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From Foraging to 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. Using a recent 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 leads to a one–way transition from foraging to agriculture.

"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

It is usual for archeologists to break prehistory into lithic ("stone") ages (see Foley (1987, chapter 2)). For Europe and the Middle East three ages are traditionally recognized: the Paleolithic, a period which began with the first evidence of stone tools about two million years ago; then the Mesolithic which began about 13,000 years ago and lasted for about 6,000 years; and finally the Neolithic which ended with the bronze age. The distinction between the Paleolithic and the Neolithic is the mode of food production, in particular, hunting and gathering (foraging) in the former and cultivation and animal husbandry (early agriculture) in the latter. The Mesolithic was a transitional and rather unstable period of broad spectrum foraging and the earliest agriculture. The long Paleolithic period is further subdivided into periods according to the type of stone tool use.[1] The potential utility of an economic approach to anthropological issues becomes obvious 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

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[1]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. Foley (1987, page 42) argues that technological development may have mirrored improved physical (manipulative skills) and cognitive skills

thousand years during the early Mesolithic. Our concern in this paper will be to provide some new theory about the transition from foraging to agriculture. Our explanation 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 the ability of foragers to form conserving institutions (bands) in avoiding over–exploitation. We then show how agriculture and private property could come to dominate even though it initially provides a lower quality of life.

2 Theories of the Transition

The stylized "facts" reported here come from archeology, modern foragers and other primates.[2]

The 19th century theory for the transition which dominated up to the 1950s was that life as forager was short, nasty, and brutish. Paleolithic 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 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. Archeology shows that they lived in semi–nomadic groups or bands of 10–100 individuals. By the upper Paleolithic, 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 Paleolithic 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)). 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 (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)).[3] In economics, the idea of reciprocity and cooperation was introduced by Akerlof (1983) in his analysis of labour contracts.

[2] Because our focus is on the transition between hunting and gathering and agriculture stylized facts for hunting and gathering will be in regard to the Upper Paleolithic which began approximately 35,000 years ago.

[3] 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.

More recently, Carmichael and MacLeod (1997) have shown, in an evolutionary model, how gift giving can lead to trust and cooperation.

Archeological evidence suggests that the forager's physical health was good implying high levels of consumption. Angel (1975) studying skeletal remains from the upper Paleolithic found that these people grew taller and had less tooth loss than all but the most recent humans (taller than during the Mesolithic and the early Neolithic). There is also little evidence of wide–spread disease. It is argued that this is associated with extremely low population densities throughout the Paleolithic (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, technological growth and environmental change. The theories differ in causation and emphasis but they all 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 upper Paleolithic was quite high and possibly higher than during the Mesolithic and Neolithic ages. Second, there is agreement among anthropologists that Paleolithic peoples controlled their populations (see Birdsell (1968), Harris (1977, chapter 2), Cohen (1980), Hassan (1980), Lee (1980), Ripley (1980), Harris (1993, chapter 13), and Megarry (1995, p.221). Population control during the Paleolithic is reflected in it being a period of extremely low population growth. Cohen (1980) estimates annual population growth of .001–.003% during the Paleolithic with a hundred fold increase during the Neolithic and a 1000 fold increase in modern times. He reports a total population of 100,000 for the Middle East at the end of the two million year Paleolithic and Harris (1977, p.13) reports a high–end estimate for the population of France at this point of 20,000. The Paleolithic was also the period of the first migrations out of Africa. Thus the extremely low population growth may not have involved any increase in population densities of populated areas, just greater dispersion.

Methods of population control which were available to Paleolithic people included culturally–demanded abstinence, disruption of the menstrual cycle through extended years of breast–feeding, abortion, direct and indirect infanticide (particularly female infanticide), and even dietary cannibalism.[4] 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%.

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)).[5] Men often did not help with

[4]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.

[5]This explanation is also consistent with the dramatic increases in population during the Neolithic due to the associated

carrying, the argument being that they needed to be free to hunt (more likely just free). 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. Further, given the band organization the infanticide decision simply may not have been a private one. There are also arguments that infanticide may have been adaptive evolutionary behaviour (Ripley (1980)). Dietary cannibalism has also become a subject of discussion in anthropology over the last two decades. It kills two birds (population pressure and hunger) with one stone (cannibalism). It is known that the practice of large scale human sacrifice in Aztec society (numbers in the tens of thousands) involved cannibalism. Harner (1977) argues that the ceremonies were actually large–scale dietary cannibalism disguised as a religious ceremony.[6] Simpson (1984) points out that among Victorian seafarers cannibalism was considered acceptable as a last ditch survival method as long as the victim was chosen by lot. In a 1884 case the English legal establishment expressed its growing disquiet over this practice by charging two sailors with murder. The sailors while adrift in a life boat for 22 days had eaten the cabin boy. The two were found guilty but then immediately released. This may suggest that taking a Malthusian–type approach to modeling anthropological issues is assuming that the "cavemen" were more Victorian than the Victorians.[7]

Some anthropologists emphasize exogenous environmental shocks. The end of the Paleolithic corresponds to the end of the last ice age. The ice retreated and there was a global warming. The warming led to a forestation of former vast grasslands 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. But this explanation has been unconvincing on its own because similar climatic events had occurred approximately twenty times during the Paleolithic (see Foley (1989, p.37)) without sparking agriculture.

Finally, there has been a trend in anthropology to turn away from the abstract/universal/explanatory models of which we are familiar in economics to a more descriptive local model (e.g. McCorriston and Hole (1991)). But one problem with a local model in this application is that the transition to agriculture happened independently in various dispersed locations (e.g. both the eastern and western hemispheres) with different local conditions at about the same point in prehistory. In other words there is a universal element to the transition, which we wish to explore.

3 The Transition as a Breakdown of Community

Because of the good evidence that foragers had the means and the incentive to control population we will diverge from existing economic work on anthropological issues (e.g. Brander and Taylor (1998)) and assume that the population is fixed. We will also not rely on exogenous environmental shocks. At the heart of

sedentary life-style.

[6]See also Megarry (1995, p.103 and p.233) for references to recent findings of cannibalism of the young by chimps. The chimp is our closest primate relative.

[7]Harris (1977, 1993) emphasizes a population pressure approach but it is an emotional or psychological population pressure associated with neglecting or killing children (i.e. an utility based explanation). What this theory lacks as a theory of transition; is why this suddenly become a serious problem? An anthropological work which does support a strict population pressure theory was Johnson and Earle (1987). But they did not discuss the infanticide argument.

our approach will be exogenous technological growth. The growth could be due to Foley's (1987) human evolution towards improved physical or cognitive abilities or simply due to learning by doing. Clearly one thing that did distinguish foragers across time was the state of the stone technology. As noted above it was used to partition the Paleolithic.

When an economist considers the Paleolithic the common property characteristic of the economic structure is obvious. 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). The purpose of the band 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 coalitions. We assume that to join a band is a 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).[8] We also provide a simple model of agriculture with the primary difference between modes of food production 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)[9] 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 results. At the lowest levels of technology the unique equilibrium band structure is the grand band of foragers—cooperation of the whole. As technology grows, leisure, consumption, and thereby utility increase. We also show that as technology grows so does the importance of cooperation to the society. 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 with the state of technology. In the end, the technological growth in our model leads to a natural one–way transition from foraging to agriculture. We show that what can be achieved with technological growth in a renewable resource model of foraging is bounded while what can be achieved from technological growth under agriculture is not. With the transition, private property comes to replace the cooperative band as the institution for avoiding the common access problem.

The transition is illustrated in an example in section 8. There, we show that at the critical state

[8] In modeling band formation we rely on models of non–cooperative coalition formation. See Ray and Vohra (1997) for an excellent discussion of the literature. The particular model of coalition formation we employ is Burbidge *et al.* (1997).

[9] 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.

of technology at which the transition takes place, there is a catastrophic increase in work, decrease in consumption and through the over–exploitation of the environment, a food crisis.[10] We also show that the transitional period can involve mixed coalition structures of both foraging bands and agricultural bands and in some cases it involves no equilibrium structure, which we interpret as transitory instability.

In summary and at the risk of over–interpreting a rather simple model, our results are broadly consistent with the stylized facts discussed in the previous section. First, there is a one way transition from the Paleolithic to the Neolithic through the Mesolithic—a transitional period characterized by mixed economic structures and instability. The transition being driven by the well–documented technological growth with a severe drop in the well–being of individuals at the transition 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.[11]

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.[12] 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 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,

[10]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.

[11]A numerical example for Cobb–Douglas preferences is available upon request (see also footnote 28).

[12]An important element of a hunting and gathering life-style was mobility and an important element of agriculture is immobility.

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.[13]

There are two stages in the overall (transition) 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 co-operatively 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 $U_i^{f*}(B) = C_{S_j^f}(B)/\left|S_j^f\right| + T - L_{S_j^f}(B)/\left|S_j^f\right| - M_{S_j^f}(B)/\left|S_j^f\right|$.[14]

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 our 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 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.[15] 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

[13] 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.

[14] 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.

[15] 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.

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 or 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 rule labeled the *similarity* rule by Burbidge *et al.* (1997).[16] 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 every set of players with the same partnership plan are in a coalition. In effect we are interpreting a player's partnership plan as a mode of production and the largest set of partners it is willing to be associated with in a coalition.[17]

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. The question now is: what would be an appropriate equilibrium concept for the model?

The solution concept most commonly invoked for games in strategic form is surely the Nash equilibrium (NE). Recall that a strategy profile is a NE if no player has a unilaterally profitable deviation. For our purpose, however, NE is far too weak a solution concept. For instance, $s = (S_1^{f_1}, S_2^{f_2}, ...S_n^{f_n})$ with $S_i^{f_i} = \{i\}^{f_i}$, $i = 1, 2, ..., n$, is immediately a NE of the coalition formation game. No individual i, taking as given the strategy choices of the other $n-1$ individuals, can affect the resultant coalition structure $\widehat{\psi}(s) = \{\{1\}^{f_1}, \{2\}^{f_2}, \ldots, \{n\}^{f_n}\}$ and hence its payoff. Therefore, the singleton coalition structure is a NE structure irrespective of the payoff functions in the game.[18]

Clearly, for a model of coalition formation such as this one, one should allow a group of players to

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

[17] 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.

[18] This is not just a property of the similarity rule, it is a property of a very wide class of rules (see Burbidge *et al.* (1997)).

coordinate on a joint deviation if such a deviation were to make each deviating player better off. We are thus led to a subset of NE which ensure that equilibrium profiles are immune to unilateral as well as joint deviations. An attractive refinement in this class is the concept 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.

We view the similarity rule as a good candidate for the choice of a coalition structure rule. An important focus in the results below is on the formation and stability of the grand band of foragers. An important characteristic of the similarity rule is that if there is a deviation by a set of players S_j from s^{HN}, the complement of S_j will remain intact in the new coalition structure. Deviators are excluded from the grand band. We felt that this characteristic of the similarity rule was important in the context of band formation as it roughly corresponds to the shunning of the deviators.

Finally, 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 a farmer is sharing security costs.[19] 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

[19] 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.

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.[20] 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,[21]

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

The simplicity of the agricultural model yields a great deal of tractability which will be useful in 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.[22] Let $\bar{K}$ be the carrying capacity in the absence of agriculture. Then we assume 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. 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[23]

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

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

[20] 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.

[21] Later, we choose functional forms for $f(\cdot)$ and $m(\cdot)$ and provide closed-form solutions.

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

[23] 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.

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

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.[24]

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

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

So the growth of the stock with foraging is

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

The biometric equilibrium 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

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

[24] The archeological 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. The point of transition in our model will involve a fall in the stock of animals (i.e. food crisis) and this could involve extinction with $\alpha > 1$.

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 assumption 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[25]

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

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 $f = A, H$.

[25] 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 providing a theory of transition 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 Paleolithic) 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

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

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.

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 obvious 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.[26]

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 Paleolithic, 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.[27] 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

[26] This assumption really is one of convenience in the sense that it is not necessarily required for any of our propositions 1–3 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 1–3.

[27] 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.

of security costs will be important. For both foraging and agriculture it seems natural to assume that in a fully cooperative society $B = \{N^f\}$ there are no security costs. Further, we will assume that it is large bands of foragers that generate security costs, so that coalitions which are maximal, in the sense that in their coalition structure there is no larger–sized band, also pay no security costs. Thus $M_{S_j^f}(B)$ becomes the cost of running into a larger group of competitors with lethal weapons.

Proposition 1: *For A.1, any λ, $M_{S_j^f}(B) > 0$ for any $S_j^f \in B$* with $\left|S_j^f\right| < \left|S_h^H\right|$ for at least one $S_h^H \in B$, *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:

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. Individuals in coalitions which are maximal in their coalition structure pay no security costs. 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 $\theta > 1/\overline{K}$.

b) We now prove that because $U_i^{H*}(\{N^H\}) > U_i^{H*}(B)$ for all $B \neq \{\{N\}\}$ 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.■

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 would be a breakdown of cooperation due to a splintering of the foraging band structure.*

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

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

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.■[28]

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: 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.■

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 it no longer is required to conserve—it 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 the technology improves and labour becomes more productive the cost of the conservation (i.e. the loss in consumption from restricting

[28]A security cost is *not necessary* for propositions 1–3 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.

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.[29]

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 transition 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).[30]

We now consider the potential for a transition to agriculture as technology improves enough that agriculture becomes viable.

Lemma 1: *As technology grows there is an upper bound on the foraging payoff.*

Proof: Note that the best case scenario for growth in the foraging payoff is when $\lambda = 0$ and therefore $K(B) = \bar{K}$, i.e. if the payoff is bounded for $\lambda = 0$, it certainly is for $\lambda > 0$. Then for $\lambda = 0$ and $K(B) = \bar{K}$, taking the limit of $U_i^{H*}(B)$ when $\theta \to \infty$ and using L'Hôpital's rule:

$$\lim_{\theta \to \infty} U_i^{H*}(B) = T + \frac{\gamma \bar{K}}{(1 + |B^H|)^2 \left|S_j^H\right|} - \frac{M_{S_j^H}(B)}{\left|S_j^H\right|} \tag{10}$$

so the foraging payoff is bounded from above.■

This is in fact a very natural result in a model of renewable resource use. Food consumption is bounded by the maximum sustainable yield and thus as technology goes to infinity utility goes to the utility associated with food consumption at the maximum sustainable yield and full–time leisure. It also seems natural at this point that people would begin to work to improve the carrying capacity but this is, of course, an element of agriculture.

Lemma 2: *There is no bound on the agricultural payoff so that improvements in foraging technology which spillover to ϕ always increase the agricultural payoff. In other words:*

$$\lim_{\theta \to \infty} U_i^{A*}(B) = \infty \tag{11}$$

Proof: The result follows from noting that $\phi'(\theta) > 0$ and taking the limit of $U_i^{A*}(B)$ in (2) when $\theta \to \infty$.■

Proposition 3: *There is eventually an equilibrium transition from the grand band of foragers to some pure agriculture coalition structure.*

[29] 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.

[30] In the illustrative example below we show that at $\theta = \underline{\theta}$ there is a discontinuous transition to the singleton band structure. This involves 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.

Proof: From Proposition 1 the initial situation is cooperative foraging. From Lemma 1, and Lemma 2 the agricultural payoff in a pure agricultural coalition structure will come to Pareto dominate the payoffs in any other pure or mixed coalition structure. Once there is Pareto dominance of one type of structure over all others then the proof that such a structure is the equilibrium outcome is as in part 1b of the proof of Proposition 1. The strategy profile is CPE as no profitable unilateral or joint deviation is possible given its Pareto dominance. Any CPE equilibrium structure must be pure agriculture as from anything else there is profitable unilateral or joint deviations which lead to it and these are credible as there are no further profitable deviations by subsets of the initial deviators.■

8 Illustrating the Transition

To illustrate the propositions and further understand the nature of transition we provide an example.

We begin by choosing functional forms in the agricultural model. We assume $\phi f(l_i, E_i) = \phi l_i^{1/2} E_i^{1/2}$ and that $m(E_i) = E_i^2/2$ so that $L_i = l_i + E_i^2/2$. Then solving the program for individual $i \in S_j^A \in B^A$ yields closed forms for all endogenous variables:

$$\begin{aligned}
l_i^{A*}(B) &= l_i^A = \frac{\phi^4}{16} \text{ for all } i \in S_j^A \in B^A \qquad (12)\\
E_i^{A*}(B) &= E_i^A = \frac{\phi^2}{4} \text{ for all } i \in S_j^A \in B^A \\
L_i^{A*}(B) &= L_i^A = \frac{3\phi^4}{32} \text{ for all } i \in S_j^A \in B^A \\
C_i^{A*}(B) &= C_i^A = \frac{1}{8}\phi^4 \text{ for all } i \in S_j^A \in B^A \\
Z_i^{A*}(B) &= T - \frac{3}{32}\phi^4 - \frac{M_{S_j^A}(B)}{\left|S_j^A\right|} \text{ for all } i \in S_j^A \in B^A \\
U_i^{A*}(B) &= T + \frac{\phi^4}{32} - \frac{M_{S_j^A}(B)}{\left|S_j^A\right|} \text{ for all } i \in S_j^A \in B^A
\end{aligned}$$

and then

$$K(B) = \bar{K} - \frac{\lambda\phi^2 \sum_{S_h^A \in B} |S_h^A|}{4} \qquad (13)$$

We then assume $N = \{1, 2, 3\}$; $T = 24$, $\overline{K} = 10$, $\gamma = 1$ and $M_{\{i\}^f}(\{\{i\}^f, \{h, k\}^H\}) = 0.225$ for $f = A, H$ and $M_{S_j^f}(B) = 0$ otherwise. The necessary restriction for positive labour supply in foraging is $\theta K(B) > 1$, given $\overline{K} = 10$ for pure foraging structures we will restrict $\theta > 0.1$ and to larger θ in mixed coalition structures where the externality becomes operative $K(B) < \overline{K}$.

Finally there is relationship of θ and ϕ. We will assume that $\phi = \theta - 1/\overline{K}$ so that in the earliest of times both begin on the verge of viability and grow one for one over time (perfect technological spillovers). This is of course a weaker assumption then A.1 because both are initially equally viable. Because it is weaker we cannot simply rely on the proofs above, for example, we must prove that an agriculture is not the initial equilibrium outcome.

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: See Appendix 1.■

Because of the added structure of the example we can go further than Proposition 2.

Result 2a: *For $\lambda = 0$ and for higher levels of technology ($1 < \theta < 2.103$), 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: See Appendix 1.■

For this example the $\underline{\theta}$ of the previous section is precisely unity which explains why the grand band breaks down but here you can go further and prove that the unique equilibrium coalition structure is the singleton coalition structure for $\lambda = 0$. The result can be extended to $\lambda \geq 0$ in a limited way.

Result 2b: *For $\lambda \geq 0$ and for higher levels of technology ($1 < \theta < 2.103$), 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: See Appendix 1.■

Thus, when farming imposes a negative externality on foraging, there can be multiple equilibria and multiple equilibrium outcomes. We interpret this result as showing, realistically, that there would be no unique path from foraging to agriculture during the Mesolithic. Note that the equilibria that can obtain with the farming externality, and that could not obtain without it, involve mixed coalition structures. The intuition for multiple equilibria is as follows. When there is no externality, the payoff from foraging is relatively high in mixed structures. Because foraging is attractive, all individuals become foragers and no one chooses farming, thereby mixed structures are avoided. Alternatively, when there is an externality, the payoff from foraging is relatively low in mixed structures. Because foraging is not so attractive, some farmers in mixed structures do not have profitable deviations to foraging, thereby supporting the mixed equilibrium.

We now illustrate Proposition 3.

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: See Appendix 1.■

We now graph the foraging stock (Figure 1) and utility (Figure 2) for $\lambda = 0$ at full equilibrium B^*.

— FIGURE 1 AND 2 —

So at $\theta = 1$, the cooperation breaks down, the band splinters and their is a catastrophic increase in work, decrease in consumption, leisure, and utility through over–exploitation of the environment and thus drop of the shared foraging stock—a food crisis. Eventually there is a smooth transition to a pure agricultural structure

We now provide a new result that could not have been obtained in the more general framework of last section.

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: The example provided in Appendix 2.■

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 Paleolithic, most anthropologists would only be satisfied with a model incorporating the notions of cooperation and 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.

We intentionally avoided the population growth explanation. As was argued in section 2, it is probably correct to say that the jump in the population growth rate observed at the start of agriculture was caused by humans switching to agriculture — not the reverse. We also avoided the exogenous environmental shock explanation. Indeed, it is hard to imagine that the 'right' transition–generating shock could have occurred in all the locations in which the transition took place, within a relatively short period of time. Also, environmental shocks of all sorts happen frequently. One would therefore need an explanation as to why, for thousands of years, shocks did not trigger the transition, and why they eventually did. This being said, we provide a new explanation, but we do not claim that others did not play an important role.

The explanation for the transition offered in this paper is based on technological growth and the incapacity of bands of foragers to maintain cooperation when foraging has become too productive. That technology improved steadily throughout human history is hardly controversial; it is a well accepted fact by all social scientists.

Our story provides an explanation for the endogenous occurrence of the transition and generates a number of other endogenous phenomena, not all of which could have been obtained with the population or the environmental shock explanations.

- 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).

- A food-crisis 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.

The study of how we became farmers thousands of years ago is, in itself, interesting. But the mechanism that we identified 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, irrigation systems, etc. 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. Of course, traditional fishermen have suffered the most from the introduction of the more effective technology.

The idea that human institutions evolve is not new in economics (North, 1993). Models that allow for the systematic and rigorous study of the non-cooperative formation of equilibrium institutions or communities which aim to facilitate cooperation, however, are only now becoming widely available.[31] If anthropologists are right, 99% of our existence and much of our evolution occurred in such communities. If Ostrom (1990) is

[31] See Ray and Vorha (1997) for a discussion of recent developments.

right, these institutions are an important and policy relevant component of modern societies. This is further strengthened by consideration of the global environmental problems we now face. Thus, we hope that the application of these models to the study of the evolution of human institutions may prove to be fruitful.

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11 Appendix 1

Proof of Result 1:

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

Using (7) and (12) 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.[32] 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

[32] 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.

$U_i^H(\{h\}^H, \{i\}^H, \{k\}^H) > U_i^A(B)$ 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 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 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.■

Proof of Result 2a:

From (7) and (12) at $\theta > 1$, $U_k^H(\{\{h,i\}^H, \{k\}^H\}) > U_k^H(\{\{h,i,k\}^H\})$ and at $\theta > 2.103$ some agricultural payoffs come to dominate some payoffs in rows 1–3 (see Table A1.3).

Table A1.3: Ranking of Payoffs, $\lambda = 0$, $1 < \theta < 2.103$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
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.■

Proof of Result 2b:

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, $\lambda > 0$, $\theta \in]1, 2.103[$

	$R_h(B)$	$R_i(B)$	$R_k(B)$
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 $S_i^H = S_k^H = \{h,i,k\}^H$.■

Proof of Result 3:

From (7) and (12) 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.■

12 Appendix 2

We now assume that parameters are as in the main text, but that $\lambda = 1$. Table A2.1 summarizes the results. Examples of payoff tables that were used to construct Table A2.1 are available upon request.

Table A2.1: Equilibrium Strategy Profiles, $\lambda = 1$

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

In earlier times ($\theta < 1$), when both technologies are relatively inefficient, the equilibrium coalition structure is a grand band of foragers. Eventually, knowledge has developed enough ($1 < \theta < 2.165$) for the grand band of foragers to collapse in favor of singleton bands of foragers. Note that still, no one has switched to agriculture. Further advances in knowledge ($2.165 < \theta < 2.399$) 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 ($2.399 < \theta < 2.716$), 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 ($\theta > 2.716$), everyone has turned to agriculture.■

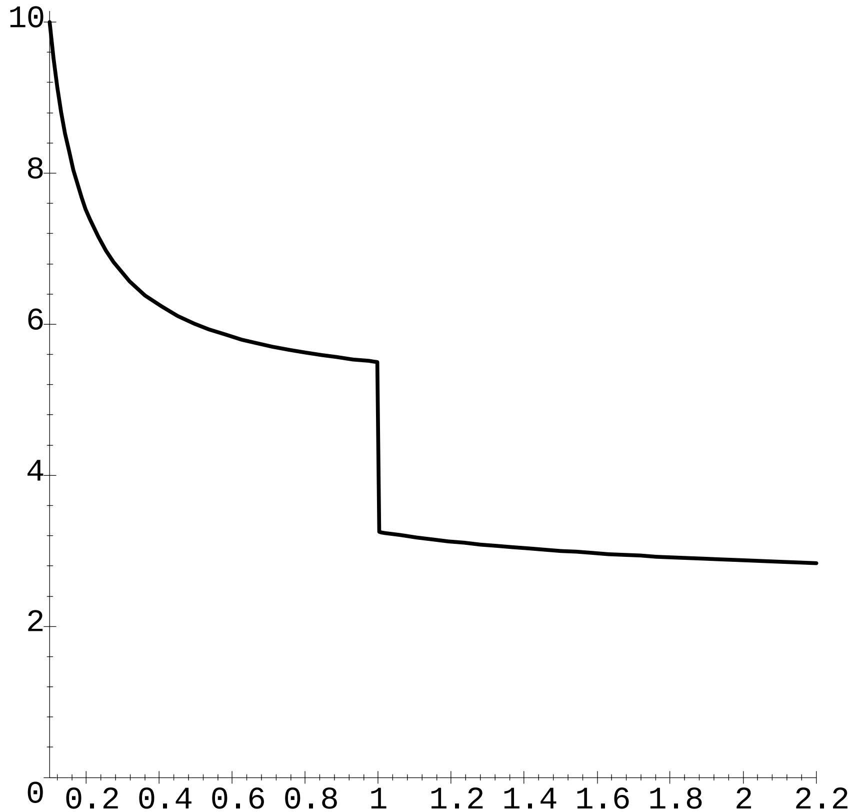

Figure 1: Equilibrium Foraging Stock

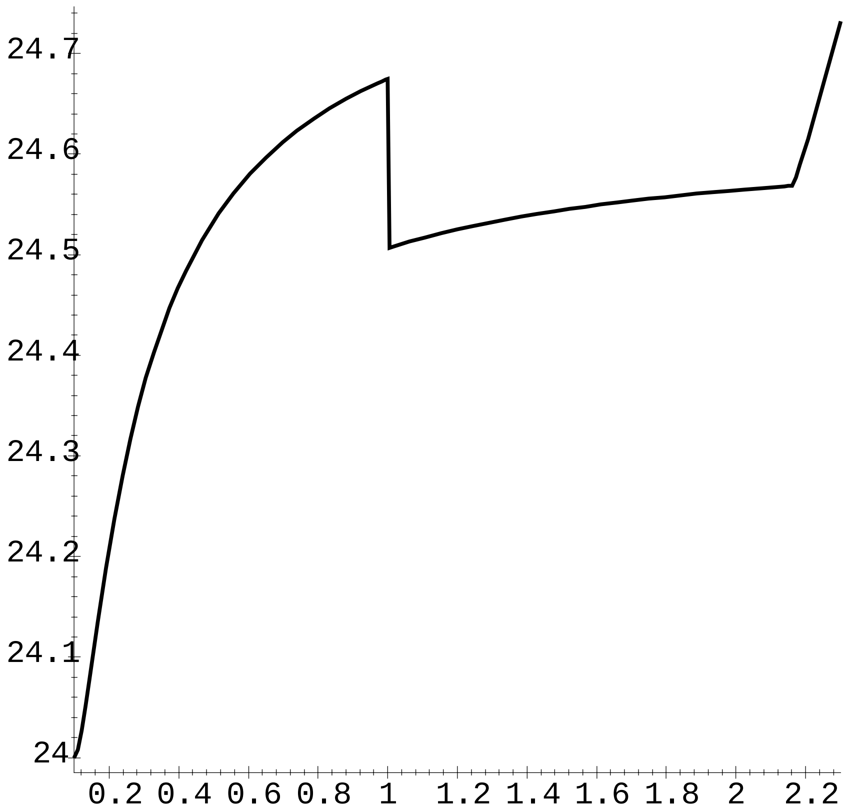

Figure 2: Equilibrium Utility