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On the Early Holocene: Foraging to Early Agriculture

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Abstract:
We consider a world in which the mode of food production, foraging or agriculture, is endogenous, and in which technology grows exogenously. Within a model of coalition formation, we allow individuals to rationally form cooperative communities (bands) of foragers or farmers. At the lowest levels of technology, equilibrium entails the grand coalition of foragers, a cooperative structure which avoids over-exploitation of the environment. But at a critical state of technology, the cooperative structure breaks down through an individually rational splintering of the band. At this stage, there can be an increase in work and through the over-exploitation of the environment, a food crisis. In the end, technological growth may lead to a one-way transition from foraging to agriculture.

Keywords: Foraging, Agriculture, Transition, Coalition Formation, Cooperation

JEL Classification: N50, O13

"People did not invent agriculture and shout for joy. They drifted or were forced into it, protesting all the way." Tudge (1998, p.3)

1 Introduction

One traditional chronology for world pre-history is based on geological epochs or the idea of a great ice age in the distant past (the Pleistocene epoch). Pre-historic time is partitioned into the Pleistocene, starting approximately 1.7 million years before present (BP), followed by the warm Holocene for the last 10,000 years. The Pleistocene is further partitioned into the lower, middle and upper periods, upper being more recent than lower. The idea of a great ice age has been modified with the recognition that there was not one but four major glacial periods during the long Pleistocene.

It is also usual for archaeologists to break prehistory into archaeological stages or lithic ("stone") ages (see Renfrew and Bahn (2000 p.125)). Three ages are traditionally recognized: the Paleolithic, a period which began with the first evidence of stone tools about two million years ago; then in Europe the Mesolithic which began about 13,000 BP and lasted for about 6,000 years; and finally the Neolithic which ended with the bronze age.[1] The distinction between the Paleolithic and the Neolithic is the mode of food production, in particular, hunting and gathering (foraging) in the former, and agriculture in the latter. The Mesolithic was a transitional and rather unstable period of broad spectrum foraging and the earliest agriculture (e.g. cultivation). The long Paleolithic period is further subdivided into periods according to the type of stone tool use.[2] The potential utility of an economic approach to Archaeological issues becomes clear when one considers that the distinction between the stone ages is economic structure and the chronological partitioning of the Paleolithic is by the state of technology.

For more than 99% of the last two million years foraging was the principal mode of food production. However, agriculture emerged independently in a number of dispersed locations in the world within a few thousand years during the early Holocene. Our explanation of this phenomenon will be driven by technological growth. A central problem in the foraging life-style was the common access environmental problem. We will show the technological growth may have eventually damaged

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[1] The equivalent terms to Mesolithic for the Near East is Epipalaeolithic, and for North and South America is Archaic.

[2] It should be pointed out that the Paleolithic involved more than one type of hominid not all of which our ancestors. For example it includes the Neanderthal and earlier periods include hominids of smaller cranial capacity.

the ability of foragers to form conserving institutions (bands) in avoiding over–exploitation. We will then show how agriculture and private property could come to dominate even though it may initially provide a lower quality of life.

The study of how we became farmers thousands of years ago is, in itself, interesting. But the mechanism that we identify in this paper may also prove useful in explaining the recent success or failure of informal common property resource management systems. Ostrom (1990) provided case studies of a large number of communities smoothly managing a common property by use of such informal resource management institutions. These institutions have typically evolved to their current structure over a long period of time. Key to the success of these institutions — as measured by the fact that the resource has not been depleted — is their design which ensures and fosters cooperation within the community. Examples of resources that have been successfully managed include fisheries, drinking water, and irrigation systems. But Ostrom is aware that these informal institutions are fragile. When discussing the impact of technological progress, she points out that it can destabilize and even destroy informal institutions: "... the management of complex resource systems depends on a delicate balance between the technologies in use and the entry and authority rules used to control access and use. If the adaptation of new technologies is accelerated, the relationship between the rules and technologies in use may become seriously unbalanced. This is particularly the case when the rules have come about through long processes of trial and error (...) The rapid introduction of a 'more efficient' technology can trigger (...) the 'tragedy of the commons' ..." [Ostrom 1990, p.241, note 29].

Indeed, there are cases where a resource management institution operated well for a period of time and then collapsed after the introduction of a new technology, triggering a 'tragedy of the commons'. One such failure, documented by Cordell and McKean (1992), concerns the management of a fish stock by small communities on the coast of Bahia in Brazil. The story they recount is similar to that developed in this paper. Until 1970, these communities, through a traditional and complex system of sea tenure, were able to avoid over–exploitation of their stock of fish. But in the early 1970s, nylon nets — an improvement over the traditional fishing technology — were introduced when the Brazilian government started providing loans and tax incentives for fishery development. The system of sea tenure rapidly collapsed and this in turn triggered a destructive tragedy of the commons. Cordell and McKean report that since then, the stock of fish has been gravely depleted.

Before turning to a complete description of our theory, it is useful to review the alternative theories that have been put forward to explain the transition from foraging to early agriculture.

2 Theories of the Transition

The information reported here comes from archaeology and studies of modern foragers and other primates.[3]

The 19th century theory for the transition which dominated up to the 1950s was that life as forager was short, nasty, and brutish. Pleistocene humans could not produce a surplus above subsistence and therefore spent all their time trying to get enough to eat in chronic hunger and sickness. The moment some genius thought of planting seeds the switch was made.

This theory has been rejected by archeologists and anthropologists (see Megarry (1995, p.225)). Serious inconsistencies came to light with studies of the fossil record and of modern foraging bands. These showed that the quality of life under foraging may well have been quite high, what Sahlins (1968) described as the original affluent society. The "cavemen" were skilled artisans who often lived in artifactual shelters rather than caves. Archaeology shows that they lived in semi–nomadic groups or bands of 10–100 individuals. By the upper Pleistocene, they had a highly developed stone technology (spear throwers, bow and arrow, very refined stone, antler, and bone blades and points) which allowed them to successfully hunt and butcher the largest animals (mammoths, horses, deer, reindeer, and bison) (Harris (1977, p.10), Smith (1975, p.729–735)). The idea that Pleistocene foragers worked around the clock has also come in for criticism. Primate studies and studies of modern forager societies living under even quite harsh conditions have shown that they may well have worked less than early agriculturalists and maybe less than we do today (Harris (1977, p.12) and Haviland (1993, p.154)). Cashdan (1989) who studied the !Kung of South Africa's Kalahari desert reports 3 hours per day in foraging time. With repair of equipment and the equivalent of our housework she reports a 40 hour work week. There is also evidence that these bands knew how to conserve resources to avoid over exploitation (Harris (1977, p.12) and (1993, p.159)). To offer one example, one of the responsibilities of the leader of a native community of the Northwest coast of North America was to decide when to open the salmon fishing season (Johnson and Earle

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[3] Because our focus is on the transition between hunting and gathering and the earliest agriculture the information for hunting and gathering will be in regard to the late Upper Pleistocene (Upper Paleolithic) which began approximately 35,000 years ago. For the same reason we are not primarily focused on the much studied issue of domestication of plants and animals which followed the earliest agriculture or cultivation and animal husbandry

(1987, p.167)). Foragers also knew how to store food when conditions permitted. Another element which is considered almost a defining characteristic of band life is food sharing. Sharing or gift exchange (reciprocity) is seen by many anthropologists as promoting cooperation (fictive kinship relationships) among genealogically unrelated individuals (Johnson and Earle (1987, p.6)).[4] In economics, the idea of reciprocity and cooperation was introduced by Akerlof (1983) in his analysis of labour contracts. More recently, Carmichael and MacLeod (1997) have shown, in an evolutionary model, how gift giving can lead to trust and cooperation.

Archaeological evidence suggests that the forager's physical health was good implying good levels of consumption. Angel (1975) studying skeletal remains from the late upper Pleistocene found that these people grew taller and had less tooth loss than all but the most recent humans. Renfrew and Bahn (2000, p.452), commenting on a number of studies, conclude that there seems to be a pattern of reduced mechanical stress (injuries) and increased infections and nutritional stress with the adoption of agriculture. Harris (1977, p.4) references studies which conclude that life expectancy conditional on birth for modern foragers (!Kung bushmen) and non-white American males in 1900 was the same, 32.5 years. It is argued that this is associated with extremely low population densities throughout the Pleistocene (Harris (1977, p.14) and below). Finally, it is also known that pre–historic foragers lived side by side with farmers (Cashdan (1989, p.44)) which implies that the foraging life–style in some cases was a choice.

More recent theories for the transition are based on some combination of population pressure and environmental change. The theories differ in causation and emphasis but most of them have a food crisis as an element in the transition from foraging to agriculture.

The extreme population pressure view captured in Malthusian models of uncontrolled population pressure leading to a subsidence existence and which is related to pre–1950's theory, would be rejected by most modern anthropologists. First, as pointed out above there is a good deal of evidence that leisure and in fact the quality of life during the late Upper Pleistocene was quite high and possibly higher than during the early Holocene. Second, there is agreement among anthropologists and archaeologists that Pleistocene peoples controlled their populations (see Birdsell (1968), Harris (1977, chapter 2), Cohen (1980), Hassan (1980), Lee (1980), Ripley (1980), Harris (1993,

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[4] Kinship theory (the selfish gene) explains why an individual may cooperate with his kin. Cultural anthropologists argue that culture can create the fictive belief that genetically unrelated individuals are kin. An example of the cultural device that can be used to create these beliefs is the individuals undertaking behaviour that is typical of kin, such as reciprocity.

chapter 13), and Megarry (1995, p.221)). Population control during the Pleistocene is reflected in it being a period of extremely low population growth. Cohen (1980) and Renfrew and Bahn (2000) report annual population growth of .001–.003% during the Pleistocene with a hundred fold increase during the Holocene and a 1000 fold increase in modern times. Renfrew and Bahn report a world population in the 5-20 million range at the end of the Pleistocene

Methods of population control which were available to Pleistocene people included culturally–demanded abstinence, disruption of the menstrual cycle through extended years of breast–feeding, abortion, direct and indirect infanticide (particularly female infanticide), child homicide, and even dietary cannibalism.[5] Among modern foragers levels of infanticide have been estimated to be as high as 50% (Birdsell (1968, p.243)). Hassan (1980) suggests percentages in the area of 25–35%. Hill and Hurtado (1996) reports evidence of child homicide among modern foragers.

Clearly besides the issue of feasibility of population control there is also the issue of individual incentive. It has been argued that woman in foraging societies had strong incentives to have few dependent children because of the problem, if not impossibility, of carrying all possessions, gathered food and more than one child over the great distances traveled in a foraging life-style (Lee (1980)).[6] The psychological stress of infanticide may have been eased by culturally defining the start of human life long after birth in much the same way we ease the stress of abortion by defining the start of human life long after conception. The stress of child homicide may have been eased by the idea that the homicide would provide companions for a dead adult. Further, given the band organization, the infanticide or homicide decision simply may not have been a private one (see Hill and Hurtado (1996) for public decision on child homicide within Ache bands). There are also arguments that infanticide may have been adaptive evolutionary behaviour (Ripley (1980)).

Agriculture emerged independently in at least seven distinct locations in the world within a few thousand years (see Smith (1995)). It then seemed natural to look at exogenous global environmental shocks as a central element in theories of the transition (e.g. Childe (1952)). The end of the Pleistocene corresponds to the end of the last ice age. The ice retreated and there was a global warming with a rising sea level. The warming led to a forestation of former vast grasslands

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[5] The emphasis on female infanticide arises from the number of females being the important population growth variable in societies without monogamous relationships. See Harris (1993, chapter 13) for a discussion of indirect infanticide in modern societies. On dietary cannibalism, see the discussion in the working paper version of this paper, Marceau and Myers (2000).

[6] This explanation is also consistent with the dramatic increases in population with the adoption of a sedentary life-style and agriculture.

which had covered much of southern Eurasia and which had supported the Pleistocene megafauna (e.g. mammoth). Through some combination of hunting and environmental change, these animals became extinct during this period and this was a force in the switch to agriculture (see Renfrew and Bahn (2000), p. 252-253 on the extinctions, and Smith and Wishnie (2000) on conservation and over exploitation). In recent decades, however, the complexity of environmental change in the Pleistocene has been recognized. During the Pleistocene there were four major glacials and approximately twenty stadials (more minor distinct cold periods) (see Renfrew and Bahn (2000), p.125-126). As a result an environmental explanation on its own has been unconvincing because similar climatic events had occurred many times during the Pleistocene without the megafauna going extinct and without sparking agriculture.[7]

Recognition of the difficulties with either population growth or an environmental shock as *the* cause of the transition seems to have led to increasingly complex explanations which are built on combining elements of environmental change and population pressure. In this line Binford (1968) and Flannery (1969) were extended to include sedentism as a central component by Bar Yosef and Kislev (1989, p.633–634) in studying the emergence of agriculture in the Jordan Valley around 10,000 BP. That explanation runs as follows (see also Bar-Yosef and Belfer-Cohen (1989) and Bar-Yosef and Meadow (1995, p.65–71)). Between 19,000 BP and 14,500 BP, small bands of hunter-gatherers occupied the Mediterranean coastal ranges and the western sector of the Trans-Jordanian plateau. The inner land was cold and dry, thereby limiting expansion in that direction. The way of life was mobile because of the spatial and seasonal distribution of resources. Between 14,500 BP and 12,500 BP, a climatic change towards more rainfall caused dispersion of the population to a much wider area and the associated increase in resources lead to a larger total population of mobile foragers. Around 12,500 BP, an abrupt climatic change towards drier conditions caused the return of foragers established inland, back into the Mediterranean coastal territories. Because of the sudden increase in population density, and the occupation of all resourceful territories, it became impossible to continue the mobile way of life. This lead to sedentism and the adoption of a broad spectrum diet. From 12,000 BP to 11,000 BP, the Natufians — i.e. the residents of this geographical area during this particular era — were based in sedentary villages and expanded in some drier territories,

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[7] There are also economists who have also been arguing for an explanation based on global environmental events. Ofek (2001) argues that there was increased climatic stability starting about 11,000 years ago and this stability was necessary for the viability of agriculture. He also argues that trade or exchange allowed early farmers to specialize in production while maintaining consumption diversity. He argues that it was a lack of exchange (attempts at self-sufficiency) that explain the serious decline in health evidenced in skeletal remains at the time of early agriculture.

possibly because of population growth associated with now more sedentary lifestyle. Between 10,500 BP and 10,000 BP, the climate changed towards even drier conditions and the available resources, despite the broad spectrum diet, were probably fluctuating at dangerously low levels in some years. Because they could no longer move to other nearby resourceful territories, the risk-reduction strategy the Natufians adopted was to switch to agriculture systematically, particularly when the climate began to improve.

This compelling theory of the transition — and variants of it — has had a significant influence on the thinking of many archaeologists (see Flannery (1986) and Marcus and Flannery (1996) on the transition for the Oaxaca Valley in Mexico, Piperno (1989) on the Panamanian tropical forests, Smith (1995) on Central and South America, or Higham (1995) on Southeast Asia). But it also has it critics. Price and Gebauer, 1995, p.7 argue that population growth and environmental shocks are probably not sufficient to generate the kind of stress that sparked agriculture. McCorriston and Hole (1991), also studying the Jordan valley, add appropriate technology (ability to store food and other goods) and cultural or social developments to population pressure and a changed environment to the list of causal factors for the transition.[8]

We would also like to suggest some further considerations. A central element in the works of Bar-Yosef and his co-authors is sedentism. It is widely accepted that sedentism leads to population growth but in the theories above, increased population densities also caused increased sedentism and this, is much more open to debate. First there is no discussion of the possibility of population control and there is the well-known case of a transition in which population growth came only after increased sedentism (see Section 8.4 on the Tehuacan Valley in Mexico). Also, the central element in this work is environmental change, as it is the improving then worsening environment which leads to the increased population density which then leads to sedentism. A basic weakness of this explanation is that the quality of the environment is a cyclical variable. The environment at the end of the Pleistocene must be sufficiently unique in pre-history to generate the transition at that particular point and not earlier. It turns out that the warming trend was dramatic but it was likely not temporally unique, even in the last 135,000 years (see Renfrew and Bahn (2000) p.227 on the previous interglacial). Further it must not be too unique globally otherwise it would be inconsistent with the transition independently taking place in a number of diverse locations and environments

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[8] The environmental characteristic emphasized by these authors is extreme seasonality in the availability of resources rather than the longer term environmental trends of Bar-Yosef and his co-authors.

around the world at approximately the same point in prehistory.

We have no doubt that the "truth" about the transition is that it was caused by multiple factors, but we also point out that there is one variable which is not inherently cyclical (like the environment), which is not directly controllable (like population size), which is global in sweep and which was at it prehistoric highest level at end of the Pleistocene. It is what these people "knew", specifically, the state of their technology. The growth of technology can be explained by Foley's (1987) human evolution towards improved physical or cognitive abilities or by learning by doing with the knowledge passed down through the generations.[9] As noted above the state of stone technology was used to partition the Paleolithic.

3 The Early Holocene as a Breakdown of Community

We will not rely on environmental shocks and we will diverge from existing economic work on archaeological issues in which population pressure was a key factor (e.g. Brander and Taylor (1998), and to a lesser extent Locay (1989)) and assume that the population is fixed. We will also not rely on environmental change. At the heart of our approach will be technological growth.[10]

When an economist considers the Pleistocene the common property characteristic of the economic structure is evident. We will follow earlier economists and use a standard model of renewable resource for the foraging economy (section 6.2). But we will diverge from existing work, such as Smith (1975), and assume that foragers had the ability to organize themselves into cooperative communities (bands).[11] The purpose of the band in our model is to conserve and thus avoid over–exploitation of the environment. We first define a band (coalition) as a non–empty subset of the individuals and a band structure (coalition structure) as a partition of the set of individuals into

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[9] For a discussion of the increased degree of refinement in stone tool manufacture see Renfrew and Bahn (2000 p.319-320).

[10] Locay (1989) builds a model in which technological growth can lead to the transition from foraging to agriculture, but the mechanism that induces the transition in his analysis is very different from ours. His explanation is based on the relative intensity of land and labour in producing food under foraging and agriculture. Foraging being relatively intensive in land while agriculture is relatively intensive in labour, an increase in the productivity of agriculture, equivalent to making labour more abundant (less efficiency units of labour are required per unit of output), can lead to the transition from foraging to agriculture. Locay also points out that if, for some reason, the number of children increases before the transition, then the density of population increases, land becomes relatively more scarce, and the transition to agriculture becomes more likely.

[11] For this purpose, we use the model of coalition formation developed by Burbidge *et al.* (1997) which is strongly related to Hart and Kurz (1983). While we do not use the alternative model developed by Ray and Vohra (1997, 1999), we show in the working paper version of the current analysis (Marceau and Myers, 2000) that our primary results would obtain if we used their approach.

coalitions. We assume that to join a band is an individual's agreement to put its production decisions under the control of the band and to share the resources of the band equally. We assume that the decision to join the band and cooperate or to not join the band and compete is voluntary and rational (section 5).

Some preliminary results on the foraging economy are provided in section 6.3: 1) given the state of technology, cooperation is good for society; 2) cooperation becomes more important for society as technology improves; and 3) given the state of cooperation (i.e. the coalition structure), technology growth is good for society. Consider the third result in the case of the grand coalition. Because we assume foragers are well informed and can avoid waste (externalities) through cooperation, any technological improvements simply allow foragers to produce more from less and thus must be good for society. This result then implies that if we are to provide a theory which is consistent with the collapse of well-being during the early Holocene, with roots in technological improvements, it must come from a breakdown in cooperation. We also provide a simple model of agriculture, the primary difference between foraging and agriculture being the private nature of property under agriculture (section 6.1). Thus a band is associated with both a set of individuals and a mode of food production.

In our model individual participation decisions lead to an equilibrium band structure. Because mixed structures of both foraging and agricultural bands are feasible in our model, we must specify the interaction (externalities) between such groups. We assume that large bands of foragers impose a security cost on smaller bands of farmers (and foragers)[12] and that farmers through their employment of land in farming reduce the carrying capacity of the environment available to foragers.

In section 7 we provide our main results. At the lowest levels of technology we show that the unique equilibrium band structure is the grand band of foragers — cooperation of the whole. As technology grows, leisure, consumption, and thereby utility increase. But at a critical level of technology the cooperation structure breaks down through a splintering of the foraging band. The logic of this result is simple. The conservation undertaken by the grand band is like the provision of a public good. And we show that the incentive of a small band to break away and hunt at an individually rational level, while free riding on the conservation undertaken by the others, increases

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[12] That warfare was in the past a common practice is discussed in Harris (1977, chapters 4 and 5). Chagnon (1968) has documented the state of perpetual warfare of the Yanomanös, a group of modern foragers living in the forests along the border between Brazil and Venezuela.

with the state of technology.

To show how the collapse of the grand band of foragers can eventually lead to a transition from foraging to agriculture, a numerical example is presented. We show that at the critical state of technology at which the grand band of foragers is broken down, there is a catastrophic increase in work, decrease in consumption and through the over–exploitation of the environment, a food crisis.[13] Having explained the occurrence of a food crisis and a drop in utility for foragers, we then illustrate the switch from foraging to agriculture. As will be seen, the transitional period can involve mixed coalition structures of both foraging bands and agricultural bands and, in some cases, it can involve no equilibrium structure, which we interpret as transitory instability.

Possibly the best natural context for the application of our work is a geographically isolated territory which confines interaction to a fixed set of individuals or families. In our story, the whole of some given territory is initially exploited by a grand band and so, provided there is cooperation within the band, there is no over-exploitation of the environment. However, when a splintering of the grand band takes place, a number of smaller bands have to share the available space, each band occupying and exploiting a portion (sub-territory) of the initial territory. Thus, the emergence of defined sub-territories — the phenomenon of "territoriality" — occurs when the grand band splinters. As was mentioned above, and as is developed below, if the various bands act in a non-cooperative fashion, over-exploitation of the environment may then occur.[14]

The Anthropological literature is full of examples of such "closed" geographies: the Tehuacan Valley of Mexico (see Harris, 1977 p.23-25) or Easter Island (see Brander and Taylor, 1998). Both of these geographically isolated territories are heavily studied and provide examples of societies being hurt by environmental depletion. In Section 8, we discuss in details the case of the Tehuacan Valley of Mexico and we argue that the events which took place there between 12,000 BP and 5,400 BP are consistent with the theory we develop below.

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[13] What we mean by catastrophic is a discrete jump in the value of an endogenous variables due to a marginal change in an exogenous variable. In our model the food crisis does not lead to extinctions, but with very minor modifications of the open access model in section 6.2 the result could be extinction.

[14] In an influential paper, Dyson-Hudson and Smith (1977) develop the "economic defensibility model" which identifies (non-formally) the ecological circumstances (resource density and resource predictability) under which various types of territoriality emerge. Baker (2003) formalizes and improves this model. He argues that tenure regimes vary: boundaries may, in some cases, be imprecise, but in others, they may be clearly defined; the boundaries of territories may be aggressively protected while in other cases, they may be transgressed easily. Baker shows how different ecological conditions can explain the emergence of the various types of land tenure. However, neither Dyson-Hudson and Smith (1977) nor Baker (2003) do take into account the impact of land tenure on the environment, which is partly the focus of our paper.

In summary and at the risk of over–interpreting a rather simple model, our results are broadly consistent with the information discussed in the previous section. First, there is a one way transition from the foraging to the agriculture through a transitional period characterized by mixed economic structures and instability. The transition being driven by the well–documented technological growth with a drop in the well–being of individuals at the collapse due to a food crisis and over–exploitation of the environment.

4 An Overview of Band Formation

Throughout there will be two goods; food and leisure. We define C_i as consumption of food and Z_i the consumption of leisure by individual i. The individual has an endowment of time T which is divided between Z_i, labour L_i and enforcement or security effort M_i, so that the individual time constraint is $T = L_i + Z_i + M_i$. We will assume that the preferences for an individual are represented by a perfect substitutes utility function or

$$U(C_i, Z_i) = C_i + Z_i = C_i + T - L_i - M_i \tag{1}$$

The simplicity of this form will allow us to solve for all endogenous variables at equilibrium in closed form and to still bring out the primary qualitative conclusions.[15]

We begin with a set of identical individuals or $N = \{1, .., i, .., n\}$. We assume that individuals are a member of one and only one band and that bands are homogenous in their mode of production, thus an individual must be either a forager or a farmer.[16] A *coalition* of individuals (band) employing food production mode $f = A, H$ is defined as a nonempty subset of N denoted S_j^f, with A and H denoting agriculture and hunting-gathering, respectively. A *coalition structure* is defined as a partition of N and is denoted B and the set of all possible coalition structures is denoted $\mathbf{B}$. We denote the set of farming bands in B as $B^A = \{S_1^A, ..S_j^A, .., S_{m'}^A\}$ and denote the set of foraging bands in B as $B^H = \{S_1^H, ..S_j^H, .., S_{m''}^H\}$. So $B = B^A \cup B^H$.

We assume that to join a band is an individual's agreement to put its labour supply decision under the control of the band leader and to share the food resources of the band according to the band's sharing rule. The labour supplied for food production and security and food consumed in

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[15] A numerical example for Cobb–Douglas preferences is available upon request (see also footnote 31).

[16] While there is some justification for this strong assumption, it is made for simplicity. Our model of homogeneous individuals does not allow for phenomena such as sex-based labour specialization within a band or the gradual transition of a given band from foraging to farming.

aggregate by a coalition S_j^f in B is denoted by $L_{S_j^f}(B)$ and $C_{S_j^f}(B)$ respectively. The dependence of these on B, not just S_j^f, allows for externalities across coalitions in a coalitional structure. For example, the labour supplied by one foraging band may affect what is feasible for another band. The labour supplied and the consumption of an individual $i \in S_j^f \in B$ is denoted $L_i^f(B)$ and $C_i^f(B)$. We have assumed that individuals are economically indistinguishable in terms of endowments and preferences so we will assume that the band sharing rule is to divide work and food equally amongst members or $L_i^f(B) \equiv L_{S_j^f}(B)/\left|S_j^f\right|$ and $C_i^f(B) \equiv C_{S_j^f}(B)/\left|S_j^f\right|$ where $\left|S_j^f\right|$ is the cardinality of the set S_j^f.[17]

There are two stages in the overall game: the band–formation stage; and the band–competition stage. In the second stage bands are already in place. We assume that the decisions of a band are coordinated by its leader to cooperatively maximize the total utility of the band; $U_{S_j^f}(B) = C_{S_j^f}(B) + \left|S_j^f\right| T - L_{S_j^f}(B) - M_{S_j^f}(B)$. The underlying economies involve strategic interaction so we will assume that the play across bands is non–cooperative. Thus at the second stage, members of each band cooperatively play a game in strategic form against other bands to maximize $U_{S_j^f}(B)$ yielding an equilibrium $U^*_{S_j^f}(B)$ for the second stage, which is then allocated to $i \in S_j^f$ by the equal division rule yielding $U_i^{f*}(B) = C_{S_j^f}(B)/\left|S_j^f\right| + T - L_{S_j^f}(B)/\left|S_j^f\right| - M_{S_j^f}(B)/\left|S_j^f\right|$.[18]

Looking ahead to that stage from the first stage, each individual will have a set of preferences (payoffs) over all possible coalition structures, $U_i^{f*}(B)$ for all $B \in \mathbf{B}$. Based on these preferences self–interested individuals in the band formation stage form coalitions which lead to a coalition structure and thus a payoff for each player i, $U_i^*(B)$

We now proceed with the formal description of the two stages starting with the first.

5 The Band Formation Stage

We start with the set of individuals N and model how these players acting in their own self interest, might choose to align themselves into bands. The approach we will follow is a modification of the approach which can be found in Burbidge *et. al.* (1997, section V).

With cognizance of the band competition stage the players know $U_i^{f*}(B)$ for all $B \in \mathbf{B}$, that

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[17] As noted in the introduction food sharing is often considered a defining characteristic of hunting and gathering bands. Further as we will explain below it will turn out that our primary results are independent of a specific sharing rule.

[18] The superscript f in $U_i^{f*}(B)$ is actually redundant, because once i and B are identified, $S_j^f \ni i$ is identified and thus the mode of production employed by i is identified. But we will include the superscript to improve clarity.

is, they would have a preference ordering over all possible coalition structures, $\mathbf{B}$. We use these preference orderings to construct a game in strategic form for this stage.

We view the group of individuals engaging in non–binding pre–play communication during which possible options for coalition formation are weighed and potential partners sought. Eventually, each player comes to formulate a plan for joining a set of partners. A *strategy* of player i will be identified with a *partnership plan* for player i: it is a choice of a mode of production and a coalition to which i wants to belong.[19] Formally, a strategy for player i is a mode of production $f_i = A, H$ and a subset of N or $S_i^{f_i}$ with $i \in S_i^{f_i}$. A combination of choices of participation plans or strategies (one for each player), $s = (S_1^{f_1}, ..., S_i^{f_i}, ..., S_n^{f_n})$, will be referred to as a *profile of partnership plans* or a *strategy profile.* The set of all partnership plans for player i will be denoted by $\mathbf{S}_i$; $\mathbf{S} = \times_{i \in N} \mathbf{S}_i$ will stand for the set of all profiles of partnership plans.

How any given profile of partnership plans $s \in \mathbf{S}$ gets reconciled into a resultant coalition structure is summarized by a function, $\psi : \mathbf{S} \to \mathbf{B}$ that assigns to any $s \in \mathbf{S}$ a unique coalition structure $B = \psi(s)$. We call the function ψ the *coalition structure rule.* Informally, the rule ψ is meant to capture the players' expectations, assumed to be commonly held and correct. The question, then, is: what is a sensible modeling choice for the function ψ in the context of our band formation game? In Burbidge *et. al.* (1997) a rather wide class of rules and two specific rules within that class are discussed. But in this paper we will focus on one of the two rules labeled the *similarity* rule by Burbidge *et. al.* (1997).[20] It is the rule which seems best suited to an application of band formation as we will explain below.

First, given any $i \in N$ and $s \in \mathbf{S}$, let $\psi_i(s)$ denote the coalition to which i belongs in the coalition structure $\psi(s)$ resulting from the profile s.

Call the coalition structure rule $\widehat{\psi} : \mathbf{S} \to \mathbf{B}$ the *similarity rule* if for any strategy profile $s \in \mathbf{S}$, and any $i \in N$, we have:

$$\widehat{\psi}_i(s) = \{j \in N \mid S_i^{f_i} = S_j^{f_j}\}$$

Thus under the similarity rule if two or more players have the same partnership plan those players are assigned into the same coalition. If a player does not share a plan with any other agent that player is alone. In effect we are interpreting a player's partnership plan as a mode of

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[19] The modification of Burbidge *et al.* (1997) is that a partnership plan for i was simply a coalition to which i wanted to belong. There was no choice over modes of production.

[20] The rule corresponds to the δ model in Hart and Kurz (1983).

production and the largest set of partners it is willing to be associated with in a coalition.[21]

We now have a well–defined game in strategic form. The coalitional players are the set N of individuals; the set of strategies available to each player $i \in N$ consists of all possible partnership plans, $\mathbf{S}_i$; every strategy profile s induces a coalition structure $\widehat{\psi}(s) = \{S_1^A, ..., S_{m'}^A, S_1^H, ..., S_{m''}^H\}$ through the similarity rule, and thus a payoff for each player $i \in N$ of $U_i^{f*}(\widehat{\psi}(s))$. We call the game at this stage the *band formation game.*

We want to identify a coalition structure B as an "equilibrium" structure if $B = \widehat{\psi}(s)$ for an "equilibrium" strategy profile s for the band formation game. Within our framework, an attractive solution concept is that of coalition proof Nash equilibrium (CPE), due to Bernheim, Peleg and Whinston (1987). Roughly, a strategy profile is coalition proof if no set of players, taking the strategies of its complement as fixed, can fashion a profitable deviation for each of its members that is itself immune to further deviations by subsets of the deviating coalition. We refer the reader to the original article for a formal definition. Because the set of CPE is a subset of the set of NE, it should be noted that any CPE is a NE.

To summarize, we call a coalition structure B a CPE *equilibrium coalition structure* or *equilibrium outcome* if $B = \widehat{\psi}(s)$ for a CPE strategy profile s for the band formation game.

6 The Band Competition Stage

At this second stage the coalition or band structure is already given. Given B, we will now layout the underlying economies for agriculture and foraging, and their interrelationships. We are working towards $U_i^{f*}(B)$ for all $B \in \mathbf{B}$. We begin with the simpler agricultural model.

6.1 Agricultural Model

We assume that the farming activities of one farmer has no impact on the payoff of other farmers, whether those other farmers are members of the same band or not. This implies that there is no gain to farmers cooperating in their production decisions through forming a band. Thus we assume that a farmer makes his own production decisions. The sole purpose of joining a band for

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[21] This allows a player to exclude any other set of players by not having those players in their plan. Further, there will be a unique s which leads to the formation of the grand coalition engaged in a mode of production — the s given by $S_i^{f_i} = N^{f_i}$ and $f_h = f_i$ for all $h, i \in N$, which we denote s^{fN}. To assume otherwise would be to assume that a grand coalition could form without unanimous consent. See Burbidge *et al.* (1997) for further discussion of this rule.

a farmer is sharing security costs.[22] We will allow for the possibility that farmers face a security cost associated with the existence of individuals outside of their community who pose a security threat. We assume the security cost of the agricultural band S_j^A is in terms of time and is denoted as $M_{S_j^A}(B)$. We will assume that all members of a farming band equally share the security cost of the band.

Agricultural output is produced according to technology $\phi f(l_i, E_i)$, with positive but decreasing marginal products, and where ϕ is an agricultural technological parameter, l_i is the time spent by individual i in the fields, and E_i is the amount of land farmed. Agricultural land is freely available but has to be improved at a labour cost which we assume to be an increasing and weakly convex function of the amount of land employed, $m(E_i)$, with $m'(E_i) > 0$ and $m''(E_i) \geq 0$. So the individual's labour supply in producing food is $L_i = l_i + m(E_i)$. Thus individual $i \in S_j^A \in B^A$, solves the following problem:

$$\max_{l_i, E_i} C_i + Z_i \text{ subject to } C_i = \phi f(l_i, E_i) \text{ and } Z_i + l_i + m(E_i) + M_{S_j^A}(B)/|S_j^A| = T$$

Solving this problem yields a labour supply and a demand for land given by $l_i(\phi)$ and $E_i(\phi)$, respectively.[23] These then can be used to yield a solution for utility as a function of ϕ and through the security cost, a function of B,[24]

$$U_i^{A*}(B) = \phi f(l_i(\phi), E_i(\phi)) + T - l_i(\phi) - m(E_i(\phi)) - M_{S_j^A}(B)/|S_j^A| \tag{2}$$

The simplicity of the agricultural model yields a great deal of tractability which will be useful in comparison to the more complicated foraging model. In modeling foraging we will assume the use of land in agriculture has an adverse effect on the carrying capacity of the environment. Specifically the carrying capacity of the environment available for foraging is reduced by the use of land in agriculture.[25] Let $\bar{K}$ be the carrying capacity in the absence of agriculture. Then we assume

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[22] Agriculture generates many possibilities for rational cooperation through the formation of a community other than security. For example, large community projects like the provision of irrigation infrastructure or a grain grinding facilities. In fact, some have argued that these projects provided the genesis of the pristine state. But our focus here is on the transition from hunting and gathering to the *earliest* agriculture. Thus we will focus on providing a more complete model for foraging and use a bare bones model for agricultural. The fundamental contrast between foraging and agriculture which we will emphasize is the private property nature of production in the latter.

[23] Note that a leader of band S_j^A choosing l_i and E_i for all $i \in S_j^A$ to maximize the sum of utilities of all $i \in S_j^A$ and given the equal sharing rule would also yield the same optimal choices. This simply reflects the point that there is no gains from the cooperation for farmers other than through the sharing of security costs.

[24] In the numerical example presented in Section 7, we choose functional forms for $f(\cdot)$ and $m(\cdot)$.

[25] See Tudge (1998) for a discussion of this interaction.

the available carrying capacity, $K(B)$, is given by $K(B) = \bar{K} - \lambda F(B)$, where $F(B)$ is the total amount of land employed in agriculture and $\lambda \geq 0$ is a parameter that measures the severity of the externality. Note that below, we interpret a change in $\bar{K}$ as an environmental shock. In our model each farmer employs $E_i(\phi)$ which is independent of B. This implies that $F(B) = E_i(\phi) \sum_{S_h^A \in B} |S_h^A|$, where $\sum_{S_h^A \in B} |S_h^A|$ is the total number of farmers in the coalition structure B. This yields

$$K(B) = \bar{K} - \lambda E_i(\phi) \sum_{S_h^A \in B} |S_h^A| \tag{3}$$

6.2 The Foraging Model

The bands in B^H share a stock of animals (or plants) at time t, $X(t)$ which we assume follows a logistic form or[26]

$$X(t) = \frac{K(B)}{1 + ke^{-\gamma t}}$$

where γ is the intrinsic growth rate and $k \equiv (K(B) - X(0))/X(0)$. This gives a natural growth rate of the stock of

$$\frac{dX(t)}{dt} \equiv g(X) = \gamma \left[1 - \frac{X}{K(B)}\right] X$$

The graph of $g(X)$ against X is described by $g(0) = 0$ and $g(K(B)) = 0$ (growth of the stock is zero at $X = K(B)$ — the environment is too crowded) and the maximizer for $g(X)$ at $X = K(B)/2$ — this point is called maximum sustainable yield.[27]

The band S_j^H combines labour with the stock to produce food

$$C_{S_j^H}(B) = \theta L_{S_j^H}(B) X$$

the catch per unit of effort being proportional to the stock. Parameter θ reflects the state of the foraging technology. Then the total harvest is

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[26] It should be noted that X through its dependence on $K(B)$ is also a function of the coalition structure B. But at this second stage B is given. So we do not include it explicitly. We explicitly write K as a function of B because K will appear in the closed form for U_i^{H*}. We will follow this convention throughout.

[27] The archaeological record involve the extinction of some animals and more generally a food crisis at the time of transition. Our model can be easily extended to allow for extinction by using a modified logistic function which gives $g(X) = \gamma[1 - \frac{X}{K}]X^{\alpha}$ which is logistic for $\alpha = 1$ but for $\alpha > 1$ has $g''(X) > 0$ at low enough X. When cooperation will break down, our model will involve a fall in the stock of animals (i.e. food crisis) and this could involve extinction with $\alpha > 1$.

$$C^H(B) = \sum_{S_j^H \in B^H} C_{S_j^H}(B) = \sum_{S_j^H \in B^H} \theta L_{S_j^H}(B) X = \theta L^H(B) X \text{ where } L^H(B) = \sum_{S_j^H \in B^H} L_{S_j^H}(B)$$

So the growth of the stock with foraging is

$$\overset{\bullet}{X} = g(X) - C^H(B)$$

The biometric equilibrium, or steady state, is where these are in balance or $\overset{\bullet}{X} = 0$ and using the logistic then

$$\gamma \left[1 - \frac{X^e}{K(B)}\right] X^e - \theta L^H(B) X^e = 0$$

or

$$X^e = \left(1 - \frac{\theta L^H(B)}{\gamma}\right) K(B) \tag{4}$$

where X^e is the biometric equilibrium stock as a function of $L^H(B)$ (from now, we drop the superscript e). And the catch for any band in biometric equilibrium is

$$C_{S_j^H}(B) = \theta L_{S_j^H}(B) \left(1 - \frac{\theta L^H(B)}{\gamma}\right) K(B) \tag{5}$$

Notice the externality associated with common access entering through $L^H(B)$. This provides the benefit of cooperation for foragers through the formation of cooperative communities. Further

$$\frac{dC_{S_j^H}(B)}{dL_{S_j^H}(B)} = \theta \left(1 - \frac{\theta L^H(B)}{\gamma} - \frac{\theta L_{S_j^H}(B)}{\gamma}\right) K(B) \text{ and } \frac{d^2 C_{S_j^H}(B)}{d(L_{S_j^H}(B))^2} = -2\theta^2 K(B)/\gamma < 0 \tag{6}$$

So the graph of $C_{S_j^H}(B)$ is described by $C_{S_j^H}(B) = 0$ at $L_{S_j^H}(B) = 0$, $C_{S_j^H}(B)$ maximized at $L_{S_j^H}^{Max}(B) = \gamma/2\theta - \sum_{h \neq j} L_{S_h^H}(B)/2$, and $C_{S_j^H}(B) = 0$ again at $L_{S_j^H}(B) = 2L_{S_j^H}^{Max}(B)$. The feasible space is strictly convex.

Given the perfect substitutes assumption and (6) a necessary condition for $dC_{S_j^H}(B)/dL_{S_j^H}(B) > 1$ at $L_{S_j^H}(B) = 0$, that is a positive labour supply, is $\theta K(B) > 1$. We will take care to choose $\overline{K}$ sufficiently large to satisfy this requirement throughout.

To maximize total utility the band leader sets $dC_{S_j^H}(B)/dL_{S_j^H}(B) = 1$. This yields a best response of[28]

$$L^*_{S_j^H}(B) = I(B) - \sum_{S_h^H \in B^H \backslash S_j^H} \frac{L_{S_h^H}(B)}{2}$$

where the summary parameter $I(B) = [\gamma(\theta K(B) - 1)]/[2\theta^2 K(B)]$. By $\theta K(B) - 1 > 0$, the intercept $I(B) > 0$ and the slope of the graph of $L^*_{S_j^H}(B)$ with respect to $L_{S_h^H}(B)$ is negative so there is a unique Nash equilibrium. Notice that the best responses are symmetric in bands which then allows us to solve for the Nash equilibrium labour supply as

$$L^*_{S_j^H}(B) = \frac{2I(B)}{1 + |B^H|}$$

Using the equal sharing rule, the time constraint (1), (4), and (5) we can solve for the all endogenous variables at the band competition equilibrium.

$$\begin{aligned}
L_i^{H*}(B) &= \frac{2I(B)}{\left|S_j^H\right| [1 + |B^H|]} \qquad (7)\\
L^{H*}(B) &= \frac{2I(B)\left|B^H\right|}{1 + |B^H|}\\
X^{H*}(B) &= \left[1 - \frac{2\theta\left|B^H\right| I(B)}{\gamma[1 + |B^H|]}\right] K(B)\\
C_i^{H*}(B) &= \theta\left[\frac{2I(B)}{\left|S_j^H\right| [1 + |B^H|]}\right]\left[1 - \frac{2\theta\left|B^H\right| I(B)}{\gamma[1 + |B^H|]}\right] K(B)\\
Z_i^{H*}(B) &= T - \frac{2TI(B)}{\left|S_j^H\right| [1 + |B^H|]} - \frac{M_{S_j^H}(B)}{\left|S_j^H\right|}\\
U_i^{H*}(B) &= T + \frac{2I(B)[\theta K(B) - 1]}{[1 + |B^H|]^2\left|S_j^H\right|} - \frac{M_{S_j^H}(B)}{\left|S_j^H\right|}
\end{aligned}$$

where the last equation was simplified using the definition of $I(B)$. With (2) and (7) we now have a solution for $U_i^{f*}(B)$ for all $B \in \mathbf{B}$ and thus $f = A, H$.

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[28] Note that the second order condition is satisfied and that the same first order condition is implied by the band leader choosing $L_{S_j^H}(B)$ or $L_i(B)$ for all $i \in S_j^H$ separately.

6.3 Some Preliminary Results for a Foraging Economy

Before working to determine an equilibrium coalition structure, we will provide some preliminary results on the relationship between the well–being in a foraging society, technological growth and cooperation. Here, to focus on a foraging society (the Pleistocene) we assume $B^A = \emptyset$. Then $B^H = B$, $S_j^f = S_j^H$, and $K(B) = \overline{K}$ so we denote $S_j^H = S_j$ for simplicity.

First, the total utility for all individuals in a band S_j

$$TU^*_{S_j}(B) = \sum_{i \in S_j} U_i^*(B) = |S_j|\, T + \frac{2I(B)[\theta K(B) - 1]}{[1 + |B|]^2} - M_{S_j}(B)$$

and then the total utility for all individuals in a coalition structure

$$TU^*(B) = \sum_{S_j \in B} TU^*_{S_j}(B) = |N|\, T + \frac{2\,|B|\, I(B)[\theta K(B) - 1]}{[1 + |B|]^2} - \sum_{S_j \in B} M_{S_j}(B) \tag{8}$$

Below we will argue that a reasonable specification for $M_{S_j}(B)$ would involve there being non–zero security costs at least for bands which are non-maximal in the coalition structure (i.e. bands which run the risk of running into larger bands of competitors carrying lethal weapons). Thus we will argue that a cost of non–cooperative societies with more than one band is the security cost, but for now we assume that $M_{S_j}(B) = 0$ for all $S_j \in B$ and for all $B \in \mathbf{B}$.

Because the act of joining a band is choosing to cooperate with other individuals we will assume that forming larger bands implies a more cooperative society, specifically, we define a more cooperative society to be one with a smaller $|B|$. The extreme examples are the grand coalition $B = \{N\}$ with $|B| = 1$ where everyone chooses to cooperate and the singleton coalition $B = \{\{1\}, \{2\}, \ldots, \{n\}\}$ with $|B| = |N|$ where everyone is non–cooperative.

The first observation arises from the environmental externalities.

Observation 1: *For any given level of technology θ, cooperation is good for the foraging society.*

Using (8), the total utility gap between two coalitions structures B' and B'' which differ by $|B'| - |B''| < 0$ so that B' is more cooperative

$$TU^*(B') - TU^*(B'') = \frac{2I(B)[\theta K(B) - 1]}{[1 + |B'|]^2\,[1 + |B''|]^2}\left[|B'| - |B''|\right]\left[1 - |B'|\,|B''|\right] > 0 \tag{9}$$

When $B' = \{N\}$ for example this result reflects the fact that only in the grand band will there be efficient labour supply decisions (all externalities are internalized). That the grand band dominates other coalition structures, in this sense, would simply be reinforced by introducing non–zero $M_{S_j}(B)$, as long as one were to make the reasonable assumption that security costs would be less in the grand band than for other coalition structures as there are simply no competitors in that structure.

Because an improvement in technology allows more consumption with no decrease in leisure, one would expect that technological growth is good for a society.

Observation 2: *For any given degree of cooperation (i.e. given a coalition structure) an increase in technology is good for the foraging society.*

The derivative of $TU^*(B)$ from (8) with respect to θ is positive.

This result implies that if we are to provide a theory of the collapse in well being during the Early Holocene with roots in technological improvements, it must come from a change in coalition structure that leads to a finer coalition structure, that is, less cooperation

Observation 3: *As technology increases cooperation becomes more important for society.*

The derivative of $TU^*(B') - TU^*(B'')$ from (9) with respect to θ is positive. Thus the importance to a society of cooperative behaviour grows with technology

But as we shall see below these positive observations about cooperation and technological growth do not preclude the possibility that technological growth can lead to a potentially catastrophic (in the mathematical sense) deterioration in the well–being of a society. Technological growth can lead to a splintering of a foraging community and thus a breakdown of cooperation.

7 Equilibrium Transitions

Our approach to the transition from foraging to agriculture will be based on the exogenous technological growth over time. Each production mode is characterized by a technological parameter: θ for foraging and ϕ for agriculture. These are modeling choices. For example, it would be possible to assume starting values such that the initial equilibrium state is agriculture. Because we want our model to be consistent with the fact that the world started with a pure foraging economy, we begin with an assumption.

A.1: In the earliest of times (low enough $\theta > 1/K(B)$) agriculture is simply not viable.

This could be formalized by assuming that for low enough $\theta > 1/K(B)$, $\phi = 0$ in which case, no agricultural production will take place.[29]

But eventually, we think it is natural to assume that improvements in the foraging technology spill over as improvements in the agricultural technology. Note that there are stages in either production process which are similar, for example, the butchering of a carcass or the grinding of grains. Thus the development of very sharp blades for butchering during the upper Pleistocene, clearly was an important positive technological development for agriculture. Formally, we will assume that there is some $\theta > 1/K(B)$ denoted $\overline{\theta}$, where agriculture becomes viable (e.g. ϕ becomes positive). From then on, we assume that the relationship $\phi(\theta)$ is strictly increasing.[30] Also note that for $\theta < \overline{\theta}$, $K(B) = \overline{K}$ and $I(B) = I$, or there is no damage to the carrying capacity due to farming until farming is viable.

We have structured the model so that agriculture is not a viable alternative initially, but that leaves the question as to what is the initial equilibrium coalition structure for foraging. In what follows, the specification of security costs will be important. For both foraging and agriculture, it seems natural to assume that security costs are lower for the grand band than for bands in other coalition structures (where there are competitors). Given this, $M_{S_j^f}(B)$ is the cost of running into a group of competitors with lethal weapons.[31]

Proposition 1: *For A.1, any* λ, $(M_{S_j^f}(B)/|S_j^f|)\ -(M_{N^H}/|N^H|) > 0$ *for any* $S_j^f \neq N^H$*, and for sufficiently low* $\theta > 1/\overline{K}$*, the unique CPE is* s^{HN} *and thus the unique equilibrium band structure in the earliest of times is the grand band of foragers* $B = \widehat{\psi}(s^{HN}) = \{N^H\}$.

Proof: See Appendix 1.

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[29] This assumption really is one of convenience in the sense that it is not necessarily required for any of our propositions 1 and 2 below. The proof of this is that in the example which we provide below we simply assume that at time zero $\theta = 1/K(B)$ and $\phi = 0$, so that both begin on the verge of viability, and then allow for θ and ϕ to grow equally quickly over time (perfect technological spillovers). We then provide results for the example which are perfectly consistent with propositions 1 and 2.

[30] Alternatively, we could have endogenized technological growth by assuming, for example, that mode f technology grows faster when more individuals use it. But this would have complicated the analysis without changing the flavour of our results. Indeed, in what follows, foraging is eventually replaced by agriculture precisely because it has become too productive (not because agriculture has grown at a faster rate), thereby making cooperation in foraging untenable. If our model was to account for endogenous technological growth, it would be possible to discuss the speed at which the transition takes place, but it would not change the basic rationale underlying the transition. It should also be noted that we do need anything specific for technological growth (e.g. constant rate of growth or discontinuities) only that it grows over time.

[31] A security cost is *not necessary* for propositions 1 and 2 to obtain. Indeed, in a 3-player example in which preferences are Cobb-Douglas (available upon request), the grand band of foragers may break down in the absence of security costs. The splintering takes place because the payoff of an individual going solo comes to dominate what he obtains within the grand band. Hence, at the critical technology level, the grand band is replaced as the equilibrium outcome by another structure.

We next consider the consequences of technology growth in foraging for the equilibrium coalition structure.

Proposition 2: *For any* λ, $N > 2$, *and for sufficiently high* $\theta > 1/\overline{K}$, s^{HN} *is not a CPE and thus the grand band of foragers,* $\widehat{\psi}(s^{HN}) = \{N^H\}$ *is not an equilibrium outcome. As technology increases beyond a critical point there is a breakdown of cooperation due to a splintering of the foraging band structure.*

Proof: See Appendix 1.

We define $\underline{\theta}$ as the critical level of technology at which the breakdown occurs. It is fully determined in Appendix 1.

One might wonder to what extent this result is due to the equal sharing rule within bands.

Observation 4: *For any* λ, $N > 2$, and for $\theta > \underline{\theta}$, *there is no way to divide the resources of the grand band of foragers to make it a CPE equilibrium band structure.*

Proof: See Appendix 1.

The intuition for the splintering is strong. The conservation undertaken by the grand band is like the provision of a public good. Now imagine a player in the grand band as technology improves. The value of a unilateral deviation by the individual is that by breaking away, he no longer is required to conserve — he can hunt to an individually rational level and free ride on the conservation done by the others. The costs of deviation are that the others may not do as much conservation, now that they compete with the deviator, and the cost of being expelled from the band which we model as a security cost. As technology improves and labour becomes more productive, the cost of the conservation (i.e. the loss in consumption from restricting your labour supply) increases but the security cost remains constant. That is, at some point the value of free riding comes to dominate even a very severe security cost and cooperation breaks down.[32] To summarize, the driving force behind the splintering is that the difference in the payoffs from a unilateral deviation and from cooperating grows with technology. As long as this difference grows faster than the security costs (which were assumed constant here), the splintering will take place.[33]

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[32] There are alternative ways to model the cost of going it alone. One is a shunning cost, but another alternative is a reduced potential for risk sharing. Risk sharing is discussed extensively in Johnson and Earle (1987). The foraging economy is obviously one characterized by a great deal of risk. The grand band provided opportunities for risk sharing which are lost in going it alone. It may be that technological growth reduces the need for risk sharing.

[33] If security costs are falling with technology, the splintering will obviously take place. In the case where security costs grow with technology, the splintering will take place provided that they grow at a slower rate than the difference

In our framework, the impact of an environmental shock, i.e. that of a change in $\bar{K}$, has an unexpected impact.

Observation 5: *A society hit by a favorable (resp. adverse) environmental shock, i.e. an increase in carrying capacity, will experience earlier (resp. later) the breakdown of cooperation due to the splintering of the foraging band structure.*

Proof: See Appendix 1.

The intuition for this result is the same as that just presented for the splintering. A favorable environmental shock increases the cost of conservation while the security cost remains constant. Since for any technology level, the payoff from deviating is larger, the level of technology at which the breakdown takes place is lower. Note that this result is in sharp contrast with the orginal environmental theories of the transition which usually argued that an exogenous and adverse environmental shock explains the transition to agriculture.

The breakdown in cooperation can lead to unfortunate consequences.

Corollary: *If the breakdown in the cooperative structure happens at a state of technology where agriculture is not yet viable, for example,* $\underline{\theta} < \overline{\theta}$, *then one of two things happen; either there is instability (in the sense of there being no CPE equilibrium coalition structure) or there is an equilibrium coalition structure other than the grand band and the collapse of the grand band involves a catastrophic (discontinuous) increase in work and decrease in the stock of animals, that is, instability and/or a potential food crisis.*

To verify that there must be a discontinuous adjustment in terms of work and the animal stock in moving away from the grand band at the critical technology, see (7).

We now turn to an illustrative example. In this example, there is a discontinuous transition from the grand band to the singleton band structure at $\theta = \underline{\theta}$. This leads to over exploitation of the environment, a resultant drop in the foraging stock and thus a food crisis, and a drop in leisure, in consumption, and thus in utility for each individual. Of course, the drop in utility accompanying the breakdown of the grand band to a singleton band structure may itself trigger a further transition, that from foraging to agriculture. This is also illustrated in our example.

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in the payoffs from deviating and cooperating. Note that security costs can be interpreted as the difference in the effectiveness of offensive and defensive weapons. The effectiveness of weapons has certainly been affected by technology throughout history. Hirshleifer (1995, p.44–46) discusses the effectiveness of weapons. He provides historical examples in which the effectiveness of offensive weapons relative to defensive weapons has increased, and others in which it has decreased.

Thus, suppose that:

- $\phi f(l_i, E_i) = \phi l_i^{1/2} E_i^{1/2}$;
- $m(E_i) = E_i^2/2$ so that $L_i = l_i + E_i^2/2$;
- $N = \{1, 2, 3\}$;
- $T = 24$;[34]
- $\overline{K} = 10$;
- $\gamma = 1$;
- $M_{\{i\}^f}(\{\{i\}^f, \{h, k\}^H\}) = 0.225$ for $f = A, H$ and $M_{S_j^f}(B) = 0$ otherwise;
- $\phi = \theta - 1/\overline{K}$.

This last assumption implies that in the earliest of times, both technologies begin on the verge of viability and grow one for one over time (perfect technological spillovers). This is weaker than Assumption A.1 because both technologies are initially equally viable. Because it is weaker, we cannot simply rely on the proofs of the above results. The results that we report below therefore required their specific proofs. These can be consulted in an appendix available upon request.

Under the above assumptions, we can show that for any level of the externality $\lambda \geq 0$, and despite the viability of agriculture, the unique CPE for the lowest levels of technology ($0.1 < \theta < 1$) is the grand band of foragers. We can also show that for higher levels of technology ($1 < \theta < 2.165$), the grand band of foragers is no longer a CPE band structure and the singleton forager band structure, $B = \{\{1\}^H, \{2\}^H, \{3\}^H\}$, is a CPE band structure. Thus, at $\theta = 1$, there is a breakdown of cooperation due to a splintering of the foraging band structure and a transition to a new structure where everyone is worse off. The transition involves over–hunting which leads to a food crisis. In this example, the $\underline{\theta}$ of the previous section is precisely unity which explains why the grand band breaks down at that point. What happens at higher levels of technology ($\theta > 2.165$) however depends on the externality parameter λ. The equilibrium outcomes for four levels of the externality parameter are presented in Table 1.

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[34] The choice of T was simply to ensure $Z > 0$.

Table 1: Equilibrium Outcomes

	Pure Foraging, Grand Band	Pure Foraging, Singleton Bands	Instability, No CPE	Mix of Foraging and Farming	Pure Farming
$\lambda = 0$	Yes $0.1 < \theta < 1$	Yes $1 < \theta < 2.165$	Yes $2.165 < \theta < 2.492$	Yes $2.492 < \theta < 3.042$	Yes $\theta > 3.042$
$\lambda = 1$	Yes $0.1 < \theta < 1$	Yes $1 < \theta < 2.165$	Yes $2.165 < \theta < 2.399$	Yes $2.399 < \theta < 2.716$	Yes $\theta > 2.716$
$\lambda = 3.5$	Yes $0.1 < \theta < 1$	Yes $1 < \theta < 2.165$	No	Yes $2.165 < \theta < 2.185$	Yes $\theta > 2.185$
$\lambda = 5$	Yes $0.1 < \theta < 1$	Yes $1 < \theta < 2.165$	No	No	Yes $\theta > 2.165$

For the case where there is no externality ($\lambda = 0$), further advances in knowledge ($2.165 < \theta < 2.492$) are associated with a time of instability. At this level of knowledge, no coalition structure satisfies the requirements of a CPE. Later, when knowledge has developed further ($2.492 < \theta < 3.042$), we observe the start of agriculture: agriculture is adopted by two individuals while an individual remains a forager. Note that farmers may or may not be members of the same band. Eventually, when knowledge continues to improve ($\theta > 3.042$), everyone has turned to agriculture.

Starting from no externality, an increase in the externality parameter λ (to $\lambda = 1$) simply shrinks the intervals of θ for which there is instability (no CPE) and that for which there are mixed coalition structures. For intermediate value of the externality parameter ($\lambda = 3.5$), the mixed structures have disappeared but the Unstable – No CPE region still exists. Finally, when the externality parameter is large enough ($\lambda = 5$), these intervals have simply disappeared and the transition is direct from pure foraging to pure farming. This makes sense since the impact of an increase in the externality parameter is to reduce the payoff of foraging when other individuals are farming. An interesting and slightly different point to note is that the transition to pure farming occurs at lower levels of technology when the externality is strong.

Thus, depending on the size of the negative externality imposed by farming on foraging, there may or may not be instability and the co-existence of foraging and farming. We interpret this result as showing, realistically, that there would be no unique path from foraging to agriculture during the Early Holocene.

8 The Tehuacan Valley in Mexico

As empirical support for our theory, we now review some of the evidence concerning the transition from foraging to agriculture that took place in the Tehuacan Valley in Mexico between 12,000 BP and 5,400 BP. The valley lies in Southeastern Mexico in a structural trench formed by its position between a branch of the Sierra de Oaxaca and a branch of the Sierra de Mixteca. The mountains create a rain shadow and consequently a cloud forest at the crest of mountains and a hot dry climate in the valley. The arid environment in the valley was ideal for preservation of the artifacts left by the millennia of valley inhabitants who exploited the varied food resources of this diverse environment. This valley has been extensively studied. The evidence reported here is taken from the findings of the Tehuacan Archaeological-Botanical Project (1961–1964), led by Richard MacNeish, which were published in *The Prehistory of the Tehuacan Valley*, a five volume set edited by Douglas S. Byers and published between 1967 and 1972.[35] We believe this valley provides a suitable environment for the evaluation of the potential empirical relevance of our theory because a well-documented archaeological record exists which begins with foraging and ends with agriculture. It is also helpful that the valley consists of a relatively closed geography.

Our model predicts that at the lowest levels of technology, a population will form a single community of non-sedentary and cooperative (non-territorial) foragers enjoying a reasonable standard of living. At a critical level of technology, we predict that incentives will change and result in the cooperative structure splintering and the introduction of multiple non-cooperative bands of foragers. So evidence for the non-cooperation present in our model would be territoriality, resource depletion, and a lower standard of living.

The archaeological record in the Tehuacan valley has been broken into nine cultural phases beginning with the first records of human inhabitation approximately 12,000 years ago and ending about 500 years ago with the Spanish Conquest. The first three phases which cover over half of the period are of direct relevance to our work. They are: the Ajuereado (12,000 BP – 9,000 BP); El Reigo (9,000 BP – 7,000 BP); and Coxcatlan (7,000 BP – 5,400 BP). The mode of food production

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[35] The five volumes of *The Prehistory of the Tehuacan Valley* are as follows. Volume 1: Environment and subsistence; Volume 2: Nonceramic artifacts; Volume 3: Ceramics; Volume 4: Chronology and irrigation; and Volume 5: Excavations and reconnaissance.

in the former period is exclusively foraging and in the latter is a mixture of foraging and agriculture. The partitioning into phases was on the basis of the appearance of new artifacts (e.g. tools) within a class and whole new classes of artifacts at specified points in time.[36]

8.1 Ajuereado (12,000 BP – 9,000 BP)

During this period of at least three millennia, the high-end estimate for population is 50 people, consisting of a few families (Byers, 1967-1972, Volume 5, p.361). Given the population size and length of the period, this is a no population growth scenario. The area consists of approximately 2000 square kilometers (Byers, 1967-1972, Volume 1, p.66) and so, there was an extremely low population density. This data strongly suggests population control. This phase coincides with late Pleistocene and the retreat of the ice sheets giving rise to a hotter climate. There is unfortunately no pollen record for the valley (due to a lack of preservation) which would have provided the best evidence for the nature of environmental change. But based on changes in fauna, the speculation on the part of researchers is that if anything, the change in environment might have been to a hotter but moister (lusher) environment in the Tehuacan (Byers, 1967-1972, Volume 1, p.64 and p.144).

The means of production was exclusively foraging (Byers, 1967-1972, Volume 1, Figure 186). Hunting, particularly herd hunting, was an important source of food (Byers, 1967-1972, Volume 5, p.362). This included now extinct horse, antelope, tortoises, and large jack rabbits (Byers, 1967-1972, Volume 1, Figure 95) and other animals which exist today. In this period, meat is estimated to have made up 70% of the diet, but was falling at the end of the period; Plants represented 30% of the diet but were increasing (Byers, 1967-1972, Volume 1, p.300 and Figure 95). The manufactured tools were all made by chipping flint. The settlement pattern of the people of the Ajuereado,[37] MacNeish concludes (Byers, 1967-1972, Volume 5, pp.361–365 and p.497) that the people of the Ajuereado Phase were nomadic based on there being no campsites with any evidence of occupation for more than one season. And based on there being no geographical clustering of campsites, he also concludes that they were not territorial. He concludes that "... either several groups with no

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[36] Also in this area in Mexico the Oaxaca Valley has been extensively studied. These studies are reported in Flannery (1986) and Marcus and Flannery (1996) and present a considerable amount of new ideas and data to the work on the Tehuacan. Although not the focus there is some discussion of the Tehuacan. Reynolds (1986) presents a systems approach computational model on foraging in the Oaxaca. For central and South America more broadly see Smith (1995).

[37] See the interesting map in Byers (1967-1972, Volume 5, Figure 141).

defined territories used the whole valley in a haphazard manner or a single group roamed the whole valley as its territory" (Byers, 1967-1972, Volume 5, p.497).

8.2 El Reigo (9,000 BP – 7,000 BP)

During this phase, the high-end estimate for population is 150 people with growth coming mainly in the latter part of the period (Byers, 1967-1972, Volume 5, p.498). Given the size of the area, this still represents an extremely low population density even by foraging standards. It was during this period that there was the first evidence of the cultivation of plants with this accounting for 5% of the diet by the end of the period (Byers, 1967-1972, Volume 1, Figure 186, Figure 188, and Table 38). Hunting was becoming less important — the horse, antelope, tortoises, and large jack rabbits had disappeared (Byers, 1967-1972, Volume 1, Figure 95). Meat is estimated to have made up 60% of the diet and was continuing to fall; wild plants represented 35% of the diet and were still increasing (Byers, 1967-1972, Volume 1, Table 36 and Figure 95).

Regarding technological development between this period and the previous there was an increase in number of types of projectile points (important for lances and dart throwers). In the former phase, there are three point types, and in the latter, ten more types of projectile points are added (Byers, 1967-1972, Volume 2, Figure 34). In regard to artifact types more generally, a time sequence for 79 time sensitive artifact types has been documented (Byers, 1967-1972, Volume 2, Table 32). In the Ajuereado 19 types exist, in the El Reigo 55 exist (36 added), and in the Coxcatlan 68 (13 added).

For our purposes, there is a telling transition in the settlement pattern between the Ajuereado and the El Reigo.[38] MacNeish concludes (Byers, 1967-1972, Volume 5, pp.366-371) that the people of the El Reigo Phase were more settled, based on there being campsites with evidence of occupation for more than one consecutive season — with relocation between sites based on exploiting seasonal local resources — large (macro) wet season sites and smaller (micro) dry season sites. Most importantly, based on there being a clustering of a complete set of seasonal camps with significant geographical isolation between clusters, he concludes that the people of the valley had become territorial.[39] He concludes there is evidence "...to favour at least three or possibly four band territories during El Reigo times" (Byers, 1967-1972, Volume 5, p.369).

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[38] Again, see the maps in Byers (1967-1972, Volume 5, Figure 141 and Figure 144).

[39] He defines territoriality as the regular procurement by a group of the resources of a particular area or region.

8.3 Coxcatlan (7,000 BP – 5400 BP)

During this phase, the high-end estimate for population is 400 people (Byers, 1967-1972, Volume 5, p.498). This phase resembled El Reigo and, in some sense, could be interpreted as the logical conclusion of the El Reigo phase. There is evidence of more established agriculture — planting of domesticated plants in plots or gardens.[40] Cultivated plants account for 14% of the diet (Byers, 1967-1972, Volume 1, p.300), meat falls dramatically to 34% and wild plants increase to 52%. By the end of Coxcatlan, the shares of both meat and wild plants is falling with the share of agricultural plants increasing (Byers, 1967-1972, Volume 1, Figure 95). These trends continue through the following six phases, but with the introduction of domesticated animals into the diet in the next Abejas Phase. During Coxcatlan, there is evidence of less seasonal migration (Byers, 1967-1972, Volume 5, p.374) and now evidence for four or five bands with territories (Byers, 1967-1972, Volume 5, Figure 147). MacNeish argues that the subtle differences between the El Reigo and the Coxcatlan were caused by the settlement pattern adopted in the El Reigo (territorial and more sedentary) and the population increase which began in the late El Reigo.

8.4 Theories of the Transition

For our purposes the important transition is from the pure foraging, nomadic, non-territorial Ajuereado to the El Reigo with its territorial and more sedentary population exploiting some very early agriculture. MacNeish argues it was an environmental shock during the Ajuereado which caused the transition, not population pressure.

> "Now the question arises as to whether or not these changes were due to population pressure and settlement pattern factors. In the Ajuereado time period population does not seem in any way to be a major force in bringing about cultural change, not only because populations were extremely small, but also because the significant population rise in the period of the two phases does not come until the late El Reigo times, long after other major changes had taken place. Also macro bands and scheduled seasonal settlement pattern occur during the El Reigo times and not before. Thus it seems conclusive that the population and settlement pattern factors were the result, not the

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[40] Recent research has pushed the dates for the earliest domesticates (pepo squash and bottle gourd) in the Tehuacan back into late El Reigo phase (see Smith (1997) and (2001)). The first evidence for domesticates in Mexico as a whole is about 10,000 BP in the Oaxaca valley.

> cause, of a shift from the Ajuereado way of life to that of the El Reigo, and the real conditions bringing about this event were the environment changes, acting in a negative feedback relationship with the changing use of subsistence options which had started relatively early in the Ajuereado times." (Byers, 1967-1972, Volume 5, p.498)

We find convincing his conclusion according to which moving to cultivation and a more sedentary way of life caused population growth (rather than the reverse).

MacNeish suggests that the transition was caused by an environmental shock. Indeed, there seems to be general agreement that environmental change took place in the Ajuereado, but as we have argued earlier, there are limits to the "environmental shock" argument as an explanation for the transition. It must also be noted that the speculation for this valley is that the environmental shock was a positive one to a lusher environment, not a negative one. Finally, MacNeish does not explain how an environmental shock would have led to the territoriality element in settlement pattern.

The introduction of territoriality and more sedentism and its potential implications for human relationships across distinct bands seems to us to be a crucially important element of the transition. One might argue that the shock caused agriculture and the agriculture caused territoriality. But that seems to be inconsistent with the archaeological record. Wild foods accounted for approximately 95% of the diet at the end of the El Reigo. This means that the territoriality element of the settlement pattern came before significant agriculture, not after. It is more likely that the partitioning of the valley into distinct band territories was a factor in the rise of agriculture. Further, given the inherent common access nature of a foraging economy, it is clear that territoriality would have been consistent with a breakdown of valley-wide conservation which could have had a catastrophic impact on the stocks of their prey. This could have accounted for the extinctions. In fact, Flannery (Byers, 1967-1972, Volume 1, p.144) argues that the speed of the extinctions of some of the larger animals suggest over-exploitation. To summarize, the rise of foraging territoriality, together with the possible breakdown of conservation, are important phenomena that seem to have taken place before the transition to agriculture.

It is precisely the occurrence of those phenomena that our theoretical model of group formation was designed to explain. By applying our model to a foraging economy, we showed that technological growth to a critical level could cause the emergence of a non-cooperative band structure together with territoriality. We also showed that an environmental shock would have to be positive to contribute to the emergence of such phenomena. Thus, we can argue that the following causal chain is possible. After millennia of slowly improving conditions supported by population control and improving technology, technology reaches a critical state, possibly in conjunction with an improving environment, and this causes a splintering of the cooperative band structure and the establishment of distinct foraging bands with territories. This in turns leads to less conservation and over-exploitation and a resultant food crisis including extinctions. The more sedentary lifestyle and the less productive foraging possibilities eventually make agriculture more attractive. The food crisis would make population growth difficult particularly in the early El Reigo but eventually the more sedentary lifestyle (less carrying of children) and the increasing importance of cultivation (with its increased possibility of exploiting child labour) would eventually make having more children attractive and result in population growth.

9 Conclusion

To explain the transition between important economic institutions, most economists would only be satisfied with a model inhabited by self–interested and non–cooperative agents. At the same time, in describing the Pleistocene, most archaeologists and anthropologists would only be satisfied with a model incorporating the notions of cooperation and the possibility of conservation within foraging bands. Therefore, because it allows for the non–cooperative formation of cooperative bands, our model seems well suited to study the transition from foraging to agriculture.

While we do not claim that these did not play an important role, we intentionally avoided a population growth or environmental shock explanation. Instead, the explanation for the transition offered in this paper was based on technological growth and the incapacity of bands of foragers to maintain cooperation when the productivity of foraging has reached some relatively high level. Our story has provided an explanation for the endogenous occurrence of the transition and generated a number of other endogenous phenomena:

- The band structure evolves in a non-trivial fashion: from large bands to smaller bands to possibly larger bands.
- Hunting-gathering and agriculture may coexist for some time.

- The over-exploitation of the environment that may precede the transition is not due to the absence of an institution to prevent over-exploitation, but rather to the endogenous collapse of such an institution (the grand band).
- According to our model, if an environmental shock is a facilitating factor in the transition, it has to be a positive environmental shock, not an adverse shock.
- A food-crisis and extinction may precede the transition.
- During the transition, individuals may want to remain foragers, but be forced into agriculture. They may therefore suffer a utility drop during the transition.

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11 Appendix 1

Proof of Proposition 1:

a) We first prove that the individual payoff in the grand band Pareto dominates the payoffs in all other coalition structures at low levels of technology or $U_i^{H*}(\{N^H\}) > U_i^{H*}(B)$ for all $B \neq \{N^H\}$ and sufficiently low $\theta > 1/\overline{K}$. For all coalition structures where all bands are of equal size (cardinality) every individual in the coalition structure has equal utility (see (7)). But the total utility in such a coalition structure is less than in the grand coalition by (8). Thus the equal share of the smaller pie implies $U_i^{H*}(\{N^H\}) > U_i^{H*}(B)$ for B with all bands are of equal size. In coalition structures with bands of unequal sizes the coalitions which are not maximal pay a security cost $M_{S_j^f}(B)> 0$, given this and by (7) at $\theta = 1/\overline{K}$ utility in the grand band will be discretely higher in the grand band. Therefore given the continuity of $U_i^{H*}(B)$ in θ and for small enough $\theta > 1/\overline{K}$, $U_i^{H*}(\{N^H\}) > U_i^{H*}(B)$ for individuals in coalitions which are not maximal in their coalition structure. If individuals in coalitions which are maximal in their coalition structure pay no security costs, then for such individuals $i \in S_j^H \in B$ by (7),

$$U_i^{H*}(\{N^H\}) - U_i^{H*}(B) = \frac{2I[\theta\overline{K} - 1]}{4N\left[1 + |B^H|\right]^2 \left|S_j^H\right|}\left[\left[1 + \left|B^H\right|\right]^2 \left|S_j^H\right| - 4N\right]$$

where $S_j^H \ \in B$ is a maximal coalition. Further $\left|S_j^H\right| > N/\left|B^H\right|$, therefore $\left[1 + \left|B^H\right|\right]^2 \left|S_j^H\right| > 4N$ for $\left|B^H\right| \geq 2$ and $\theta > 1/\overline{K}$. So the payoff for the grand band dominates. Therefore, if those individuals in coalitions which are maximal in their coalition structure paid per member security costs larger than those of members of the grand band, then the grand band payoff would be even more dominant.

b) We now prove that because $U_i^{H*}(\{N^H\}) > U_i^{H*}(B)$ for all $B \neq \{\{N^H\}\}$ for sufficiently low $\theta > 1/\overline{K}$ that the unique CPE is s^{HN} and thus the unique equilibrium band structure in the earliest of times is the grand band of foragers $B = \widehat{\psi}(s^{HN}) = \{N^H\}$. The strategy profile s^{HN} is CPE because there are no profitable deviations. From any $s \neq s^{HN}$ there are profitable joint deviations by all players with strategies $S_i^H \neq N^H$ and these deviations are credible because there is no profitable deviations by any subset of initial deviators.■

Proof of Proposition 2:

From (7) and the definition of the summary parameter I and with simplification the difference

$$\Delta = U_i^{H*}(\{\{N\}^H\}) - U_i^{H*}(\{\{i\}^H, \{N\backslash i\}^H\}) = \frac{\gamma\left(\theta\overline{K} - 1\right)^2 (9 - 4N)}{36\overline{K}N\theta^2} + M_{\{i\}}(\{\{i\}^H, \{N\backslash i\}^H)$$

Thus the difference is positive at $\theta\overline{K} - 1 = 0$, has a negative first derivative with respect to θ for

$\theta\overline{K} - 1 > 0$, and a negative limit as $\theta \to \infty$. Therefore there is one and only one critical level of θ for $\theta > 1/\overline{K}$ denoted $\underline{\theta}$ at which the difference is zero. The difference is a quadratic in θ. Denoting $M_{\{i\}}(\{\{i\}^H, \{N\backslash i\}^H\})$ by M,

$$\begin{aligned}
\underline{\theta} &= \frac{9\gamma\overline{K} - 4\gamma\overline{K}N + 6\sqrt{\left(-9M\overline{K}N\gamma + 4M\overline{K}N^2\gamma\right)}}{9\gamma\overline{K}^2 - 4\gamma\overline{K}^2N + 36M\overline{K}N} \\
&\text{for } 0 < 9\gamma\overline{K} - 4\gamma\overline{K}N + 36MN \\
\underline{\theta} &= \frac{9\gamma\overline{K} - 4\gamma\overline{K}N - 6\sqrt{\left(-9M\overline{K}N\gamma + 4M\overline{K}N^2\gamma\right)}}{9\gamma\overline{K}^2 - 4\gamma\overline{K}^2N + 36M\overline{K}N} \\
&\text{for } 0 > 9\gamma\overline{K} - 4\gamma\overline{K}N + 36MN
\end{aligned}$$

When $9\gamma\overline{K} - 4\gamma\overline{K}N + 36MN > 0$ it is as shown, because the other root is negative for $N > 2$. When $9\gamma\overline{K} - 4\gamma\overline{K}N + 36MN < 0$ it is possible that both roots are positive for $N > 2$ but given the argument above only one can be such that $\theta > 1/\overline{K}$ and it will necessarily be as shown — the larger root — the other root is negative or positive but less than $1/\overline{K}$.

Therefore at the critical technology $\underline{\theta}$ a marginal increase in θ leads to a unilateral profitable deviation by player i from s^{HN} to $S_i = \{i\}^H$ which leads to $\widehat{\psi}(s) = \{\{i\}^H, \{N\backslash i\}^H\}$ and unilateral deviations are always credible. Thus s^{HN} is not CPE (it is not even a NE). Therefore the grand band of foragers, *is not* an equilibrium outcome and there is a breakdown of cooperation due to a splintering of the foraging band structure.$\blacksquare$

Proof of Observation 4:

For singleton bands a sharing rule is redundant. The total utility in the grand band of foragers available for distribution through asymmetric sharing of work and consumption is $NU_i^{H*}(\{\{N\}^H\})$. But because $NU_i^{H*}(\{\{i\}^H, \{N\backslash i\}^H\}) > NU_i^{H*}(\{\{N\}^H\})$ there is no way to divide the resources of the grand band to make s^{HN} immune to profitable unilateral and therefore credible deviations by *each* individual and thus to make s^{HN} a CPE.$\blacksquare$

Proof of Observation 5:

Recall that $\Delta(\theta, \bar{K})$ is the difference in utilities (see the Proof of Proposition 2). We already know that $\partial\Delta/\partial\theta < 0$. It can also be shown that for any feasible θ (i.e. $\theta\bar{K} > 1$ and $N > 2$), we have $\partial\Delta/\partial\bar{K} < 0$.

Since $\underline{\theta}$ is the solution to $\Delta(\underline{\theta}, \bar{K}) = 0$, we can apply the implicit function theorem (we have continuity of $\Delta(\cdot)$ in the neighbourhood of $\underline{\theta}$) to get:

$$\frac{\partial\Delta}{\partial\theta} \,.\, d\underline{\theta} + \frac{\partial\Delta}{\partial\bar{K}} \,.\, d\bar{K} = 0 \qquad \Longleftrightarrow \qquad \frac{\partial\underline{\theta}}{\partial\bar{K}} = -\frac{\partial\Delta/\partial\bar{K}}{\partial\Delta/\partial\theta} < 0 \qquad \blacksquare$$

12 Appendix 2

In section 7 of the main text, we discuss an example using the following functional forms and parameters:

- $\phi f(l_i, E_i) = \phi l_i^{1/2} E_i^{1/2}$;
- $m(E_i) = E_i^2/2$ so that $L_i = l_i + E_i^2/2$;
- $N = \{1, 2, 3\}$;
- $T = 24$;
- $\overline{K} = 10$;
- $\gamma = 1$;
- $M_{\{i\}^f}(\{\{i\}^f, \{h, k\}^H\}) = 0.225$ for $f = A, H$ and $M_{S_j^f}(B) = 0$ otherwise;
- $\phi = \theta - 1/\overline{K}$.

Then, solving the program for individual $i \in S_j^A \in B^A$ yields closed forms for all endogenous variables:

$$\begin{aligned}
l_i^{A*}(B) &= l_i^A = \frac{\phi^4}{16} \text{ for all } i \in S_j^A \in B^A \qquad (10)\\
E_i^{A*}(B) &= E_i^A = \frac{\phi^2}{4} \text{ for all } i \in S_j^A \in B^A\\
L_i^{A*}(B) &= L_i^A = \frac{3\phi^4}{32} \text{ for all } i \in S_j^A \in B^A\\
C_i^{A*}(B) &= C_i^A = \frac{1}{8}\phi^4 \text{ for all } i \in S_j^A \in B^A\\
Z_i^{A*}(B) &= T - \frac{3}{32}\phi^4 - \frac{M_{S_j^A}(B)}{\left|S_j^A\right|} \text{ for all } i \in S_j^A \in B^A\\
U_i^{A*}(B) &= T + \frac{\phi^4}{32} - \frac{M_{S_j^A}(B)}{\left|S_j^A\right|} \text{ for all } i \in S_j^A \in B^A
\end{aligned}$$

and then

$$K(B) = \bar{K} - \frac{\lambda\phi^2 \sum_{S_h^A \in B} |S_h^A|}{4} \qquad (11)$$

The discussion of section 7 in the main text is based on the following results.

Result 1: *For any λ and for the lowest levels of technology ($0.1 < \theta < 1$), the unique CPE is s^{HN} and thus the unique band structure is the grand band of foragers $B = \widehat{\psi}(s^{HN}) = \{N^H\}$.*

Proof:

Part 1: Consider the case with $\lambda = 0$

Using (10) and the parameters in the example we derive the following tables which provide ordinal rankings, $R_i(B)$ for all $B \in \mathbf{B}$ and $0 < \theta < 1$. The indexes we use for players are $h = 1, 2, 3$ and $i = 1, 2, 3 \neq h$ and $k \neq h$ and $k \neq i$ and the highest ranking is indicated by a 1 etc..

Table A1.1: Ranking of Payoffs, $\lambda = 0$, $0.1 < \theta < 0.182$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
1) $\{\{h\}^H, \{i\}^H, \{k\}^H\}$	5	5	5
2) $\{\{h, i\}^H, \{k\}^H\}$	6	6	8
3) $\{h, i, k\}^H$	4	4	4
4) $\{\{h\}^A, \{i\}^A, \{k\}^A\}$	7	7	7
5) $\{\{h, i\}^A, \{k\}^A\}$	7	7	7
6) $\{h, i, k\}^A$	7	7	7
7) $\{\{h\}^H, \{i\}^A, \{k\}^A\}$	1	7	7
8) $\{\{h\}^H, \{i, k\}^A\}$	1	7	7
9) $\{\{h\}^H, \{i\}^H, \{k\}^A\}$	3	3	7
10) $\{\{h, i\}^H, \{k\}^A\}$	2	2	9

At $\theta \simeq 0.182$, $U_k^H\{\{h, i\}^H, \{k\}^H\}$ cuts U_i^A from below and thereby the rankings change. The multiple rankings in the first two rows simply indicate that over this range of θ, these elements can take on these rankings — first $U_k^H\{\{h, i\}^H, \{k\}^H\}$ cuts $U_h^H\{\{h, i\}^H, \{k\}^H\}$ from below and then $U_h^H\{\{h\}^H, \{i\}^H, \{k\}^H\}$ from below. But the multiple rankings do not alter the proofs used below, so we include them in one table.

Table A1.2: Ranking of Payoffs, $\lambda = 0$, $0.182 \leq \theta < 1$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
1) $\{\{h\}^H, \{i\}^H, \{k\}^H\}$	5,6	5,6	5,6
2) $\{\{h, i\}^H, \{k\}^H\}$	6,7	6,7	5,6,7
3) $\{h, i, k\}^H$	4	4	4
4) $\{\{h\}^A, \{i\}^A, \{k\}^A\}$	8	8	8
5) $\{\{h, i\}^A, \{k\}^A\}$	8	8	8
6) $\{h, i, k\}^A$	8	8	8
7) $\{\{h\}^H, \{i\}^A, \{k\}^A\}$	1	8	8
8) $\{\{h\}^H, \{i, k\}^A\}$	1	8	8
9) $\{\{h\}^H, \{i\}^H, \{k\}^A\}$	3	3	8
10) $\{\{h, i\}^H, \{k\}^A\}$	2	2	9

The problem now is to take these rankings to the coalition formation stage to determine an equilibrium band structure.

Part 1a: For $0.1 < \theta < 0.182$ (Table A1.1)

From the strategy profile s^{HN} (or $B = \widehat{\psi}(s^{HN}) = \{\{1, 2, 3\}^H\}$) there are no profitable deviations as the only $U_i^{f*}(B) > U_i^{H*}\{\{1, 2, 3\}^H\}$ requires an s with at least one coalition deviating from s^{HN} to a strategy with A as its mode of production (rows 7–10), but this is not profitable for that coalition. Therefore s^{HN} is a CPE.

From any s which leads to the coalition structures in rows 1, 2, 4, 5, and 6 there are always profitable and credible deviations by the subset of players with $S_i^f \neq N^H$ to $S_i^H = N^H$. They are profitable (see Table A1.1) and credibility is established by s^{HN} being CPE. From any s which leads to the coalition structures in rows 7 and 8, there is always a profitable and credible deviation by i to $S_i^H = \{i\}^H$. It is profitable for i as this deviation necessarily leads to row 9 and a unilateral deviation is always credible. From any s which leads to the coalition structure in row 9, there is always a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$ as this leads to row 1. From any s which leads to the coalition structure in row 10, there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$ as this leads to row 2. Therefore the unique CPE is s^{HN} and the unique band structure is the grand band of foragers $B = \widehat{\psi}(s^{HN}) = \{N^H\}$.

Part 1b: For $0.182 < \theta < 1$ (Table A1.2)

From the strategy profile s^{HN} (or $B = \widehat{\psi}(s^{HN}) = \{\{1, 2, 3\}^H\}$) there are no profitable deviations as the only $U_i^{f*}(B) > U_i^{H*}\{\{1, 2, 3\}^H\}$ requires an s with at least one coalition deviating from s^{HN} to a strategy with A as its mode of production (rows 7–10), but this is not profitable for that coalition. Therefore s^{HN} is a CPE.

From any s which leads to the coalition structures in rows 1, 2, 4, 5, and 6 there are always profitable and credible deviations by the subset of players with $S_i^f \neq N^H$ to $S_i^H = N^H$. They are profitable (see Table A1.2) and credibility is established by s^{HN} being CPE. From any s which leads to coalition structures in rows 7–10 requires at least one player say k with a $S_k^{f_k}$ and $f_k = A$, but then there will always be a unilateral profitable deviation to $S_k^{f_k}$ with $f_k = H$ and unilateral deviations are always credible. Therefore the unique CPE is s^{HN} and the unique band structure is the grand band of foragers $B = \widehat{\psi}(s^{HN}) = \{N^H\}$.

Part 2: Extending to $\lambda > 0$

This extension only affects the payoffs of foragers and only in rows 7–10 where there are farmers. In particular it lowers the foragers payoffs and more so in coalition structures with more farmers, that is, rows 7 and 8.[41] So as λ increases from 0 the payoffs in row 10 for foragers will still dominate those in 9 but those in 10 will come to dominate 7 and 8 and eventually those in 9 will dominate 7 and 8 and then rows 7–10 will start falling in the rankings against row 3.

Part 2a: Extending to $\lambda > 0$ for $0.1 < \theta < 0.182$

Notice that these changes in all cases leave the proof that s^{HN} is a CPE, as in part 1a. The proof that any s which leads to the coalition structures in rows 1, 2, 4, 5, and 6 is not CPE is also as in part 1a.

From any s which leads to either of the coalition structures in row 7 and 8 if $U_i^A(\{\{h\}^H, \{i\}^A, \{k\}^A\}) = U_i^A(\{\{h\}^H, \{i,k\}^A\}) < U_i^H(\{\{h\}^H, \{i\}^H, \{k\}^A\})$ then exactly as with $\lambda = 0$ there is a profitable unilateral and therefore credible deviation by i to $S_i^H = \{i\}^H$. If on the other hand $U_i^A(\{\{h\}^H, \{i\}^A, \{k\}^A\}) = U_i^A(\{\{h\}^H, \{i,k\}^A\}) \geq U_i^H(\{\{h\}^H, \{i\}^H, \{k\}^A\})$ and if $S_h^H = \{h,i,k\}^H$ then there is a profitable joint deviation by i and k to $S_i^H = S_k^H = \{h,i,k\}^H$ which is profitable by a farming payoff being dominated by any foraging payoff with $B = \{\{h,i,k\}^H\}$ and is credible by s^{HN} being a CPE. And if $S_h^H \neq \{h,i,k\}^H$ then there is profitable joint deviation by i and k to $S_i^H = \{i\}^H$ and $S_k^H = \{k\}^H$ which is profitable by any farmer payoff being dominated by any foraging payoff with $B = \{\{h\}^H, \{i\}^H, \{k\}^H\}$ and is credible by $U_i^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_i^H(\{h\}^H, \{i,k\}^H)$, and $\{\{h,i,k\}^H\}$ not being possible with $S_h^H \neq \{h,i,k\}^H$, and $U_i^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_i^A(B)$ and $U_k^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_k^A(B)$ for any other B with $\{h\}^H$ for both i and k.

From any s that leads to the coalition structure in row 9 we must have $S_h^H \neq S_i^H$ therefore there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. Because it leads to row 1 it is profitable.

From any s which leads to the coalition structure in row 10 there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. It is profitable for k as this deviation necessarily leads to row 2.

Part 2b: Extension to $\lambda > 0$ for $0.182 < \theta < 1$

Notice that in all cases the proof that s^{HN} is a CPE is as in part 1b.. The proof that any s which leads to the coalition structures in rows 1, 2, 4, 5, and 6 is not CPE is also as in part 1b.

From any s which leads to the coalition structures in row 7 and 8 if $U_i^A(\{\{h\}^H, \{i\}^A, \{k\}^A\}) = U_i^A(\{\{h\}^H, \{i,k\}^A\}) < U_i^H(\{\{h\}^H, \{i\}^H, \{k\}^A\})$ then exactly as before there is a profitable unilat-

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[41] For foragers mixed with farmers (rows 7–10) and with $\lambda > 0$ it may even be the case that the carry capacity is sufficiently lowered that foraging is not viable in the sense that $K(B) < 1/\theta$ for $\theta > 0.1$. The payoff in these cases would be T net of any security costs. Even in this case our proofs below go through.

eral and therefore credible deviation by i to $S_i^H = \{i\}^H$. If on the other hand $U_i^A(\{\{h\}^H, \{i\}^A, \{k\}^A\}) = U_i^A(\{\{h\}^H, \{i,k\}^A\}) \geq U_i^H(\{\{h\}^H, \{i\}^H, \{k\}^A\})$ and if $S_h^H = \{h,i,k\}^H$ then there is a profitable joint deviation by i and k to $S_i^H = S_k^H = \{h,i,k\}^H$ which is profitable by any farmer payoff being dominated any foraging payoff with $B = B^H$ and is credible by s^{HN} being a CPE. And if $S_h^H \neq \{h,i,k\}^H$ then there is profitable joint deviation by i and k to $S_i^H = \{i\}^H$ and $S_k^H = \{k\}^H$ which is profitable by any farmer payoff being dominated any foraging payoff with $B = B^H$ and is credible by $U_i^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_i^H(\{h\}^H, \{i,k\}^H)$, and $\{\{h,i,k\}^H\}$ not being possible with $S_h^H \neq \{h,i,k\}^H$, and $U_i^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_i^A(B)$ and $U_k^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_k^A(B)$ for any other B with $\{h\}^H$ for both i and k.

From any s that leads to the coalition structure in row 9 we must have $S_h^H \neq S_i^H$ therefore there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. Because it leads to row 1 it is profitable.

From any s which leads to the coalition structure in row 10 there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. It is profitable for k as this deviation necessarily leads to row 2.■

Result 2a: *For $\lambda = 0$ and for higher levels of technology ($1 < \theta < 2.165$), the unique CPE band structure is the singleton forager band structure, $B = \{\{1\}^H, \{2\}^H, \{3\}^H\}$, that is, at $\theta = 1$, there is a breakdown of cooperation due to a splintering of the foraging band structure and a transition to a new structure where everyone is worse off. The transition involves over–hunting which leads to a food crisis.*

Proof:
From (10) at $\theta > 1$, $U_k^H(\{\{h,i\}^H, \{k\}^H\}) > U_k^H(\{\{h,i,k\}^H\})$ and at $\theta > 2.165$ some agricultural payoffs come to dominate some payoffs in rows 1–3 (see Table A1.3).

Table A1.3: Ranking of Payoffs, $\lambda = 0$, $1 < \theta < 2.165$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
1) $\{\{h\}^H, \{i\}^H, \{k\}^H\}$	6	6	6
2) $\{\{h,i\}^H, \{k\}^H\}$	7	7	4
3) $\{h,i,k\}^H$	5	5	5
4) $\{\{h\}^A, \{i\}^A, \{k\}^A\}$	8	8	8
5) $\{\{h,i\}^A, \{k\}^A\}$	8	8	8
6) $\{h,i,k\}^A$	8	8	8
7) $\{\{h\}^H, \{i\}^A, \{k\}^A\}$	1	8	8
8) $\{\{h\}^H, \{i,k\}^A\}$	1	8	8
9) $\{\{h\}^H, \{i\}^H, \{k\}^A\}$	3	3	8
10) $\{\{h,i\}^H, \{k\}^A\}$	2	2	9

From the strategy profile s^{HN} there is a profitable unilateral, and therefore credible deviation, by k to $S_k^H = \{k\}^H$. From any s which leads to the coalition structure in row 2 there is a profitable unilateral, and therefore credible, deviation by i to $S_i^H = \{i\}^H$. Any s which leads to coalition structures in rows 4–10 requires at least one player, say 1, with S_1^A, but then there will always be a unilateral profitable, and therefore credible deviation to $S_1^H = \{k\}^H$.

Therefore if there is a CPE band structure it must be the singleton foraging structure. The profile of partnership plans $s = (\{1\}^H, \{2\}^H, \{3\}^H)$ is immune to any deviation with $f_i = A$ as these are not profitable. It is immune to any unilateral deviations with $f_i = H$ because it takes a joint deviation to create a multi–player coalition. It is immune to any joint deviation by two players to $S_h^H = S_i^H$ (which is required to form the coalition $\{h, i\}^H$) because such a deviation is not profitable. Finally, it is immune to a joint deviation by all players to s^{HN} (which is required to form the grand band of foragers) because s^{HN} is not CPE of the subgame of all players. Therefore the singleton coalition structure of foragers is the unique equilibrium band structure.■

Result 2b: *For $\lambda \geq 0$ and for higher levels of technology ($1 < \theta < 2.165$), the grand band of foragers is not a CPE band structure and the singleton forager band structure, $B = \{\{1\}^H, \{2\}^H, \{3\}^H\}$ is a CPE band structure. But for some $\lambda > 0$, $B = \{\{h\}^H, \{i\}^A, \{k\}^A\}$ or $B = \{\{h\}^H, \{i, k\}^A\}$ may also be CPE band structures.*

Proof:
From the strategy profile s^{HN} there is a profitable unilateral, and therefore credible deviation, by k to $S_k^H = \{k\}^H$. From any s which leads to the coalition structure in row 2 there is a profitable unilateral, and therefore credible, deviation by i to $S_i^H = \{i\}^H$.

The profile of partnership plans $s = (\{1\}^H, \{2\}^H, \{3\}^H)$ is immune to any deviation with $f_i = A$ as these are not profitable. It is immune to any unilateral deviations with $f_i = H$ because it takes a joint deviation from $s = (\{1\}^H, \{2\}^H, \{3\}^H)$ to create a multi–player coalition. It is immune to any joint deviation by two players to $S_h^H = S_i^H$ (which is required to form the coalition $\{h, i\}^H$) because such a deviation is not profitable. Finally, it is immune to joint deviation by all players to s^{HN} (which is required to form the grand band of foragers) because s^{HN} is not CPE of the subgame of all players. Therefore the singleton coalition structure of foragers is a CPE band structure.

From any s which leads to coalition structures in rows 4–6 there is a profitable joint deviation to $s = (\{1\}^H, \{2\}^H, \{3\}^H)$. It is profitable as it leads to row 1 and is credible because $s = (\{1\}^H, \{2\}^H, \{3\}^H)$ is CPE of the subgame of all players.

From any s which leads to the coalition structure in row 9 we must have $S_h^H \neq S_i^H$ therefore there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. Because it leads to row 1 it is profitable.

From any s which leads to the coalition structure in row 10 there is a profitable unilateral and therefore credible deviation by k to $S_k^H = \{k\}^H$. It is profitable for k as this deviation necessarily leads to row 2.

This leaves rows 7 and 8. Consider the $\widehat{s}$ consisting of $S_h^H = \{h, i, k\}^H$ and $S_i^A = \{i\}^A$, and $S_k^H = \{k\}^A$ and the following table

Table A1.4: Possible Ranking of Payoffs, $\lambda > 0$, $\theta \in]1, 2.165[$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
1) $\{\{h\}^H, \{i\}^H, \{k\}^H\}$	4	4	4
2) $\{\{h, i\}^H, \{k\}^H\}$	5	5	2
3) $\{h, i, k\}^H$	3	3	3
4) $\{\{h\}^A, \{i\}^A, \{k\}^A\}$	6	6	6
5) $\{\{h, i\}^A, \{k\}^A\}$	6	6	6
6) $\{h, i, k\}^A$	6	6	6
7) $\{\{h\}^H, \{i\}^A, \{k\}^A\}$	1	6	6
8) $\{\{h\}^H, \{i, k\}^A\}$	1	6	6
9) $\{\{h\}^H, \{i\}^H, \{k\}^A\}$	8	8	6
10) $\{\{h, i\}^H, \{k\}^A\}$	7	7	9

With these payoffs $\widehat{s}$ is CPE. There is no deviation of any type involving h because it would not be profitable for h. There is also no unilateral profitable deviations by either i or k because these lead to rows 9 or 10. A joint deviation by i and k to $S_i^H = S_k^H = \{h, i, k\}^H$ is profitable but not credible because there is a further profitable deviation by i to $S_i^H = \{i\}^H$. A joint deviation by i and k to $S_i^H = S_k^H = \{i, k\}^H$ is profitable but not credible because there is a further profitable deviation by i to $S_i^H = \{i\}^H$. A joint deviation by i and k to $S_i^H = \{i\}^H$ and $S_k^H = \{k\}^H$ is profitable but not credible because there is a further profitable deviation by i and k to $S_i^H = S_k^H = \{h, i, k\}^H$.■

Result 3: *At a sufficiently high state of technology, $\theta > 3.042$, there will be a transition to a purely agriculture structure where all individuals are farmers. For example s^{AN} is CPE and then $B = \widehat{\psi}(s^{AN}) = \{\{1, 2, 3\}^A\}$ is an equilibrium coalition structure.*

Proof:

From (10) it can be verified that for $\theta > 3.042$, $\lambda \geq 0$, for $f_i = A, H$ and for all $B \in \mathbf{B}$, $U_i^A(B^A) \geq U_i^{f_i}(B)$. That is, as technology grows payoffs for farmers in agricultural coalition structures come to Pareto dominate all other structures (in the tables all entries in rows 4–6 are 1s). Then any strategy profile s which leads to the coalition structures in rows 4–6 are CPE as there are no profitable deviation.

From any s which leads to the coalition structures in rows 1, 2, 3, 7, 8, 9, and 10 all agents with S_i^H have profitable joint deviations (or unilateral deviations if there is only one such agent) to S_i^A. The joint deviation is obviously profitable and is credible by all s leading to rows 4, 5, and 6 being CPE.■

Result 4: *The transition from the grand band of foragers to a purely agricultural structure can involve unique mixed coalition structure outcomes with bands of both foragers and farmers. The transition can also be characterized by instability where we interpret the lack of existence of a CPE equilibrium structure as instability.*

Proof:

We consider in turn the equilibrium outcomes for four values of λ ($\lambda = 0, 1, 3.5$, and 5). Table A2.1 to A2.4 summarize the results in these cases and were used to construct Table 1 which appears in the main text. Examples of payoff tables that were used to construct Table A2.1 to A2.4 are available upon request.

Table A2.1: Equilibrium Outcomes, $\lambda = 0$

	$\theta < 1$	$1 < \theta < 2.165$	$2.165 < \theta < 2.492$	$2.492 < \theta < 3.042$	$\theta > 3.042$
$\{\{h\}^H, \{i\}^H, \{k\}^H\}$	—	CPE	—	—	—
$\{\{h, i\}^H, \{k\}^H\}$	—	—	—	—	—
$\{h, i, k\}^H$	CPE	—	—	—	—
$\{\{h\}^A, \{i\}^A, \{k\}^A\}$	—	—	—	—	CPE
$\{\{h, i\}^A, \{k\}^A\}$	—	—	—	—	CPE
$\{h, i, k\}^A$	—	—	—	—	CPE
$\{\{h\}^H, \{i\}^A, \{k\}^A\}$	—	—	—	CPE	—
$\{\{h\}^H, \{i, k\}^A\}$	—	—	—	CPE	—
$\{\{h\}^H, \{i\}^H, \{k\}^A\}$	—	—	—	—	—
$\{\{h, i\}^H, \{k\}^A\}$	—	—	—	—	—

Table A2.2: Equilibrium Outcomes, $\lambda = 1$

	$\theta < 1$	$1 < \theta < 2.165$	$2.165 < \theta < 2.399$	$2.399 < \theta < 2.716$	$\theta > 2.716$
$\{\{h\}^H, \{i\}^H, \{k\}^H\}$	—	CPE	—	—	—
$\{\{h, i\}^H, \{k\}^H\}$	—	—	—	—	—
$\{h, i, k\}^H$	CPE	—	—	—	—
$\{\{h\}^A, \{i\}^A, \{k\}^A\}$	—	—	—	—	CPE
$\{\{h, i\}^A, \{k\}^A\}$	—	—	—	—	CPE
$\{h, i, k\}^A$	—	—	—	—	CPE
$\{\{h\}^H, \{i\}^A, \{k\}^A\}$	—	—	—	CPE	—
$\{\{h\}^H, \{i, k\}^A\}$	—	—	—	CPE	—
$\{\{h\}^H, \{i\}^H, \{k\}^A\}$	—	—	—	—	—
$\{\{h, i\}^H, \{k\}^A\}$	—	—	—	—	—

Table A2.3: Equilibrium Outcomes, $\lambda = 3.5$

	$\theta < 1$	$1 < \theta < 2.165$	$2.165 < \theta < 2.185$	$\theta > 2.2.185$
$\{\{h\}^H, \{i\}^H, \{k\}^H\}$	—	CPE	—	—
$\{\{h,i\}^H, \{k\}^H\}$	—	—	—	—
$\{h,i,k\}^H$	CPE	—	—	—
$\{\{h\}^A, \{i\}^A, \{k\}^A\}$	—	—	—	CPE
$\{\{h,i\}^A, \{k\}^A\}$	—	—	—	CPE
$\{h,i,k\}^A$	—	—	—	CPE
$\{\{h\}^H, \{i\}^A, \{k\}^A\}$	—	—	CPE	—
$\{\{h\}^H, \{i,k\}^A\}$	—	—	CPE	—
$\{\{h\}^H, \{i\}^H, \{k\}^A\}$	—	—	—	—
$\{\{h,i\}^H, \{k\}^A\}$	—	—	—	—

Table A2.4: Equilibrium Outcomes, $\lambda = 5$

	$\theta < 1$	$1 < \theta < 2.165$	$\theta > 2.165$
$\{\{h\}^H, \{i\}^H, \{k\}^H\}$	—	CPE	—
$\{\{h,i\}^H, \{k\}^H\}$	—	—	—
$\{h,i,k\}^H$	CPE	—	—
$\{\{h\}^A, \{i\}^A, \{k\}^A\}$	—	—	CPE
$\{\{h,i\}^A, \{k\}^A\}$	—	—	CPE
$\{h,i,k\}^A$	—	—	CPE
$\{\{h\}^H, \{i\}^A, \{k\}^A\}$	—	—	—
$\{\{h\}^H, \{i,k\}^A\}$	—	—	—
$\{\{h\}^H, \{i\}^H, \{k\}^A\}$	—	—	—
$\{\{h,i\}^H, \{k\}^A\}$	—	—	—