

Stagnation and Innovation Before Agriculture

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Abstract. During the roughly 190,000 years between the emergence of anatomically modern humans and the transition to agriculture, sustained economic progress was rare. Although there were important innovations in the Upper Paleolithic, evidence from paleodemography indicates that population densities were driven more by climatic conditions than by technological innovations in food acquisition. We develop a model in which technological knowledge is subject to mutation and selection across generations. In a static environment, long run stagnation is the norm. However, climate shocks can induce experimentation with latent resources. This generates punctuated equilibria with greater technical capabilities and higher population densities at successive plateaus. The model is consistent with archaeological data on climate, population, diet, and technology from the Upper Paleolithic through the early Neolithic.

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1. Introduction

For almost all of the 200,000 years during which anatomically modern humans have existed, technological progress has been extremely slow. Even if one accepts the controversial view that modern human brains have existed for only 40,000 years (Klein, 2001; Ervard et al., 2002), it remains the case that there was very limited progress over tens of millennia. Only in the last 10,000 years do we see precursors of modern society such as settled agriculture, draft animals, metallurgy, writing, and cities. Indeed, many foraging societies continued to use stone-age techniques until they encountered the modern world (Johnson and Earle, 2000).

Economists have usually viewed such matters through the lens of growth theory (Kremer, 1993; DeLong, 1998; Becker, Glaeser, and Murphy, 1999; Galor and Weil, 2000; Jones, 2001; Galor, 2005; Olsson and Hibbs, 2005). These authors note that world population growth before agriculture was extraordinarily slow compared to growth rates afterward. They also suggest reasons why low levels of population might limit the rate of technological innovation, which helps to explain the slow rate of population growth. We agree with these general points, but some further facts about foraging societies do not fit as comfortably into current models of long run growth.

Climate. Archaeologists have found that climate is a crucial determinant of prehistoric population. This is true both for colonization of new continents and for population density at the local and regional level. Until the onset of the Holocene about 11,600 years ago, climate shocks were large, frequent, and had massive effects on natural resources and population levels across much of the world.

The natural environment remains important for contemporary foragers. Baker (2008) has studied the technological sophistication and population density of indigenous cultures using data on 167 societies. For hunter-gatherers, the variables that successfully

predict population density are rainfall, number of frost months, land slope, and habitat diversity. All are determined by climate, geography, or ecological conditions.

Population. Economists who have written on the subject of prehistory tend to cite world population estimates obtained by identifying the inhabited regions of the world at various dates and multiplying these areas by modern hunter-gatherer population densities (e.g. Deevey, 1960; McEvedy and Jones, 1978). This yields a very small positive growth rate simply because humans slowly colonized new continents over time. Such estimates do not imply technological progress because migration opportunities could have arisen through climate change instead. To make a strong case for technological progress, one would need to show that population density increased within a fixed geographic region with fixed natural resources, and that this increase was not driven solely by migration.

Data that can be used to make such assessments are increasingly available from paleodemography. We will say more about this in section 2, but in general there is little evidence for exponential population growth (even at very low rates) within well-defined geographic regions prior to agriculture. At least as often, one finds population densities that remain roughly static for several millennia or fluctuate in ways that can be attributed with considerable confidence to exogenous climate events.

Technology. Direct archaeological evidence reveals a number of technological innovations beginning about 45 KYA (forty five thousand years ago). This history will be surveyed in section 2. These innovations were episodic and did not lead to sustained growth. Most long run growth models, on the other hand, predict continuous (albeit slow) technical progress that is causally linked with continuous population growth. An advantage of our approach is that we can explain both stagnation and innovation, while conventional growth theory addresses only the latter.

We suggest the following way of thinking about these issues. Nature provides many potential food resources that could be exploited if a society had access to suitable technology. In a static environment, foragers become very competent at exploiting some

subset of these resources, but they face long run stagnation because (a) there is an upper bound on productivity for each resource; (b) latent resources remain unexploited due to the limitations of existing knowledge; and (c) knowledge does not improve for resources that are never used.

To escape from such a trap, a foraging society must be exposed to shocks from nature. For example, an improved climate tends to increase population in the long run. If this scale effect is big enough, it may become attractive to exploit latent resources. Once this occurs, cultural evolution generates improvements in the techniques used to harvest, process, or store the new resources. As long as knowledge gains are irreversible, a series of positive and negative shocks can generate a ratchet effect in technological capabilities.

We define 'progress' to mean the increased capacity of a human population to obtain food in a given geographic region with given natural resources. We make the Malthusian assumption that the productivity gains from new techniques are absorbed through population growth in the long run. Therefore, on an archaeological time scale technological progress should become visible through higher population densities. But population density can rise either because natural resources improve (holding technology constant) or because technology improves (holding resources constant). Our definition of progress excludes the former effect and focuses on the latter.

We want to stress that the use of population density as a proxy for technology only works for innovations that involve better techniques for food acquisition, processing, or storage, or that facilitate colonization of new regions through better clothing, shelter, or transport. Our theory does not address innovations involving painting, sculpture, jewelry, music, dance, and related cultural matters.

Another important conceptual point is that technical progress cannot be inferred directly from migration into new geographic regions. For example, suppose that climate change creates a land bridge between continent A (previously inhabited) and continent B (previously uninhabited). Assume the two continents have identical natural endowments.

One would expect people to move from A to B until long run population equilibrium has been reached. Such migration could involve simple replication of existing techniques in a new location without being caused by (or leading to) any technological change. For this reason, we focus on intensive growth (indicated by rising population densities in a given region) rather than extensive growth (indicated by the spread of humans into new regions). Of course, some migrations did require specific innovations such as boats or cold-weather clothing. We return to these issues in section 6.

Our theory can explain the lengthy periods of economic stagnation observed in pre-agricultural societies, both in the distant past and among surviving hunter-gatherers. In addition, our theory accounts for two major episodes of technological progress known from archaeology: the transition from the Middle to the Upper Paleolithic, and the transition from the Upper Paleolithic to the Mesolithic. In each case the causal sequence runs from improved climate to population growth, greater dietary breadth, and finally more productive technology. We also show how a series of positive or negative climate shocks can stimulate migration into harsh environments, such as Siberia or the Sahara. Finally, we sketch how a large negative climate shock triggered the Neolithic transition to agriculture in southwest Asia (for details, see Dow, Reed, and Olewiler, 2008).

Another contribution involves our model of technological innovation. We treat the techniques used to acquire, process, and store food resources as finite binary strings, which are modified across multiple generations through cultural mutation and selection. This approach has several advantages. First, it is consistent with the fact that forager technology demands substantial human capital transfers to children (Robson and Kaplan, 2006). Second, it captures the idea that foragers face an upper bound on labor productivity for any given resource, and can only progress in the long run by broadening the spectrum of resources they use. Finally, it enables us to derive an explicit functional form for the probability of technical progress, which depends on (a) the labor time used to exploit a specific resource (a function of total population and the natural environment); (b) the current

productivity level for the resource in question; (c) the rate of population growth; and (d) the mutation rate in the transmission of technical knowledge from adults to children. Existing models generally include these causal channels (if at all) through ad hoc specifications, rather than deriving them from consistent theoretical foundations.

The literature includes a number of papers that address related topics. Ashraf and Michalopoulos (2006) argue that technological progress in foraging societies is driven by mild negative climate shocks. This contrasts with our more general framework, in which both positive and negative shocks can yield progress under suitable conditions. Ashraf and Michalopoulos also rely on a reduced-form specification of the process through which techniques are transmitted from parents to children. Shennan (2001) models the evolution of technology during the Upper Paleolithic but does not emphasize economic aspects of the problem. Our model of technological change is similar in spirit to the models of cultural evolution developed by Boyd and Richerson (1985, 2005). Our use of binary strings has some similarity to models based on genetic algorithms (e.g. Arifovic, Bullard, and Duffy, 1997), but we derive analytic results rather than employing simulation techniques.

Section 2 summarizes the archaeological data that constrain our analysis. Section 3 models technological change, section 4 defines equilibrium concepts, and section 5 studies responses to climate shocks (proofs of all propositions are in a separate appendix available from the authors). In section 6 we use our theory to interpret the Upper Paleolithic, Mesolithic, and Neolithic transitions. Section 7 provides brief concluding remarks.

2. The Archaeological Record

Data from ice cores and other sources reveal a long series of glacial periods (Ice Ages) lasting about 100,000 years on average, interrupted by milder interglacial periods lasting about 10,000 years on average (Cronin, 1999; McManus, 2004; Wolff et al., 2004). Glacial periods are characterized by low atmospheric CO₂, cold and dry climate, high variability in weather, and low sea levels. Interglacial periods exhibit the opposite

conditions. Combining climate data with archaeological evidence yields the following chronology (migration dates are based on Fagan, 2006, except where noted).

Fully modern human skeletons date from around 200 KYA in tropical Africa (McDougall, Brown, and Fleagle, 2005). Glacial and desert conditions confined humans to Africa at that time. An interglacial period occurred from about 126 to 116 KYA, after which glacial conditions gradually returned.

The earliest evidence for migration out of Africa into southwest Asia dates from around 100 KYA. Initial population levels were very low, perhaps as few as 50 migrants. Other migrations from Africa to Asia involving larger populations probably occurred after 70 KYA. During 78 to 64 KYA, glacial conditions intensified. Modern humans moved along the southern coast of Asia as far as Indonesia at about this time.

From 64 to 32 KYA there was a warming phase, although temperatures remained cold compared to the previous and present interglacials. By 40 KYA, modern humans had arrived in western Europe. Settlement in Australia is well documented after 36 to 38 KYA, where colonization required crossing at least 55 miles of open ocean. Migration into China apparently did not occur until around 35 KYA.

Intense glacial conditions again prevailed from about 32 to 15 KYA, with the last glacial maximum (LGM) occurring about 21 KYA. Migration into the Americas is now believed to have occurred by 15 KYA (Goebel et al., 2008). The Mesolithic period after the LGM was warm and wet, with sedentary villages appearing in southwest Asia from 15 to 13 KYA. Semi-glacial conditions returned from 13 to 11.6 KYA (a climate event called the Younger Dryas). In this period, plant cultivation began in southwest Asia and possibly also in China and Mesoamerica (Dow, Reed, and Olewiler, 2008).

The boundary between the Middle and Upper Paleolithic is normally defined by the transition from primitive flake tools to a more sophisticated blade technology. This technology originated before 40 KYA, possibly in southwest Asia (Bar-Yosef, 2002a), and thereafter spread into Europe, central Asia, and Africa. Blade technology involved more

efficient use of flint and similar materials, and allowed production of specialized implements such as awls, burins, knives, and scrapers. These tools had the sharp edges needed to carve antler, bone, and ivory (Fagan, 2006: 130). There is some evidence of bone tools and jewelry in South Africa by 77 KYA (Campbell et al., 2006: 397), but Bar-Yosef (2002a) believes that these precursors were isolated and had no lasting impact.

Other markers of the Upper Paleolithic include grinding and pounding tools for processing plant foods; long-distance exchange of raw materials; food storage facilities; structured hearths; specialized habitation areas for butchering, cooking, waste disposal, and sleeping; and various types of jewelry and artwork. Subsequent improvements in hunting methods included spear throwers, bows and arrows, and boomerangs. However, some of these markers are limited to specific regions and cannot be used to characterize the Upper Paleolithic on a global basis (Bar-Yosef, 2002a).

Archaeologists often refer to the Upper Paleolithic as a 'revolution' in comparison with the Middle Paleolithic. The sharp contrast in technological capabilities between the two periods warrants this label. From an economic perspective, however, it is important to appreciate the extraordinary slowness of the innovation process. Well over 100,000 years elapsed between the emergence of anatomically modern humans and the end of the Middle Paleolithic. The Upper Paleolithic lasted about 30,000 years, and the diffusion of this toolkit across regions is measured in tens of millennia. This implies an infinitesimal rate of technological progress by conventional economic standards. Throughout much of Africa, Asia, and the Americas, as well as all of Australia and the Arctic, use of an Upper Paleolithic toolkit continued into the modern era.

As we noted in the introduction, there are two main ways to detect technological progress using archaeological data. The first is through direct evidence on tools, and the second involves changes in population density within a well-defined region. Evidence from paleodemography, taken as a whole, indicates that prior to agriculture (a) climate was clearly

the primary driving force behind population changes; and (b) technological progress had at most only a faint effect on population.

Relevant studies include Gamble et al. (2005) on western Europe during 25 – 10 KYA; Shennan and Edinborough (2007) on Germany, Denmark, and Poland during 9 – 4 KYA; Rick (1987) on Peru during 13 – 3 KYA; Lourandos and David (2002) on Australia from 35 KYA until European contact; and Holdaway and Porch (1995) on Tasmania during 35 – 10 KYA. Several of these studies find lengthy periods of static population and some find long swings or cycles that are clearly related to climate change. Rick (1987) cannot reject slow exponential growth for coastal Peru but this could reflect potential biases in the data, since rising sea levels may have erased early sites from the sample and unobserved agriculture may have occurred late in the period.

Two major improvements in climate appear to have induced population growth, a broader diet, and technological progress (in that order). The first is associated with the boundary between the Middle and Upper Paleolithic. Stiner et al. (2000) infer an upward jump in the population of southwest Asia sometime between the late Middle Paleolithic (60-48 KYA) and the early Upper Paleolithic (about 44 KYA). This ‘demographic pulse’ coincided with a warming phase in the prevailing glacial conditions. The second led to Mesolithic society in southwest Asia after the LGM, with large increases in population density (Bar-Yosef, 2002b, 2002c). We discuss both of these transitions in section 6.

Although prehistoric foragers may have had adequate leisure time (Kelly, 1995: 14-23) and ample nutrition (Clark, 2006), there is very little information on changes in living standards in prehistory. Most archaeologists agree that in the millennia leading up to agriculture there was neither a systematic deterioration in nutrition or health, nor any pronounced gain (Cohen and Armelagos, 1984; Cohen, 1989). Of course, productivity improvements could have been taken in the form of increased leisure, which would be difficult to detect. Still, due to the power of compound interest even very small growth rates in population density or technological capabilities would have led to an observable

transformation in pre-agricultural economies over 190,000 years, or 10,000 years, or as little as 1000 years (Richerson, Boyd, and Bettinger, 2001). There is no indication that such dramatic transformations took place. Thus it is reasonable to conclude that before agriculture, equilibrium growth rates were typically centered on zero.

3. Technological Evolution in a Static Environment

We consider a foraging society that has access to an array of natural resources indexed by $r = 1 \dots R$. Each resource can be converted into food (measured in some homogeneous units such as calories) according to a production function

$$(1) \quad F_r(a_r, k_r, n_r) = a_r g_r(k_r) f_r(n_r)$$

where a_r is the abundance of resource r (regarded as a flow provided by nature in a given time period); k_r is the technique used to harvest it; and n_r is the labor used for harvesting. We will refer to $a = (a_1 \dots a_R) > 0$ as ‘climate’. The functions f_r are twice continuously differentiable and satisfy $f_r(0) = 0$; $0 < f'_r(n_r) < \infty$ for all $n_r \geq 0$ with $f'_r(n_r) \rightarrow 0$ as $n_r \rightarrow \infty$; and $f''_r(n_r) < 0$ for all $n_r \geq 0$.

Techniques are modeled as binary strings of uniform length Q so $k_r = (k_{r1} \dots k_{rQ}) \in \{0, 1\}^Q$. Let k_r^* be the best method of converting resource r into food: $0 < g_r(k_r) < g_r(k_r^*)$ for all $k_r \neq k_r^*$. The function $g_r(k_r)$ is increasing in the number of digits of k_r that match k_r^* . It does not matter which digits are matched.

Q is assumed to be large enough that an exhaustive search for the ideal strings is infeasible. Instead, each generation inherits a repertoire of techniques from its parental generation. The repertoire available to the adults of generation t is $K^t = \{k_1^t \dots k_R^t\}$. This set summarizes the state of technological knowledge.

The repertoire K^{t+1} for the next generation is derived as follows. Let there be N^t adults in period t . Each is endowed with one unit of labor time. The society’s labor

allocation is $n^t = (n_1^t \dots n_R^t)$ where $\sum_r n_r^t = N^t$. All adults allocate time in the same way, so each spends n_r^t/N^t time units on resource r .

A typical child in period t has X opportunities to watch parents or other adults harvest resources, where X is a large number. Xn_r^t/N^t of these observations involve resource r (there are no observations for latent resources with $n_r^t = 0$). Each time a child i sees the exploitation of resource r , the string $k_r^t = (k_{r1}^t \dots k_{rQ}^t)$ is copied. For each of the Q positions on the string there is a probability p that an error is made in copying the current digit, and with probability $1-p$ the digit is copied accurately. Mutations are independent across loci, observations, and agents. The copy is k_{rix}^t where x indexes observations.

Whenever a copy of k_r^t is made, child i uses a negligible amount of labor $\epsilon > 0$ to determine the marginal product $a_r^t g_r(k_{rix}^t) f_r'(0)$. If the new copy achieves a higher value than the best previous copy, the child retains the new copy and discards any earlier copy. Otherwise, the best previous copy is retained and the new copy is discarded. At the end of this learning process, child i has a best string for resource r , which we denote by k_{ri}^{t+1} . We ignore food acquired by children, who are relatively unproductive in contemporary foraging societies (Robson and Kaplan, 2006).

The number of children who survive to adulthood is N^{t+1} . When the parents from period t die and their children become adults, these new adults compare their strings for resource r and coordinate on (one of) the best available. The result for resource r is $k_r^{t+1} = \text{argmax} \{g_r(k_{ri}^{t+1}) \text{ for } i = 1 \dots N^{t+1}\}$.

This process gives updated strings for r such that $n_r^t > 0$. In most of the paper, we assume passive updating for latent resources: that is, $n_r^t = 0$ implies $k_r^{t+1} = k_r^t$. We discuss alternative productivity assumptions for latent resources at the end of section 5. The full updated repertoire $K^{t+1} = (k_1^{t+1} \dots k_R^{t+1})$ is freely available to the adults in generation $t+1$.

Let q_r^t be the number of correct digits in the string $k_r^t \in K^t$. To model technical progress for active resources, we need to know the probability distribution over q_r^{t+1} .

Proposition 1. Assume $n_r^t > 0$ and define $\rho^t \equiv N^{t+1}/N^t$. Let the number of observations per child (X) approach infinity while the mutation probability (p) approaches zero such that $\lambda \equiv Xp > 0$ remains constant. In the limit, $\text{Prob}(q_r^{t+1} = q_r^t + 1) = 1 - \exp[-\lambda n_r^t \rho^t (Q - q_r^t)]$ and $\text{Prob}(q_r^{t+1} = q_r^t) = \exp[-\lambda n_r^t \rho^t (Q - q_r^t)]$. All other transition probabilities for resource r go to zero in the limit.

Proposition 1 shows that technical evolution for an active resource is directional. Regress requires every observation of k_r^t to have a negative mutation and the probability of this is zero in the limit. But progress only requires that at least one observation have a positive mutation and the probability of this does not vanish. The probability of progress is an increasing function of the mutation rate, the labor input for the resource, the population growth rate, and the distance from the ideal string. These results do not require a large population of agents; it is sufficient for each child to have many opportunities to observe adult behavior. Proposition 1 implies that if the transition probabilities are continuous at $n_r^t = 0$, the strings for latent resources remain constant.

4. Equilibrium in a Static Environment

Let $A_r(a_r, k_r) \equiv a_r g_r(k_r)$ be the productivity of resource r when its abundance is a_r and the string k_r is used. We will indicate the vector of productivities by $A(a, K)$, where one or both arguments may be dropped when climate or technology is fixed. If the ideal string k_r^* is available, this is indicated by A_r^* . The repertoire consisting entirely of ideal strings is denoted by K^* and the corresponding productivity vector is A^* .

In each period the adult labor supply N is allocated across resources to maximize total food, which is shared equally. For given productivities $A > 0$ and population $N \geq 0$, a short run equilibrium (SRE) is a labor allocation $n(A, N) = [n_1(A, N) \dots n_R(A, N)]$ that achieves

$$(2) \quad H(A, N) \equiv \max \sum_{r=1 \dots R} A_r f_r(n_r) \text{ subject to } n_r \geq 0 \text{ for all } r \text{ and } \sum_{r=1 \dots R} n_r = N.$$

Proposition 2. The solution in (2) is unique and continuous in (A, N) . Moreover:

- (a) Scale effect. Fix $A > 0$ and suppose $0 < N' < N''$. If $0 < n_r(A, N')$ then $n_r(A, N') < n_r(A, N'')$.
- (b) Substitution effect. Fix $N > 0$ and suppose $0 < A_r' < A_r''$ with $0 < A_s' = A_s''$ for all $s \neq r$. Also suppose $0 < n_r(A', N)$ and $0 < n_s(A', N)$ for some $s \neq r$. Then $n_r(A', N) < n_r(A'', N)$ and $n_s(A', N) > n_s(A'', N)$.
- (c) $H(A, N)$ is strictly concave in N and $y(A, N) \equiv H(A, N)/N$ is decreasing in N .
- (d) $\lim_{N \rightarrow \infty} H(A, N)/N = 0$.
- (e) $\lim_{N \rightarrow 0} H(A, N)/N = H_N(A, 0) = \max \{A_r f_r'(0)\}$ where $H_N(A, N)$ is the derivative with respect to N .

We turn now to the determination of population N . Every adult has an identical demand $\rho(y)$ for surviving children, where y is the adult's food income. We assume $\rho(0) = 0$ and $\rho(\infty) > 1$, where ρ is continuous and increasing. Surviving children are thus a normal good. This is consistent with the idea that surviving children are an argument in the adult's (direct) utility function, or with the Darwinian perspective that $\rho(y)$ is in fact the adult's (indirect) utility function. In either interpretation there is a unique income $y^* > 0$ such that $\rho(y^*) = 1$. Integer problems involving the number of children are ignored.

The population evolves according to

$$(3) \quad N^{t+1} = \rho[y(A^t, N^t)]N^t$$

where $y(A, N)$ is defined in Proposition 2. We restrict population dynamics as follows.

Monotone population adjustment (MPA). Suppose there is a population $N^* > 0$ such that $H(A, N^*)/N^* = y^*$. Keep A constant over time. If $H(A, N^0)/N^0 > y^*$ then $N^{t+1} > N^t$ for all $t \geq 0$. If $H(A, N^0)/N^0 < y^*$ then $N^{t+1} < N^t$ for all $t \geq 0$. In either case $\lim_{t \rightarrow \infty} N^t = N^*$.

MPA rules out oscillations around N^* . It holds when the direct positive effect of N^t on N^{t+1} in (3) outweighs the indirect negative effect of N^t through $y(A^t, N^t)$.

$N = 0$ is always a steady state in (3). From parts (c)-(e) of Proposition 2 there is a (unique) non-trivial steady state $N(A) > 0$ such that $y[A, N(A)] \equiv y^*$ if and only if some resource has $A_r f_r'(0) > y^*$. When such a steady state exists, population converges to it from any $N > 0$ due to MPA. In this case the steady state $N = 0$ is unstable and will be ignored. When $A_r f_r'(0) \leq y^*$ for all r , $N = 0$ is the only steady state and it is stable.

For a given productivity vector A , a long run equilibrium (LRE) is the population $N(A)$ defined by

$$(4) \quad \begin{array}{ll} y[A, N(A)] \equiv y^* & \text{when } \max \{A_r f_r'(0)\} > y^* \quad \text{or} \\ N(A) \equiv 0 & \text{when } \max \{A_r f_r'(0)\} \leq y^*, \end{array}$$

along with the associated SRE labor allocation $n[A, N(A)]$ from (2).

In every non-null LRE, per capita food consumption is y^* . As the vector A varies with climate or technology, the long run population $N(A)$ will generally vary but the long run standard of living will not. This is the Malthusian aspect of the model: an improved climate or technological progress can raise food consumption per person in the short run, but it yields a larger population with unchanged food per person in the long run.

We use the term ‘very long run equilibrium’ (VLRE) for a situation in which the LRE requirements are satisfied and in addition, the repertoire K is transmitted to the next generation with probability one. Proposition 1 showed that for an active resource ($n_r > 0$) there is a positive probability of progress whenever $k_r \neq k_r^*$. This implies that in a VLRE the repertoire K must include the ideal string for every active resource. Strings for latent resources ($n_r = 0$) must be compatible with corner solutions for these resources in SRE.

Formally, a very long run equilibrium (VLRE) for a fixed climate vector $a > 0$ is an array (K, N, n) such that

- (a) $k_r = k_r^*$ for all r such that $n_r > 0$;
- (b) $N = N[A(a, K)]$ is derived from (4); and
- (c) $n = n[A(a, K), N]$ is derived from (2).

We say that (K, N, n) is a null VLRE if $N = 0$.

To characterize the set of VLREs, we require some additional terminology and notation. Let $S \subseteq \{1 \dots R\}$ be a non-empty set of resources. A VLRE is said to be of type S if $k_r = k_r^*$ for $r \in S$ and $k_r \neq k_r^*$ for $r \notin S$. Let k_r^{\min} be the string with the lowest productivity for resource r . Define the repertoire K^S by setting $k_r^S = k_r^*$ for $r \in S$ and $k_r^S = k_r^{\min}$ for $r \notin S$. Let A^S be the associated productivity vector, let $N^S = N(A^S)$ be the LRE population level for A^S , and let $n^S = n(A^S, N^S)$ be the SRE labor allocation for (A^S, N^S) .

Proposition 3. The array (K^S, N^S, n^S) is a non-null VLRE if

- (a) $A_r^* f_r'(0) > y^*$ for at least one $r \in S$ and
- (b) $H_N(A^S, N^S) \geq A_r(k_r^{\min}) f_r'(0)$ for all $r \notin S$.

Every other non-null VLRE of type S has the same population $N^S > 0$ and the same labor allocation n^S . If either (a) or (b) fails to hold, every VLRE of type S is null.

Corollary. Let K^* be the ideal repertoire with $N^* = N(A^*)$ and $n^* = n(A^*, N^*)$. If $\max \{A_r^* f_r'(0)\} > y^*$ then (K^*, N^*, n^*) is a non-null VLRE. If $\max \{A_r^* f_r'(0)\} \leq y^*$ then every VLRE is null.

A resource that satisfies $A_r^* f_r'(0) > y^*$ as in condition (a) of Proposition 3 will be called a staple. Such resources can support a positive population even in the absence of any other resource. Every non-null VLRE must have at least one staple in the set S and every staple in S must be active. Resources with $A_r^* f_r'(0) \leq y^*$ are called supplements. The set S may include one or more supplements but these resources need not be active.

Every resource $r \notin S$ is latent, whether it is a staple or a supplement. Condition (b) in Proposition 3 requires that for each of these resources, there is a harvesting method so

unproductive that the resource is unexploited. If highly unproductive techniques exist for many different resources, then in general many VLREs will exist. All of the VLREs of type S are essentially identical: they support the same population and involve the same allocation of labor. The only distinctions among them involve the techniques for $r \notin S$, which must be sufficiently unproductive but are otherwise indeterminate.

The corollary provides a simple existence test. Whenever at least one staple exists, there is a non-null VLRE of the form (K^*, N^*, n^*) . We call this the maximal VLRE because no other equilibrium supports a larger population, and any VLRE with fewer active resources must have a smaller population. VLREs with populations below the maximum level will be called stagnation traps.

5. Climate Change and Technical Progress

We are now ready to address a central theoretical question: what environmental conditions are most conducive to technical progress? In particular, can climate change help a society escape from a stagnation trap?

As explained in section 1, we define progress to mean changes in technique that enable a society to support a larger population with a given climate. This requires us to separate population growth due to technological change (holding climate constant) from population growth due to climate change (holding technology constant). We solve this problem by the following thought experiment: let climate jump from an initial state a^0 to a new state a' and then back to a^0 . If population in the final equilibrium is higher than in the initial one, this can only be due to technological progress along the adjustment path.

The first task is to show that the system converges to a VLRE from any initial state. This is done in Proposition 4. The second task is to study the impact of climate shocks on technology, population, and labor allocation. Proposition 5 provides such an analysis for neutral shocks that affect all resources in the same proportion. We show that in this case, positive shocks can stimulate progress while negative shocks cannot.

We then discuss biased shocks in a setting with two resources. Our analysis shows that negative shocks biased toward latent resources can generate progress, but this depends on the outcome of a race between rising productivity and declining population. Finally, we discuss the possibility of regress when active resources shut down.

Before defining convergence to a VLRE, we need to spell out how techniques and population are updated over time for a fixed climate vector $a = (a_1 \dots a_R) > 0$. Let (K^t, N^t) be the state in period t . We obtain (K^{t+1}, N^{t+1}) as follows.

- (a) K^t determines the productivities $A^t = [a_1 g_1(k_1^t) \dots a_R g_R(k_R^t)]$.
- (b) A^t and N^t determine the SRE labor allocation n^t as in (2).
- (c) $H(A^t, N^t)$ determines N^{t+1} as in (3).
- (d) K^t, n^t , and N^{t+1} determine the probability distribution over K^{t+1} as in Proposition 1.

This yields a new state (K^{t+1}, N^{t+1}) .

Proposition 1 is expressed using q_r^t (the number of digits in k_r^t that match the ideal string k_r^*), but it generates a probability distribution for k_r^{t+1} conditional on k_r^t because there is an equal probability of mutation at every locus of k_r^t that does not yet match k_r^* . We assume existing strings for latent resources are retained with probability one.

Proposition 4. Fix the climate $a > 0$ and consider any initial state (K^0, N^0) with $N^0 > 0$.

- (a) Each sample path $\{K^t, N^t\}$ has some finite $T \geq 0$ and K' such that $K^t = K'$ for all $t \geq T$. We call K' the terminal repertoire for the sample path and $A' = A(K')$ the terminal productivity vector. Along a fixed sample path, $\{N^t\} \rightarrow N' = N(A')$ and $\{n^t\} \rightarrow n' = n(A', N')$. Accordingly, we say that K' generates (K', N', n') .
- (b) With probability one, the terminal array (K', N', n') is a VLRE.
- (c) If $N^0 < N[A(K^0)]$ then $\{N^t\}$ is increasing. If $N^0 = N[A(K^0)]$ then $\{N^t\}$ is non-decreasing. If $N^0 > N[A(K^0)]$ then $\{N^t\}$ may decrease for all $t \geq 0$, or it may decrease until some $T > 0$ and become non-decreasing for $t \geq T$.

Because regress is impossible for active resources and strings are conserved for latent resources, $\{A^t\}$ is non-decreasing and the system cannot converge to any VLRE whose productivity vector is dominated by A^0 . However, it is difficult to say much about the probability of converging to a specific VLRE because this depends in a complex way on how mutations affect productivities, which affect population dynamics, which then feed back to the mutation probabilities as in Proposition 1.

Fortunately, more can be said about responses to neutral climate shocks, which do not alter relative resource abundances.

Proposition 5 (neutral shocks). Let (K^0, N^0, n^0) be a non-null VLRE for the climate $a^0 > 0$. Define $A^0 = A(a^0, K^0)$ and consider a permanent climate change $a' = \theta a^0$ where $\theta > 0$.

(a) Negative shocks. Suppose $\theta \in (0, 1)$. The system converges to the new VLRE (K', N', n') with $K' = K^0$; $N' = N(\theta A^0) < N^0$; and $n' = n[\theta A^0, N(\theta A^0)]$. The set of active resources in n' is a subset of the active resources in n^0 . If $N' > 0$ and the climate returns permanently to a^0 starting from (K', N', n') , the system converges to the original VLRE (K^0, N^0, n^0) .

(b) Positive shocks. Suppose $\theta > 1$. Due to Proposition 4(b), with probability one the system converges to a VLRE (K', N', n') . This new VLRE has $K' \neq K^0$ iff

$$(*) \quad n_r[\theta A^0, N(\theta A^0)] > 0 \text{ for some } r \text{ such that } k_r^0 \neq k_r^*.$$

The new population satisfies $N' \geq N(\theta A^0) > N^0$, where $N' > N(\theta A^0)$ iff $(*)$ holds. If a^0 is permanently restored starting from (K', N', n') and $(*)$ does not hold, the system converges to the original VLRE (K^0, N^0, n^0) . If a^0 is permanently restored starting from (K', N', n') and $(*)$ does hold, the system converges to the VLRE (K'', N'', n'') where $K'' = K' \neq K^0$ and $N' > N'' \geq N^0$. The last inequality is strict iff $n[A(a^0, K''), N^0] \neq n^0$. In this case, some resource with $n_r^0 = 0$ has $n_r'' > 0$.

Proposition 5(a) shows that a neutral negative shock cannot stimulate technical progress because it cannot change the repertoire K . Population falls and some of the previously active resources may become latent (the diet may narrow). Reversing the shock returns the system to the original VLRE and restores the previous population, as long as the society has not gone extinct in the meantime. Restoration of the status quo population reflects the absence of technical progress in response to the climate change.

Proposition 5(b) shows that a neutral positive shock can stimulate permanent progress. A necessary and sufficient condition for this outcome is that the shock must lead to exploitation of a latent resource whose technique can be improved. This cannot occur in the short run through substitution effects because relative resource abundances are unchanged. Instead, the key channel is a scale effect involving population.

Without technical change, the improved climate would lead to a larger population $N(\theta A^0)$ in the long run. This population growth could make one or more latent resources active. If so, the technical repertoire improves through learning by doing, and population expands beyond the level $N(\theta A^0)$ induced by climate change alone. But if the scale effect is too small to activate a latent resource, technology remains static and population grows only to the extent that climate permits.

If the climate returns to its original state a^0 and technology has not improved in the meantime ($K' = K^0$), clearly population must return to its original level N^0 . The same is true if technology improves as a result of the climate shock, but not by enough to alter the set of active resources used in the original climate a^0 . For progress to become visible in the population level ($N'' > N^0$) after climate reverts back to a^0 , the string for at least one previously latent resource must improve to a point where the old labor allocation n^0 is no longer optimal at the old population level N^0 . In this case, at least one new resource will be used after the climate returns to a^0 . Simultaneously, some resources initially active at a^0 may be abandoned due to substitution effects.

Provided that strings for latent resources are conserved, the new technical plateau will be permanent. Proposition 5(a) shows that subsequent negative shocks cannot force a technological retreat. The result is a ratchet effect in which knowledge can gradually improve. But unlike conventional growth models, our framework predicts a ‘punctuated’ process where occasional productivity gains stimulated by positive climate shocks can be separated by long periods of stagnation during which technology does not change and the average population growth rate is zero. During these intervals population will fluctuate in response to climate, and individual resources may go in and out of use as a result, but there is no lasting improvement in technological capabilities.

Thus far we have made two key assumptions: that climate shocks are neutral, and that strings for latent resources are conserved. In the rest of this section we consider the consequences of relaxing each assumption.

Shocks biased toward or against particular resources create short run substitution effects that can activate latent resources even before population has time to adjust. It will be convenient to discuss these effects in the context of two resources ($R = 2$). We start from an initial VLRE (K^0, N^0, n^0) associated with climate a^0 in which resource 1 is active and resource 2 is latent. Because a negative shock to a latent resource cannot affect the system, this case will be ignored in what follows.

A positive shock to the latent resource. There is an immediate substitution effect away from resource 1 toward resource 2 with N^0 constant. If the shock is large enough, $n_2^0 > 0$ will occur (otherwise the shock is irrelevant). In the long run population grows and the productivity A_2 rises. For both reasons, n_2^t increases. With probability one, the ideal string k_2^* is eventually identified and the ideal repertoire K^* is achieved.

A positive shock to the active resource. An immediate substitution effect keeps resource 1 active and reinforces the latency of resource 2. However, population grows in the long run and this scale effect may eventually outweigh the substitution effect to give n_2^T

> 0 at some $T > 0$. If resource 2 ever becomes active it remains so, and the analysis from that point on is identical to the preceding case.

A negative shock to the active resource. An immediate substitution effect favors resource 2 at the expense of resource 1. If the shock is large enough, $n_2^0 > 0$ may occur. There are then two possibilities: (a) $n_2^t > 0$ for all $t \geq 0$; or (b) there is a $T > 0$ such that $n_2^t = 0$ for all $t \geq T$. Case (a) occurs when technical progress for resource 2 is rapid enough to outweigh the population decline resulting from the negative shock. In this scenario, population could eventually begin to grow and the ideal repertoire K^* could be achieved. Case (b) occurs when technical progress for resource 2 is too slow, so that this resource eventually shuts down due to the declining population. This aborts further progress and leads to a new VLRE in which resource 2 is again latent.

Proposition 5 is restricted to neutral shocks, and shows that within this class only positive shocks can generate technical progress. The same logic applies to any situation in which scale effects dominate substitution effects. However, negative shocks that are biased against active resources can nevertheless generate permanent progress. This occurs only if the productivity gains associated with previously latent resources occur quickly enough relative to the rate at which population declines.

These conclusions are all tilted in favor of progress by our assumption that strings for latent resources remain intact. This assumption is appealing on grounds of tractability and because it is the limiting case of Proposition 1. However, techniques may deteriorate if they are passed down through oral traditions in the absence of any practical experience with the resource in question. An extreme way to introduce regress would be to assume that when a resource shuts down, the associated string drops out of the repertoire entirely. Then the only way to revive the resource would be to borrow a string already in use for an active resource. In this situation, it can be shown for a two-resource framework that negative shocks can lead to regress and the population may not fully recover when such shocks are

reversed (for a different modeling framework and some examples of regress, see Alyar, Dalgaard, and Moav, 2008).

The analysis of this section identifies several prerequisites for sustained progress. First, climate shocks must be large enough to trigger experimentation with new resources. Second, they should permit the preservation of existing knowledge. Strong substitution effects that flip the system from one corner solution to another interrupt the process of 'remembering by doing'. Finally, a new climate state must persist long enough for new techniques to evolve. If a shock is brief, there is little opportunity for productivity to rise for new resources, and the system will return to the previous equilibrium after the status quo is restored. As was shown in Proposition 1, productivity gains are accelerated if a society allocates a large amount of labor time to newly active resources. It is also helpful if population grows quickly in response to positive shocks and does not decline rapidly in response to negative shocks.

6. Progress in Prehistory

The theory developed in sections 3-5 can be used to understand several episodes of technological innovation in the archaeological record. We consider four of these here: the Upper Paleolithic transition; migration into northern Asia; the Mesolithic period after the last glacial maximum; and the Neolithic transition to agriculture.

The Upper Paleolithic. Section 5 showed that a positive neutral climate shock, if sufficiently large, leads to a causal cascade involving: (a) population growth; (b) greater dietary breadth; and (c) technological progress. The latter can feed back to population growth, generating further rounds of (a), (b), and (c) until the system settles into a new equilibrium. This process does not require exact neutrality. It is sufficient that scale effects dominate substitution effects, as is likely for major climate improvements.

Adverse climate led to especially low human populations (a 'bottleneck') around 70 KYA (Shennan, 2001: 13; Bar-Yosef, 2002a: 379). A warmer period during 64 – 32 KYA led to population growth in southwest Asia by 44 KYA and probably earlier (Stiner et al.,

2000). This growth is documented from the effects of human predation on the size distribution of prey species. Blade technology emerged in southwest Asia around 44 KYA. Stiner et al. (1999: 193) observe that “in western Asia, . . . human populations increased substantially before the remarkable and rapid technological innovations (radiations) that mark the Upper and Epi-Paleolithic periods”. This sequence, in which climate stimulates population growth and the latter stimulates technological progress, is consistent with our theory (for a related argument and data, see Shennan, 2001: 13-15).

Modern humans moved into Europe from southwest Asia around 45 – 40 KYA. Since blade technology already existed in southwest Asia at this time, it can be assumed that the migrants brought this toolkit with them. Indeed, the new technology may have encouraged the migration, but milder climate likely played a major facilitating role. The availability of large prey on the European steppe (bison, horses, reindeer, mountain goats, woolly mammoth, woolly rhinoceros, oxen, deer) no doubt stimulated further refinements in Upper Paleolithic technology.

Our model predicts that population growth and technological progress should be associated with a broader diet, as previously latent resources are increasingly exploited. The diet broadened in Italy to include birds around 35 KYA, a date that coincides with the arrival of the Upper Paleolithic there. Such prey were previously available but had been unexploited. Exploitation of birds began in modern-day Israel around 28-26 KYA (Stiner et al., 2000). This dietary expansion was linked to the diffusion and refinement of blade technology, and perhaps also to population growth.

Migration into northern Asia. Modern humans arrived in China by about 35 KYA and Siberia by about 20 KYA (dates for Siberia are controversial; see Fagan, 2006: 150). They reached the Americas using a combination of the Beringian land bridge and coastal watercraft by about 15 KYA. This colonization process required tailored clothing, new forms of housing, and a new toolkit. In particular, microblades emerged among mobile hunters in northern China around 30 KYA and spread into Siberia by 18 KYA (Fagan,

2006: 150-2). Humans have gradually adapted to other harsh environments, including deserts, but the migration into northern Asia was especially consequential.

As we pointed out in section 1, migration is an ambiguous indicator of technical progress because migration opportunities can result from changes in climate or sea level with technological capabilities held constant. Indeed, our theory gives a sharp prediction: transplanting a small group of colonizers into a region with natural resources identical to their region of origin will not trigger technological progress. To see why, recall from Proposition 5(a) that a neutral negative climate shock followed by a return to the status quo cannot alter the technological repertoire. This parallels the thought experiment for colonization: the neutral negative shock pushes down population just as migration does, and the return to the status quo yields a population rebound that is analytically identical to population growth among the colonizers in the new region.

How then to explain migration into harsh environments like Siberia? We first need to develop the idea of a habitation frontier. Recall from Proposition 3 that positive population in a very long run equilibrium requires at least one staple food. Imagine a spatial gradient along which food resources become less abundant due to harsher environmental conditions (e.g. higher latitude in Asia). For a given technological repertoire, there will be a boundary beyond which no staple foods exist and equilibrium population is zero.

There are two ways in which climate shocks could shift this habitation frontier further north. First, consider a series of positive shocks followed by reversions to the status quo. In the absence of technological progress, the frontier would simply move back and forth. But we know from Proposition 5(b) that a sequence of such shocks can cause a ratchet through which technology gradually improves. Because technological capabilities substitute for natural resource abundance, the habitation frontier gradually moves into successively harsher environments.

The other mechanism that could yield a geographic ratchet effect is a series of biased negative shocks followed by reversions to the status quo. From Proposition 5(a) we

know that neutral negative shocks cannot improve technology. But a negative shock biased in favor of a latent resource could create a substitution effect that trumps the scale effect. If productivity gains for newly active resources are rapid enough relative to the rate of population decline, improvements in technology can persist after the status quo is restored. Repeated rounds can lead to cumulative movement in the habitation frontier.

In this light, it is interesting to consider the geographic distribution of innovation during the Upper and Epi-Paleolithic. Many important developments, including tailored clothing, microblades, spear throwers, and the bow and arrow are associated empirically with temperate or arctic Eurasia rather than Africa or tropical Asia. The data could be biased by differences in research efforts across continents because sub-Saharan Africa, south Asia, and southeast Asia have received only limited archaeological attention (Bar-Yosef, 2002a). Nevertheless, the concentration of technological advances in temperate and arctic climate zones is striking.

Our theory suggests an explanation. As we discussed at the end of section 5, the natural environment best suited to innovation in a foraging economy involves occasional roughly neutral climate shocks. Frequent shocks give new techniques less time to evolve. Strongly biased shocks, whether positive or negative, tend to shut down active resources and therefore strain a society's ability to preserve existing knowledge, although progress might still occur. The environment least suited to innovation is one in which shocks are small or absent, because then it is impossible to escape from a stagnation trap.

Until about 11.6 KYA, the temperate regions of the world were buffeted by very large climate shocks on time scales ranging from decades to millennia (Richerson, Boyd, and Bettinger, 2001). Although far from ideal, these conditions apparently generated a ratchet effect through which innovations gradually accumulated. This process was likely assisted by the diffusion of techniques across regions, which increased the total number of experimenters and created a permanent reservoir of technical knowledge (Diamond, 1997).

Tropical regions were sheltered from such Ice Age shocks, giving the people of Africa and southern Asia less reason to experiment with latent resources.

The Mesolithic transition. The end of the Ice Age led to substantial population growth in southwest Asia and Europe (Gamble et al., 2005). An important feature of the associated Mesolithic transition was the inclusion of smaller prey (hares and rabbits) in the diet throughout West Asia, Europe, and North Africa. By 19 – 17 KYA hares and rabbits had been added to the diet in Italy, and the same occurred by 13 – 11 KYA in southwest Asia (Stiner et al., 2000). As with birds in the Upper Paleolithic transition, these prey species had previously been available but remained latent until the climate moderated and population grew. Stiner (2001: 6996) comments: “early indications of expanding diets in the eastern Mediterranean precede rather than follow the evolution of the kinds of tools (specialized projectile tips, nets, and other traps) needed to capture quick small animals efficiently.” Again, this sequence is consistent with our model.

By 14.5 KYA, the Natufian culture in southwest Asia showed rapid population growth, with site areas five times larger on average than in the preceding Geometric Kebaran (see Bellwood, 2005: 51). These hunter-gatherers consumed a very wide range of prey shortly before the onset of agriculture, including gazelle, goat, sheep, cattle, bear, deer, badger, marten, beaver, hedgehog, boar, hare, rodents, fox, dog, cat, birds, fish, reptiles, amphibians, crab, and mollusk (Savard, Nesbitt, and Jones, 2006).

Dietary breadth with respect to plant foods during the Mesolithic is controversial. It is clear that at the last glacial maximum, the inhabitants of southwest Asia relied heavily on small-seeded grasses (Weiss et al., 2004). As climate improved, large-seeded grasses became more common (especially the wild precursors of wheat, barley, and rye). According to one school of thought, represented by Weiss et al., the people of the region increasingly specialized in these grasses, which smoothed the path to agriculture. Another school of thought, represented by Savard et al., argues that climate change and population growth led to a gradual broadening of the diet to include a wider range of wild plant species (the ‘broad

spectrum revolution' or BSR). In this view, large-seeded grasses were a minor part of the overall Mesolithic diet, despite their later importance for agriculture.

In a re-analysis of data from sites in southwest Asia shortly before agriculture, Savard et al. (2006) find that the plant component of the diet was highly diverse at each site, and also that there was substantial diversity in the composition of the diet across sites. The increased abundance of large-seeded grasses after the LGM did not drive out consumption of the small-seeded grasses that were important at the LGM. The results for the region as a whole “fit with elements of . . . the broad spectrum model” (Savard et al., 2006: 192). In a similar vein, Hillman et al. (2001) report that just before the Younger Dryas climate shock and the start of cultivation, more than 100 species of edible seeds and fruits were used in southwest Asia. This broad pattern of plant exploitation was accompanied by considerable technological paraphernalia, such as querns, mortars, pestles, bowls, grinders, pounders, whetstones, choppers, and sickles.

The original BSR hypothesis from archaeology involved exogenous population pressure and a resulting deterioration in living standards, which drove people to use less desirable species. By contrast, in our model the BSR is a response to a positive climate shock (the end of the Ice Age), and the resulting endogenous population growth is not 'pressure'. Rather, it is a response to improved living standards and leads to increased dietary breadth as people find it more profitable to exploit latent resources. In turn, this stimulates technical innovation aimed at more efficient harvesting of the new resources.

The Neolithic transition. Technological progress was patchy and infrequent until the Holocene period of the last 11,600 years. This poses a puzzle: if climate shocks are a necessary stimulus to technological progress, why did progress accelerate with the arrival of the more stable Holocene climate regime?

The answer is closely linked to the emergence of agriculture. We argue elsewhere that plant cultivation arose in southwest Asia due to the Younger Dryas, a large negative climate shock (Dow, Reed, and Olewiler, 2008). Following an interval of mild climate

lasting 1500-2000 years during which regional population accumulated, an abrupt shift to colder and drier conditions led to local population spikes at a few sites, as people moved from arid areas to locations with reliable water supplies. The resulting local decline in the marginal product of foraging labor made plant cultivation attractive. Our focus on intra-regional migration is consistent with archaeological evidence on population shifts, and allows us to account for the onset of cultivation without appealing to direct resource biases (substitution effects) associated with the negative climate shock.

Agriculture brought more of the reproductive cycle of plants and animals under human control. Rather than merely harvesting resources given by nature, humans could intervene at earlier stages in the production process, which led to learning by doing with respect to planting, irrigation, weeding, and the like. Over many generations, processes of artificial selection led to fully domesticated plants and animals, generating enormous productivity gains. Stone-age foraging techniques and low population densities persisted in areas where conditions were unsuitable for farming (for example, the Arctic; the deserts of Australia and southern Africa; and rain forests in the Amazon basin, Africa, and southeast Asia). Elsewhere, agriculture brought an end to stagnation.

Furthermore, although the size and frequency of climate shocks has decreased dramatically in the last 11,600 years, there is a sense in which the Holocene itself has been a single huge positive shock. Around the time that agriculture arose and began to spread, world climate improved both in the mean (warmer and wetter conditions) and through reduced variance. This created a permissive environment in which population could grow, new resources could be explored, and new techniques could be perfected. The rest is history.

7. Concluding Remarks

We have developed a theory to explain why technological progress was slow and sporadic before agriculture, a period that encompassed almost all of human existence. In our model, foragers typically exploit a subset of the resources provided by nature. While

they often achieve high productivity levels for these resources, further advances require the exploration of latent resources, and this is not attractive given current knowledge. We refer to this situation as a stagnation trap.

Climate shocks (either positive or negative) can induce experimentation with latent resources. This generates a punctuated series of equilibria in which foragers achieve greater technical capabilities and higher population densities at successive plateaus. Assuming that a foraging society can retain knowledge of inactive techniques, this leads to a ratchet effect through which technology improves. However, the Pleistocene climate regime in temperate regions involved frequent large shocks, while in tropical regions shocks may have been too small. In the first case there was little opportunity for refinement of new techniques, and in the second case there was little inducement to explore latent resources. In the more stable Holocene climate regime, large shocks no longer disrupted knowledge accumulation. We believe this theory is consistent with archaeological information on climate, population, diet, and technology from the Upper Paleolithic through the early Neolithic.

We do not model technological change after the transition to agriculture. However, our analysis has implications for understanding stagnation and innovation in more recent times. A striking fact is that stagnation was the norm before agriculture, while innovation was the norm afterward (apart from foraging societies occupying extreme environments). One explanation is that in foraging societies, nature has a dominant role. Such societies harvest wild resources supplied directly by nature, so advances in technology are limited to the harvesting phase. Agriculture, by contrast, offers opportunities for learning by doing over the entire cycle of production from planting to weeding and irrigation to harvesting.

As nature's role diminished relative to these new learning opportunities, sustained (albeit Malthusian) progress became possible after agriculture. Over time, the productivity gains in agriculture and the emergence of large manufacturing and service sectors reduced nature's influence still further. This created the preconditions for positive feedback loops involving population density, technological change, institutional innovation, and investment

in human capital. The eventual result was modern economic growth.

Such progress was hardly inevitable. Suppose that world climate had continued to follow the pattern of glacial periods lasting 100,000 years interrupted by interglacial periods lasting 10,000 years. This would have implied a reversion to glacial conditions beginning about 5000 years ago, a time when agriculture was spreading across southwest Asia, China, and Mesoamerica. The result would have been a contraction in population and a reduction in the geographic regions of human habitation. One plausible trajectory would have been a return to hunting and gathering -- in short, to a world with little or no progress.

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