period of ‘bad’ climate must arrive suddenly enough that gradual population decline through fertility decisions does not solve the problem; a small number of sites must remain permanently habitable when the climate turns ‘bad’, while others are partly or fully abandoned; migration within the region must be sufficiently free of impediments; the ‘bad’ climate cannot last for too long or too short a time; and learning by doing in agriculture must occur quickly enough. In addition, nature must provide an endowment of wild plants that are relatively easy to domesticate.

Multiplying the associated probabilities together yields a very low probability of agriculture, which is consistent with the handful of pristine cases observed in the historical record.

We close this section by emphasizing that our theory is open to refutation. If future research shows that agriculture evolved at some pristine location that was not vulnerable to climate shocks or where domestication did not coincide closely with a climate reversal, our theory would not apply and other explanations would be needed. A similar verdict would be in order if pristine agriculture were found in a region of initially low population density, if climate reversal did not lead to increased heterogeneity in the quality of local sites, or if there were no migration from marginal sites to those located in more favorable natural settings.

7. Conclusion

This paper contributes to the existing literature in three ways: by showing that some frequently emphasized factors are not critical in explaining the agricultural transition (biased climate change, sedentism, resource depletion); by showing that some previously neglected factors could be important (heterogeneous local sites, migration); and by endogenizing the roles of population and technology. We briefly discuss each point in turn.

Biased climate change. Much of the literature assumes either that a better climate made agriculture more attractive in relation to foraging, or that a worse climate had the same effect (see section 1). We are not aware of convincing evidence for the existence of such biases. As explained in section 4, our formal analysis was carried out on the assumption that climate changes are neutral with respect to the choice between foraging and agriculture.

Our model can, however, be modified to incorporate biased climate effects. If bad weather reduces foraging productivity more than agricultural productivity, in Figure 2 this shows up as a larger downward shift in the marginal product of foraging as compared with the marginal product of agriculture. Thus bad weather would shift the threshold population density for agriculture (n^a) to the left, making agriculture more likely. One can then argue that the Younger Dryas induced agriculture in southwest Asia because it made the weather worse. Such an interpretation implies that the better sites had higher minimum population thresholds for agriculture, which runs counter to the fact that the transition occurred first at sites with the best local environments. This makes our mechanism for generating local population spikes even more essential. Conversely, if good weather favored agriculture one can see why it would arise first at the best sites, but it becomes harder to understand why agriculture did not arise during the initial warming phase prior to the Younger Dryas.

Nomadism and sedentism. Anthropologists generally agree that foraging people have strong incentives to keep fertility low due to their nomadic lifestyle. The main cost of children in this context is that women have great difficulty carrying two or more young children at once, and therefore prefer to space births at least four years apart. A sedentary lifestyle makes large families correspondingly less costly (Locay, 1989, 1997). From our standpoint, the costs and benefits of children are captured in the adult utility function from section 4. In the formal analysis we assumed that this function was constant across the transition from foraging to agriculture, but one could include a cost of children that varies with the method of food acquisition.

Our theory does not, however, assign a direct causal role to sedentism. The early Natufians, the Jomon, and the people of the Pacific Northwest were all sedentary but made little or no use of agriculture. Conversely, the anthropological literature has documented societies that practice slash-and-burn agriculture without sedentism. If a foraging society happens to become sedentary and this yields a larger regional population, other things equal this larger population increases the probability of an agricultural transition. But our model is consistent with nomadism among pristine agriculturalists in situations where the physical location of good sites changes frequently due to high variance in local weather conditions.

A related issue involves the role of leisure. One can find frequent assertions in the literature that foragers have high levels of leisure but few children, while early agricultural populations choose lower levels of leisure but more children. Our model suggests a way of explaining this pattern without appealing to mobility costs. In the short run, the Younger

Dryas reduced food availability as in Figure 4. If leisure was a normal good, we would expect more labor per person in the Younger Dryas at the start of the transition. Gradual improvements in agricultural technology would then have created a growing substitution effect toward labor that partly or fully offset the income effect from rising living standards. If children were a normal good and food production eventually surpassed the foraging level due to technical change and climate recovery, the net result could have been less leisure but more children under agriculture as compared with previous long run foraging equilibria.

Resource depletion. Various economists (Smith, 1975; North and Thomas, 1977; Marceau and Myers, 2005) have attributed agriculture to a failure by foraging populations to restrain overuse of wild resources. In a related vein, Brander and Taylor (1998) explain the economic collapse on Easter Island as resulting from inadequate conservation of natural resources. Similar ideas can be found among anthropologists (Johnson and Earle, 2000).

Our model treats natural resources as flows rather than stocks and does not appeal to depletion of wild stocks as a basis for the agricultural transition. For similar reasons, we do not rely on defective property rights or inadequate incentives for conservation. The model could, however, be extended to address such issues. For example, if depletion of wild stocks shifts the marginal product of foraging labor down in Figure 2, this reduces the minimum local population needed for agriculture and could stimulate a transition.

Even if foragers have no problem conserving wild resources, agricultural societies might tend to destroy nearby habitat as a by-product of farming activities. This could lock in farming because over time the potential returns from foraging would drop. It could also give neighboring foragers more reason to adopt agriculture. This factor, coupled with the technical advantages of domesticated crops and the military advantages of large populations (Diamond, 1997), may help explain the diffusion of agriculture out of its pristine centers.

Heterogeneity and migration. Previous theories of the agricultural transition have rarely distinguished between regional and local levels. In our view this distinction is critical. Regionally, the Younger Dryas led to greater nomadism, higher mortality, and lower food consumption in southwest Asia. This was compatible with continued sedentism, increased population, and reliance on agriculture at local refuges such as Abu Hureyra. Economic models that fail to capture migration among heterogeneous local sites are unlikely to do justice to the archaeological record because they neglect a key feature of the transition: the increased scarcity of high-quality sites during a climate reversal.

Population and technology. In recent decades there has been considerable debate as to whether climate, population, or technology should be regarded as the fundamental factor behind the emergence of agriculture. Although we see climate as the underlying exogenous variable, population and technology cannot be ignored. Without a large regional population, a climate reversal cannot create a local population spike sufficient to trigger an agricultural transition. Moreover, without rapid technical change once agriculture gets underway, falling regional population during the reversal will take society back to foraging rather than forward to a farming economy. By endogenizing population and technology, our model helps to clarify the structure of the interactions among these variables.

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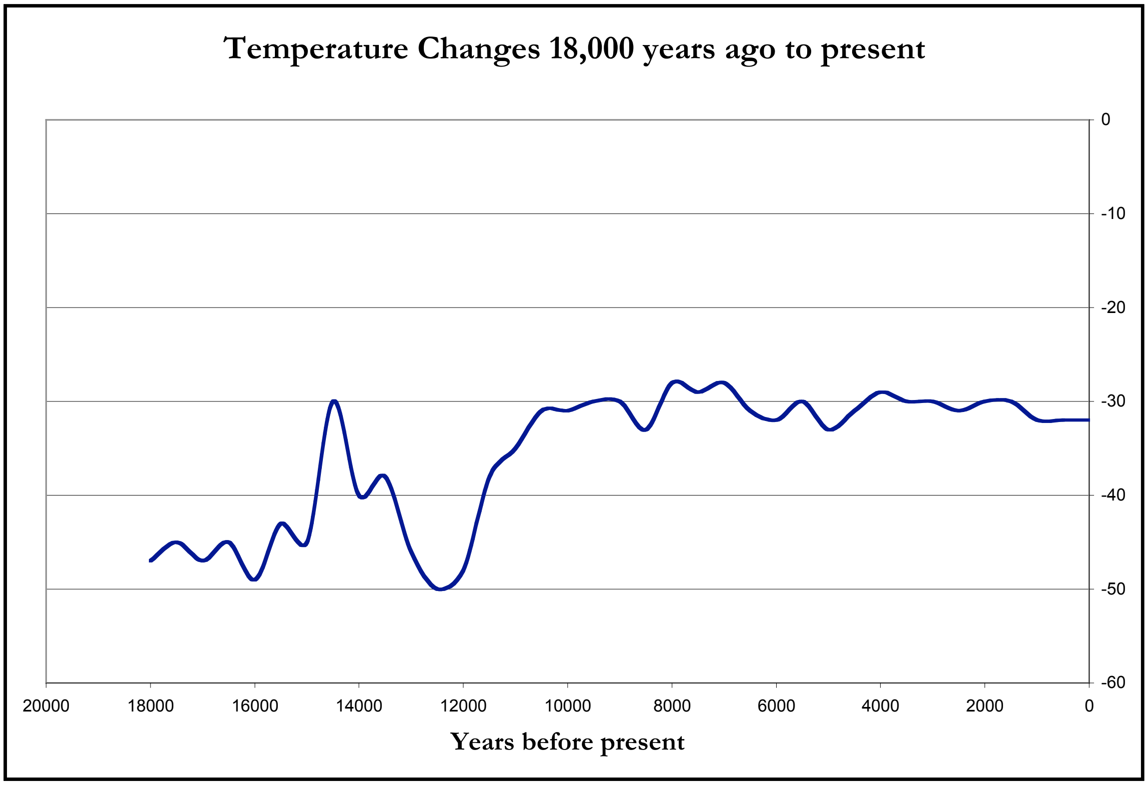


Figure 1

Temperature Estimates (degrees Celsius) for Central Greenland

The data are a reconstruction of temperature estimates taken from ice cores (National Research Council, 2002). Temperature changes in much of the rest of the world are similar to the changes shown for Greenland. In addition to the Younger Dryas (c. 13,000 BP to 11,600 BP), other important periods of temperature reversal occurred around 8200 years ago and around 5000 years ago.

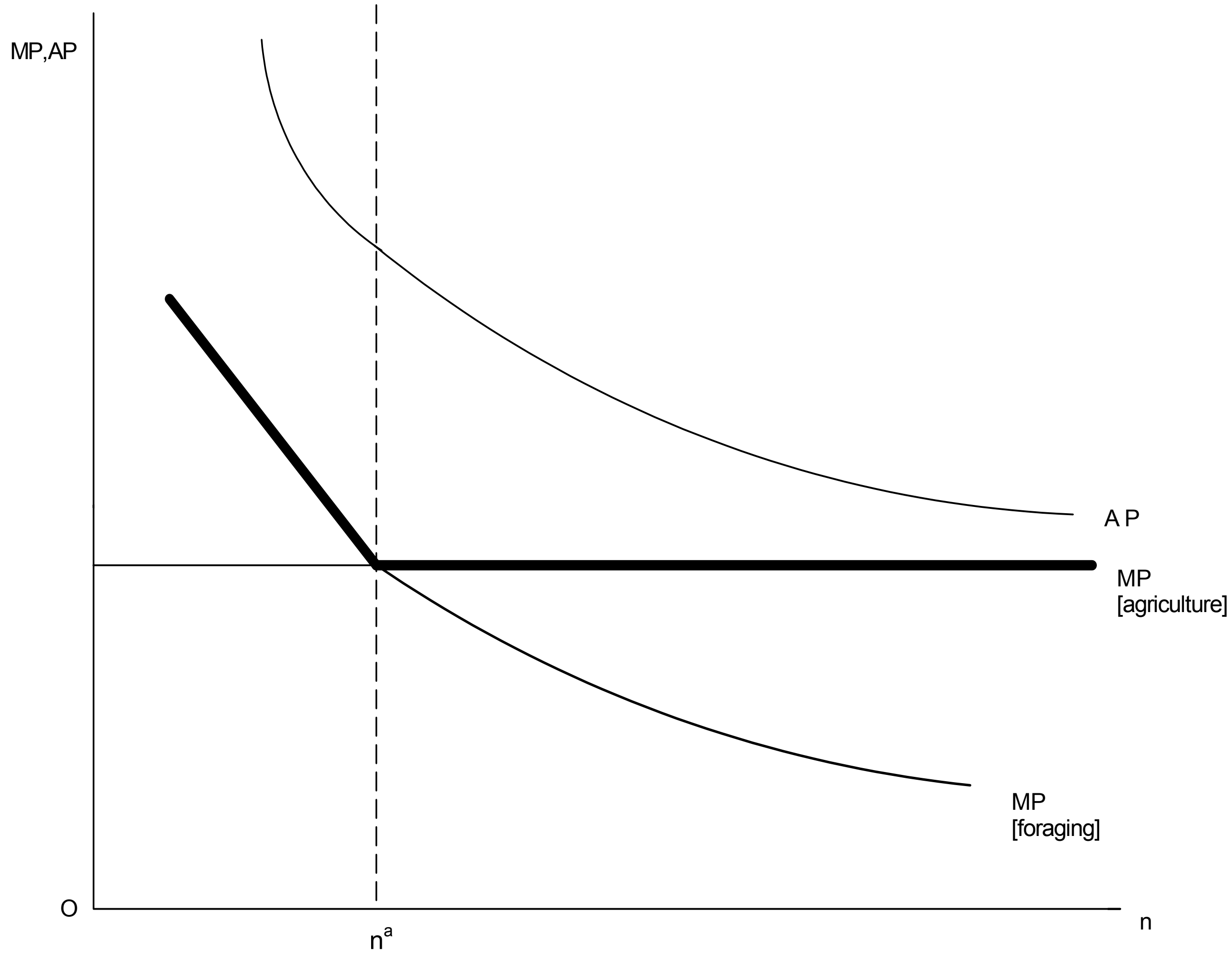


Figure 2

Marginal and Average Products

of Labor

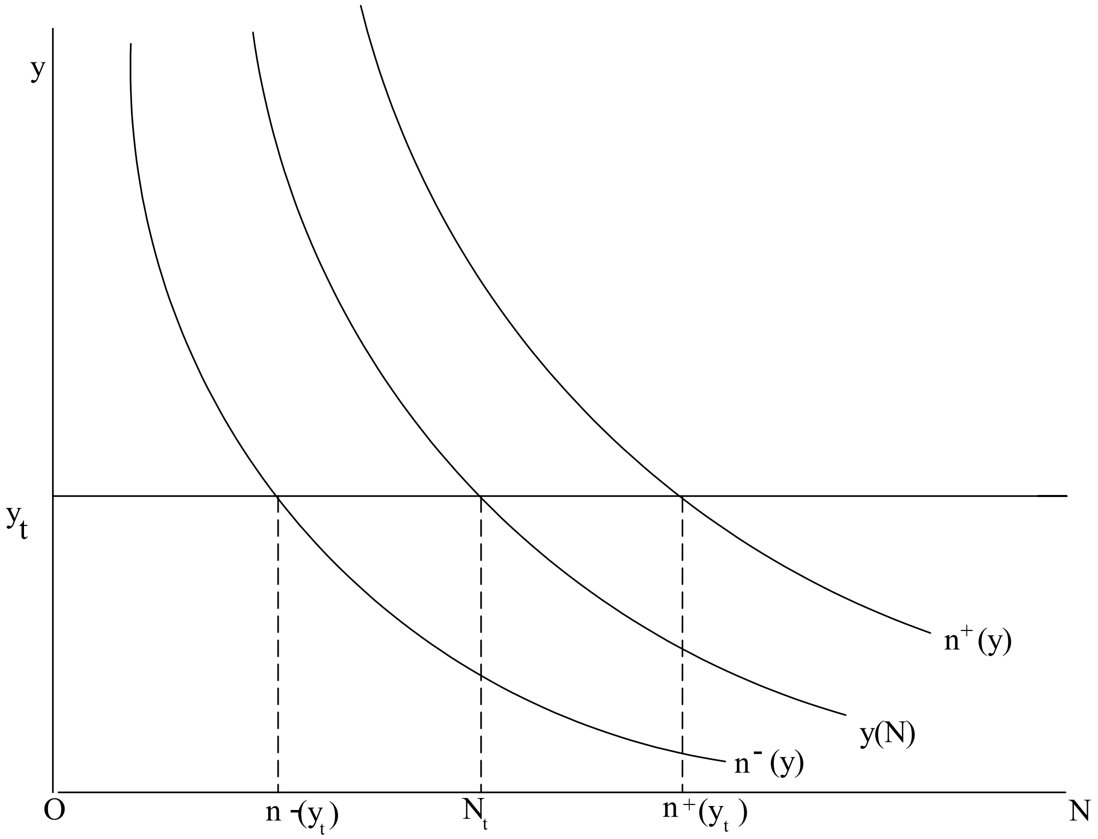
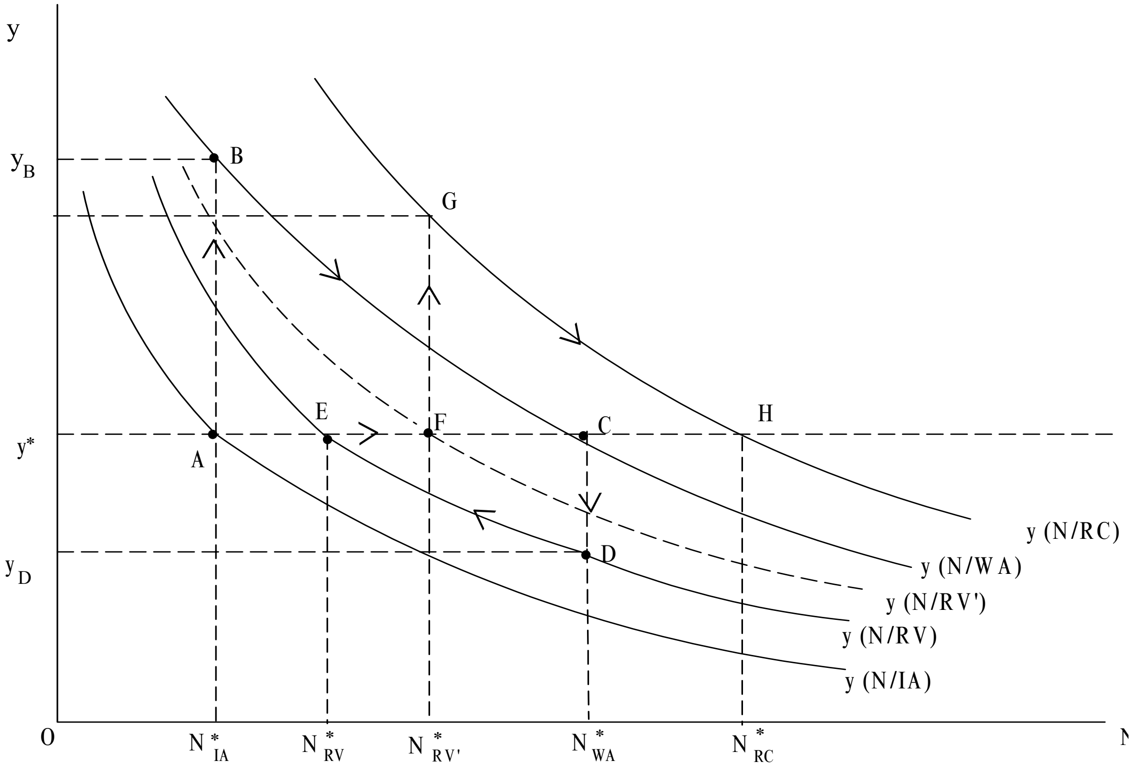


Figure 3

Short Run Equilibrium for Fixed

Climate Parameters



IA = Ice Age

WA = Initial Warming

RV = Climate Reversal

RV’ => better agricultural technology

RC = Climate Recovery

Figure 4

Short Run and Long Run Effects

Of Climate Change

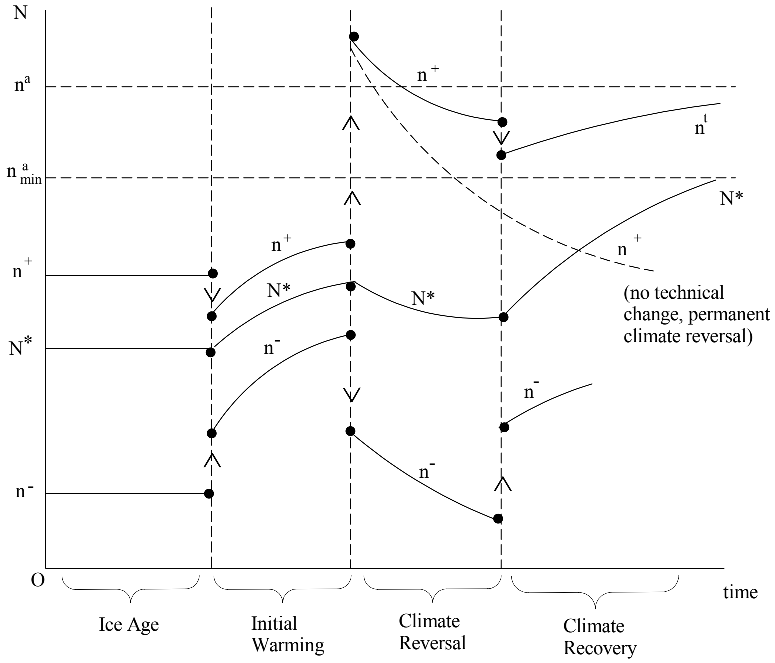


Figure 5

Climate Change, Population Density,

And Induced Innovation

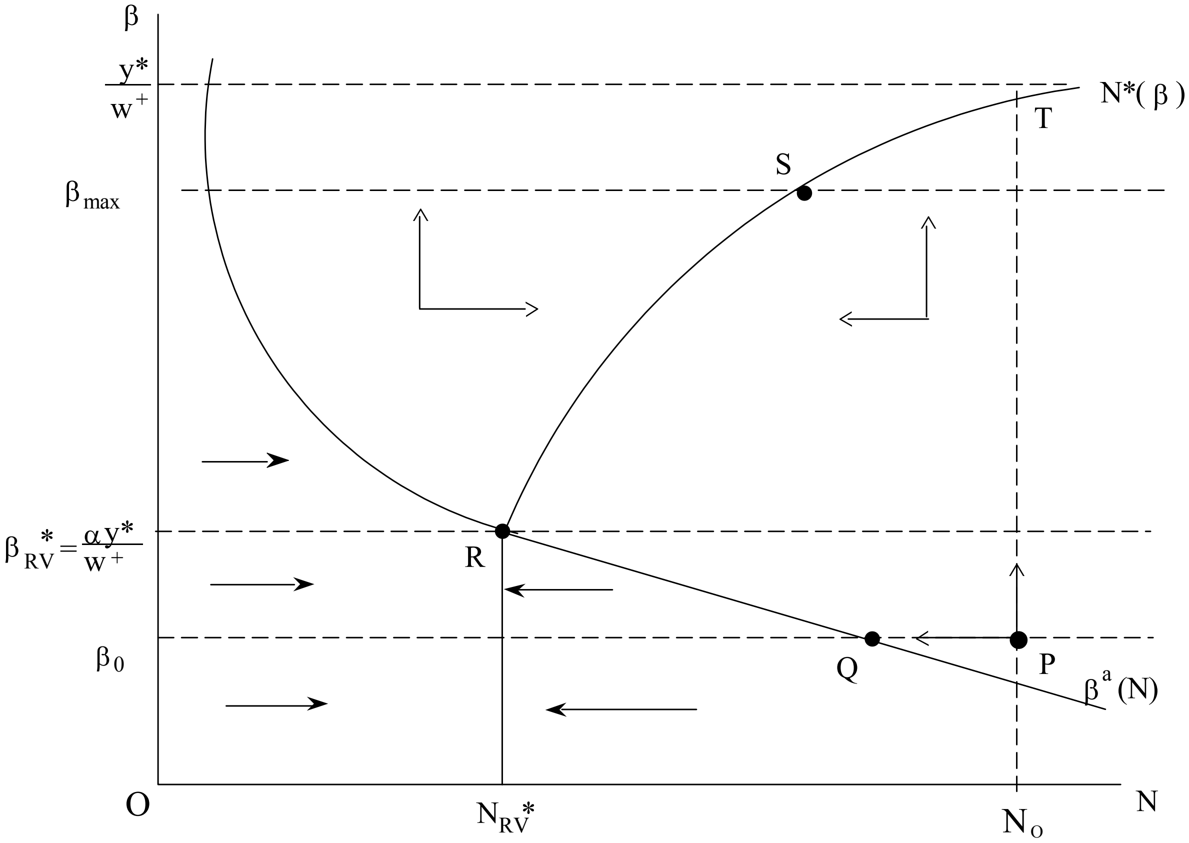


Figure 6

Population and Technical Change
During a Climate Reversal